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Dedication

To the One that sees me, Psalms 139.

ABSTRACT	4
Chapter 1 – Introduction.....	7
Chapter 2 - Multiscale structural analyses of Mesozoic shallow-water carbonates, Viggiano Mt., southern Italy.....	22
2.1 Introduction	22
2.2 Geological Setting	23
2.3 Methods	26
2.3.1 Field structural analyses.....	26
2.3.2 Digital structural analyses	28
2.4 Results	29
2.4.1 Field fracture analyses	37
2.4.2 Digital structural analyses	30
2.5 Discussion	34
2.5.1 Diffuse vs localised deformation.....	45
2.5.2 Deformation of single carbonate units	46
2.5.3 Outcrop to reservoir scale fault and fracture properties	49
2.6 Conclusions	49
Chapter 3 - Multiscale Discrete Fracture Network Modelling of shallow-water carbonates: East Agri Valley Basin, southern Italy	52
3.1 Introduction	52
3.2 Geological setting	54
3.2.1 The Southern Apennines	54
3.2.2 The High Agri Valley Basin	55
3.2.3 Viggiano Mt.....	55
3.3 Methods	58
3.3.1 Photolineament Interpretation	58
3.3.2 Field acquisition.....	58
3.3.3 Digital structural data acquisition and analysis	59
3.3.4 Discrete fracture network modelling	60
3.4 Results	64
3.4.1 Morphological lineaments	64
3.4.2 Field structural data	69
3.4.3 Digital structural data.....	70
3.4.4 Input data for DFN modelling	72
3.4.5 Results data for DFN modelling.....	75
3.5 Discussion.....	81
3.5.1 Geometry of the fracture and fault networks.....	81
3.5.2 Storage capacity and fluid flow properties.....	83
3.5.3 Conceptual model.....	84
3.6 Conclusion	85
Chapter 4 - Stress-induced permeability anisotropy and fluid flow dynamics in a Mesozoic fractured carbonate aquifer of southern Italy.....	87
4.1 Introduction	87
4.2 Method.....	89
4.2.1 Discrete fracture network modelling	89
4.2.2 dfnWorks	89
4.2.3 Fluid flow simulation	93
4.2.4 Stress-Aperture correlation.....	95
4.2.5 Solute transport simulation.....	98
4.3 Results.....	99

4.3.1 Discrete fracture network modelling results.....	100
4.3.2 Effective permeability results.....	101
4.3.3 Solute transport simulation results.....	107
4.4 Discussion.....	109
4.4.1 Permeability anisotropy in open fracture DFN models and stressed DFN models	109
4.4.2 Effective permeability-depth correlations	111
4.4.2 Conclusion	112
Chapter 5 Conclusion.....	113
Acknowledgement	119
Reference list	120
Appendix 3.1.....	153
Appendix 3.2.....	153
Appendix 3.3.....	154
Appendix 3.4.....	154
Appendix – Structural analyses and DFN modelling of faulted and fractured platform carbonates, Raparo Mt. Southern, Italy.....	155
A.1 Introduction to the Raparo Area	155
A.2 Methods	159
A.3 Carbonates of Top Raparo.....	159
A.4 Carbonates of Raparello Mt.	166
A.5 Carbonates of Castelsaraceno.....	173
A.6 DFN modelling for the carbonates of Castelsaraceno	187
A.7 Results from DFN modelling.....	188
Code 1.....	199
Code 2.....	201
Code 3.....	204

ABSTRACT

This dissertation investigates the Lower Jurassic to Cretaceous fractured shallow-water carbonate aquifer of Viggiano Mt., located on the eastern edge of Italy's High Agri Valley Basin. Covering approximately 13 km² with a thickness of 500-600 meters, this unconfined aquifer represents a significant hydro-structure bordered by semi-permeable to impermeable siliciclastic rocks and basinal carbonates. The entire succession resides within the Southern Apennines fold-and-thrust belt. This aquifer's hydrodynamics is defined by an intricate network of fractures, faults, and karst features, associated with the East Agri Fault System (EAFS) and characterized by a polygonal-like structural configuration, in which the N90-120E, N20-30E, and N130-150E high-angle sets are the most common. Recharge is predominantly driven by meteoric fluids entering the aquifer through these faults, while major springs serve as primary discharge points. The boundary of the hydro-structure is defined by the contact between limestone and flyschoid sediments, as well as by the overthrust plane of the Apennine platform on Miocene basinal units.

To advance the innovative exploration and sustainable utilization of groundwater within these carbonate aquifers, this study integrates field and digital outcrop structural survey techniques for a multiscale spatial, geometrical, and dimensional analysis of fractures and faults, to assess the overall contribution provided by mesoscale fracture network to aquifer storage and transport properties. Field data were collected through linear and circular scanlines, complemented by drone surveys, with structural data extracted via specialized software (Openplot®). By assessing the influence of carbonate lithofacies, structural position, and observation scales, this research quantifies the 1D and 2D fracture density and intensity and characterizes the dimensional properties of individual fault and fracture sets.

Additionally, field and digital structural data were used as input parameters for Discrete Fracture Network (DFN) models of geocellular volumes reflecting the observed bed packages (5m volumes), outcrops (50m volumes), and reservoir-scale carbonate cliffs (500m volumes). DFN models, calibrated with minimum mechanical aperture values from field data for porosity and theoretical hydraulic aperture values for permeability, address challenges posed by weathering and dissolution on field-measured apertures. High-resolution DFN models simulate the impact of varying aperture values under depth-equivalent stresses, analysing their effects on effective permeability and solute transport.

Our first assessment enabled us to compute a 2D fracture intensity (P21) of ca. 20 for over 3 orders of magnitude, while P20 (2D fracture density) values exhibited inconsistency. Without considering the control exerted by the single carbonate lithofacies, at a reservoir scale, we document local variation in the computed P21 values due to small-scale faults which impacted computed results. Also, we recorded notable variability in fracture density and intensity across carbonate lithofacies.

Secondly, our findings reveal that a scale-dependent geometry characterizes the Cretaceous carbonates over three orders of magnitude. These results support previously published data, and contrast with those obtained for the Lower Jurassic carbonates, which suffer of some bias due to the quality of the exposures. DFN modelling indicates that fracture porosity is predominantly due to SB and NSB fractures, with increased equivalent permeability within faulted rock volumes. In terms of horizontal permeability, which is the most reliable result after DFN modelling, we document near isotropic horizontal permeability ellipses at all scales of observations. At individual outcrops, we note that the permeability ellipses are elongated parallel to the dominant fault sets highlighting the influence of strain on fluid flow directionality. The results are summarized in form of a conceptual model that illustrates the

modalities of meteoric fluid infiltration through the vadose zone, and then subsequent horizontal flow in the phreatic zone present within the fracture carbonates at shallow depths.

Stressed DFN models demonstrate enhanced anisotropy and early solute particle breakthroughs due to channelized flow paths within stressed fracture networks, underscoring the dynamic fluid transport properties of fractured carbonates under realistic stress conditions. This work contributes a framework for groundwater exploration within similar geologic settings by demonstrating the spatial variability, petrophysical and hydromechanical behaviour of fractured carbonates across multiple scales.

The contribution provided by this research provides high resolution data to better optimize results from hydrogeological studies, and their application to the assessments of groundwater flow dynamics within the Viggiano mt. aquifer, especially pertaining to groundwater contamination and remediation. The outcome finds application in similar hydrogeological settings, where the Mesozoic carbonate aquifer is characterized by a network of multiple fracture sets and is not heavily karstified.

CHAPTER 1 – INTRODUCTION

Fractured and karstified carbonate aquifers underlie a land area covering ~15% of the earth's surface, and account for ~25% of the Earth's drinkable water (Ford and Williams, 1989, 2007; Flugel, 2013; Stevanović, 2018; Medici et al., 2021). This type of aquifers possesses heterogeneous petrophysical properties that are heavily dependent upon the depositional settings, diagenetic evolution, and tectonic history of the carbonate rocks (Pollard and Aydin, 1988; Peacock and Sanderson, 1995; Kelly et al., 1998; Agosta and Aydin, 2006; Tavani et al., 2008; Lavenu et al., 2013). Often, the primary porosity is very low due to the profound influence exerted by diagenetic processes such as physical compaction, mechanical compaction and cementation on the present-day properties of the carbonate rocks (Tucker and Wright, 1990; Lucia, 2001, 2007; Flugel, 2004). Accordingly, most of the fractured and karstified carbonates form type I and type II reservoirs, which are heavily dependent on fracture porosity for the extraction of geofluids (Nelson, 2001; Ahr, 2011).

It is well known that faults and fractures form preferential pathways for geofluid flow within low-porosity carbonates (Micarelli et al., 2006; Rustichelli et al., 2013a, b; Sibson 2020; Medici et al., 2021). In terms of main failure modes, besides the Mode II and III shearing modes, low-porosity carbonates often include Mode I fractures and pressure solution cleavage (Alvarez, 1978; Pollard and Aydin, 1988; Tanner 1989; Brahana et al., 1988; Ritzi and Andolsek 1992; Peacock and Sanderson, 1995; Odling et al., 1999; Kelly et al., 1998; Graham et al., 2003; Agosta and Aydin, 2006; Marchegiani et al., 2006; Tavani et al., 2008; Lavenu et al., 2013, 2014; Rustichelli et al., 2015; Agosta and Aydin, 2006; Kresic, 2013; Medici 2021; Manniello et al., 2023; Manniello et al., 2024). These fractures can develop within unconfined reservoirs and thus affect the modalities of meteoric water infiltration at depth (Palmer and Palmer, 2008). In fact, this type of fractures affects the directionality of fluid flow (Gillespie et al., 1993; Bonnet et al., 2001; Agosta et al., 2010; Ceccato et al., 2022; Smeraglia et al., 2024) and possibly lead to permeability anisotropies within rock masses (Lorenz et al., 1988, 1989; Le Garzic et al., 2011; Holdsworth et al., 2019; Abdallah et al., 2024). Hence, together with small faults, these sub-seismic structural elements, although mostly overlooked, profoundly affect the reservoir characteristics (Roehl and Choquette, 1985; Giorgioni et al., 2016; Zambrano et al., 2016; Panza et al., 2018; Giuffrida et al., 2019; Abdallah et al., 2024).

Small faults (sub-seismic scale) in low porosity carbonates can also inhibit flow as they form compaction bands with relatively lower value of porosity with respect to the surrounding host

rock (Micarelli et al., 2006; Tondi et al., 2006, 2010, 2012, 2014; Antonellini et al., 2014). Differently, shear bands in them can act either as barriers or conduits to fluid flow, depending on their mechanical processes (Aydin et al., 2006).

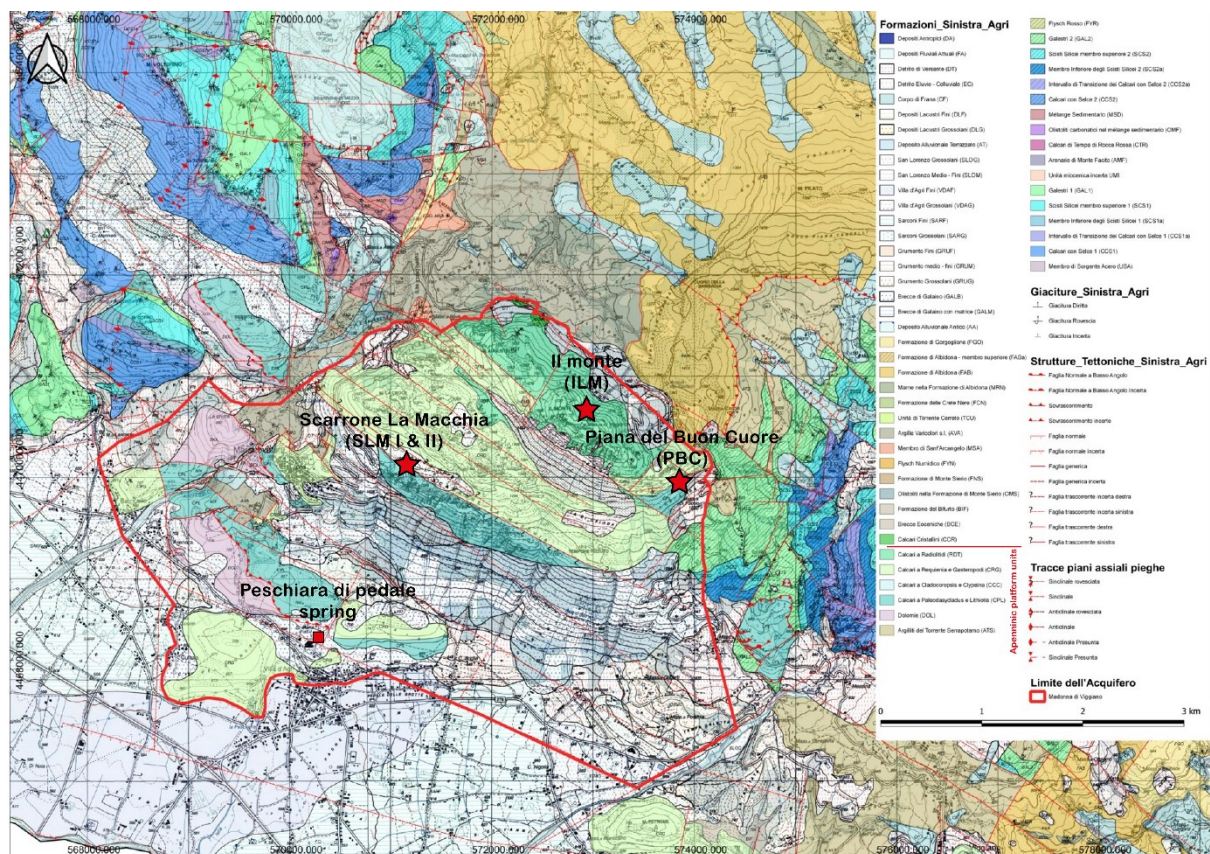
The properties of fractures within carbonates are controlled by the stratigraphic setting of the carbonates (Laubach et al., 2009; Bai et al., 2000; Manniello et al., 2023). Fractures such as those investigated in the present study occur as Strata Bound (SB) fractures, confined within single beds, Non-Strata Bound (NSB), those that cut across multiple beds but do not solve any significant amount of slip. The earlier ones are those whose propagation was arrested by the bed interfaces or any other traction-free heterogeneity (Schwarzacher and Fisher, 1982; Cooke et al., 2006; Helgeson and Aydin, 1991; Gross and Engelder, 1995), whereas NSB fractures as incipient faults that might result from the linkage of pre-existing SB fractures (Sornette et al., 1993; Cooke and Underwood, 2001; Graham et al., 2003; Crider and Peacock, 2004). The linkage processes typically result in vertically persistent discontinuities crosscutting and displacing multiple beds, and in the formation of new fractures within the narrow rock volumes bounding the mechanical interfaces (Peacock et al., 2017; Graham et al., 2003; Agosta et al., 2009, 2015; Antonellini et al., 2008; Aydin et al., 2010).

This doctoral dissertation investigates the contribution of meso-scale fracture networks to the storage and migration potential of the unconfined Lower Jurassic to Cretaceous shallow-water carbonate aquifer of the Viggiano Mt., southern Italy. Through a detailed multiscale structural analysis and the application of Discrete Fracture Network (DFN) modelling, the study examines the dimensional, geometrical, and spatial characteristics of these fractures, highlighting their significant contribution to fracture porosity and equivalent permeability. The research provides compelling evidence of the role of mesoscale faults and fractures dissecting Mesozoic shallow-water carbonates exposed along the axial zone of the southern Apennines fold-and-thrust belt.

This study finds its application not only in the exploitation and protection of groundwater resources (Strenltsova, 1976; Corniello et al., 2018; Odling et al., 2013; Medici et al., 2019), but also for the study of geothermal systems (Faulkner et al., 2010; Wrage et al., 2017; Peacock et al., 2022; Smeraglia et al., 2021; 2023; 2024; Rashid and Olorode, 2024), of nuclear repositories (Witherspoon et al., 1980; SKB, 2011; Mattila and Tommisto, 2012), and of carbon capture and storage (Zweigel et al., 2004; Iding and Ringrose, 2009).

The carbonate aquifer of Viggiano Mt. occupies an area of about 13 km² (Figures 1.1, 1.2), with a thickness of approximately 500-600 meters. This unconfined aquifer represents a significant hydro-structure, bordered by semi-permeable to impermeable terrigenous units and basinal carbonates. The aquifer's hydrodynamics is defined by an intricate network of fractures, faults, and karst features, associated with the East Agri Fault System (EAFS). Recharge is predominantly driven by meteoric fluids entering the aquifer through these faults, while major springs serve as primary discharge points (Figures 1.1, 1.2). The boundary of the hydro-structure is defined by the contact between limestone and flyschoid sediments (Figures 1.1, 1.2), as well as by the overthrust planes of the Apennine platform on Miocene basinal units (Figure 1.2) (Grimaldi, personal communication).

The study sites (Figures 1.1) of the Viggiano Mountain are respectively labelled as Il Monte (ILM), Piano del Buon Cuore (PBC), and Scarrone La Macchia (SLM I and SLM II). ILM marks the culmination of the shallow-water carbonates, lying in close proximity to the thrust front, and exposes Albian-Cenomanian carbonate rudstones and grainstones with gastropods, bivalves, rudists (radiolitidae) and foraminifera originally deposited along the paleo-slope of the carbonate platform (Lechler et al., 2012; Manniello et al., 2022). At the foothills of the ILM outcrop, PBC exposes Lower Cretaceous - Upper Jurassic limestones whose clasts consist of oolites, oncolites and intraclasts. The limestones were likely deposited in a high-energy platform margin environment (Palladino et al., 2023). Both SLM I and SLM II expose Lower Jurassic limestones. The rocks consist of oolitic carbonates (SLM I), and carbonate wackestone-packstones to grainstones arranged in well-layered, discrete bed packages bounded by mm-to-cm thick, clay-rich interfaces (SLM II). The Toarcian oolitic carbonates are characterized by bed amalgamation and were originally deposited in a ramp setting rimmed by oolitic sand shoals. The well-layered carbonate succession is Sinemurian–Pleinsbachian in age and was originally deposited in a low-energy open lagoon environment (Lechler et al., 2012; Manniello et al., 2022).



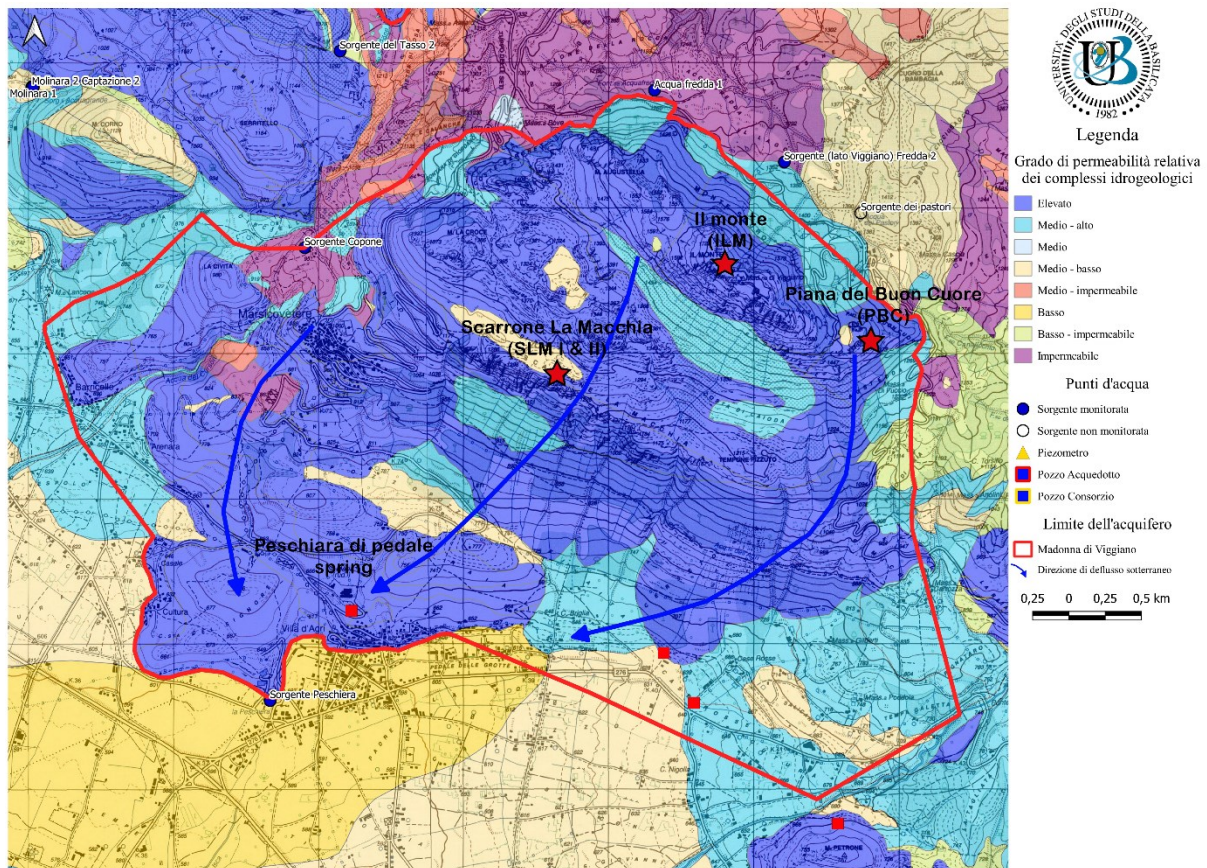


Figure 1.2 Hydrogeological map of the Viggiano mountain aquifer (Grimaldi, personal communication)

According to the afore-mentioned motivation, the main objectives of this doctoral research work carried out during the last three years of activity are the following:

- (1) to assess the influence exerted by high angled basin-bounding faults on carbonate lithofacies and geometry and distribution of networks of fractures across different scales, from outcrop to reservoir scale (Chapter 2).
- (2) to assess the control exerted by mesoscale structural elements on the storage and transport properties of fractured carbonates; and to investigate the variation in computed values of fracture equivalent permeability and flow anisotropy throughout the carbonate succession. This will be achieved by building multiscale DFN models with Move ® software, with data acquired by means of integrated field and digital structural analyses (Chapter 3).
- (3) Build DFN models with high-resolution-computational-mesh using the parallel processing and high computational code, dfnWorks®, to compute depth-equivalent effective permeability results (eff_{kxx}/eff_{kyy}) for the fracture network, hence achieving more realistic values for flow anisotropy as a function of aperture closure/opening as a function of local

stresses. Carry out non-reactive Lagrangian solute transport simulation to assess the flow dynamics and determine the modalities of contaminant dispersion in similar fractured networks (Chapter 4).

(4) Carry out a preliminary structural investigation and DFN modelling of Mesozoic carbonates of Mt. Raparo. High Agri Valley Basin, southern Italy using methodologies applied in Chapter 2 and 3 (Appendix A)

Each one of the specific points listed above is addressed in a specific chapter of this PhD Thesis Dissertation, which consists of the following:

CHAPTER 2: MULTISCALE STRUCTURAL ANALYSES OF MESOZOIC SHALLOW-WATER CARBONATES, VIGGIANO MT., SOUTHERN ITALY

This chapter was published as a research paper in [Volume 176](#), November 2023, of the [Journal of Structural Geology](#) 104978. It was accepted for publication 8th October 2023, and titled, “Multiscale structural analyses of Mesozoic shallow-water carbonates, Viggiano Mt., southern Italy”. The Authors were: I.B Abdallah, C. Manniello, G. Prosser, and F. Agosta.

In this paper, analyses were performed on outcrops of on single outcrops of 5 – 100m in lateral extension. The field of study was the Mesozoic carbonates of the Viggiano Mt. of Basilicata, southern Italy. Laboratory modelling activity (Photogrammetry and digital structural analyses) was carried out at the university of Basilicata, Italy.

The abstract of the published research article is the following:

The high-angle faults bounding the High Agri Valley Basin eastwards are well-exposed at the Viggiano Mt., southern Italy. There, these faults crosscut Mesozoic shallow-water carbonates and permit multiscale analysis of fault and fracture geometry and distribution. Aiming at assessing the control exerted by carbonate lithofacies and scales of observation, we combine field and digital structural analyses to compute the values of 1D and 2D fracture density and intensity, and the dimensional properties of single fault and fracture sets. As a result, from outcrop to reservoir scales we document a scale-variant geometry of faults and fractures, and the great variation of both fracture density and intensity among the carbonate lithofacies studied. Furthermore, we compute a P21 dimensional scaling factor of ca. 20 for over 3 order magnitude, whereas inconsistent results are achieved for the P20 values. Not considering the

control exerted by the single carbonate lithofacies, at a reservoir scale we document that the small-scale faults greatly impact the computed P21 values.

Chapter 3: Multiscale discrete fracture network modelling of shallow-water carbonates: East Agri Valley Basin, Southern Italy

This chapter was published as a research paper in [Marine and Petroleum Geology, Volume 169](#), November 2024, 107048. It was accepted for publication 5th August 2024, and titled, “Multiscale discrete fracture network modelling of shallow-water carbonates: East Agri Valley Basin, Southern Italy”. I. B Abdallah, E. Panza, S. Dastoli, C. Manniello, G. Prosser and F. Agosta. This paper builds on the earlier published paper of Chapter 2 and expands the database for outcrop of up to 500 m in lateral extension. The field of study was the Mesozoic carbonates of the Viggiano Mt. of Basilicata, southern Italy. Laboratory modelling activity (photogrammetry, digital structural analyses, discrete fracture network modelling) was carried out at the university of Basilicata, Italy.

The abstract of the published research article is the following:

We investigate the multiscale geometrical and dimensional properties of fracture and fault networks crosscutting Lower Jurassic to Cretaceous shallow-water carbonate rocks. The carbonates are exposed along the flanks of the Viggiano Mt., on the eastern side of the High Agri Valley Basin of southern Italy. Furthermore, we employ the results of field and digital structural analyses to derive the input parameters for subsequent Discrete Fracture Network modelling (DFN) of geocellular volumes whose dimension and architecture resemble those of the investigated sites. DFN modelling is carried out for geocellular volumes representing the studied bed packages (5m-side volumes), outcrops (50m-side volumes), and reservoir-scale carbonate cliffs (500m-side volumes). Notably, modelling is obtained considering the minimum mechanical aperture value obtained in the field for porosity computations and theoretical values of fracture hydraulic aperture for permeability computations. This is because the mechanical aperture values and roughness profiles collected in the field along single fractures are unreliable due to weathering and localized karst-related dissolution. Our findings reveal that a scale-dependent geometry characterizes the Cretaceous carbonates over three orders of magnitude. These results support previously published data, and contrast with those obtained for the Lower Jurassic carbonates, which suffer of some bias due to the quality of the exposures. After DFN modelling, we show that the amount of computed fracture porosity is

mainly due to the SB and NSB fractures, and that equivalent permeability is greater within faulted rock volumes. In terms of horizontal permeability, which is the most reliable result after DFN modelling, we document near isotropic horizontal permeability ellipses at all scales of observations. At individual outcrops, we note that the permeability ellipses are elongated parallel to the dominant fault sets that denotes how localized strain affects the directionality of fluid flow. Finally, we summarize the original data in a conceptual model illustrating the modalities of meteoric fluid infiltration through the vadose zone, and then subsequent horizontal flow in the phreatic zone present within the fracture carbonates at shallow depths.

chapter 4: Stress-induced permeability anisotropy and fluid flow dynamics in a Mesozoic fractured carbonate aquifer of southern Italy

This chapter is an unpublished research work. It includes the results of fluid flow and solute transport simulation carried out at The University of Manchester, where I collaborated with Prof. Cathy Hollis, professor of carbonate sedimentology and head of carbonate geoscience laboratory, Professor David Healy, an expert in Geomechanics and director of Geosolutions at the University of Leeds, UK., and Dr. Jeffrey De' Haven Hyman, who is the developer of the dfnWorks code, at the Computational Earth Science Group (EES-16), Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM, USA. Fluid transport simulation was performed at the Basins laboratory at the university of Manchester and virtually from the University of Basilicata accessing the Computational Shared Facility (CSF) and High-Performance Computing (HPC) devices of The University of Manchester.

The abstract of the research article is the following:

Understanding the impact of local stress states on fluid flow and permeability anisotropy in fractured rock aquifers is essential across a wide range of geological and engineering disciplines, including groundwater management, hydrocarbon extraction, and geothermal energy development. One region where these effects are particularly relevant is the Mesozoic fractured carbonate aquifers of Southern Italy, a complex geological system where fluid flow is heavily influenced by fracture to fault - induced permeability.

Covering approximately 13 km² with a depth of 500-600 meters, this unconfined aquifer represents a significant hydro-structure bordered by semi-permeable to impermeable basal carbonates. The entire succession resides within the Southern Apennines fold-and-thrust belt. This aquifer's hydrodynamics are defined by an intricate network of fractures, faults, and karst

features, associated with the East Agri Fault System (EAFS), which form a polygonal-like system including N90-120 left-lateral transtensional faults, N20-30 right-lateral transtensional faults, and N130-150 extensional faults. Recharge is predominantly driven by meteoric fluids entering the aquifer through these faults, while major springs serve as primary discharge points.

By employing existing data collected from integrated field and digital structural analysis and subsequent realisations of 5m-side Discrete Fracture Networks (DFN) models with high-resolution computational meshes capable of non-reactive solute transport simulation, we impose depth-equivalent stresses and assess the varying effective permeability ($effk_{xx}/effk_{yy}$) as a function of aperture closure or opening due to shear displacement.

Focusing on the results achieved at Viggiano mt.-aquifer-depth of 500m, coupled with equivalent stresses of ~13MPa, 10 MPa, and 7.58 MPa, σ_v , σ_{Hmax} , σ_{Hmin} , respectively, and comparing with the scenario of unstressed-open fracture-DFN models, effective permeability results from SLM I, PBC, ILM exhibit an increase in permeability anisotropy ratio as a function of the stresses, hence, supporting flow channelling within the network. Lagrangian solute transport simulation supports the afore-mentioned results by marked changes in primary flow path, increase in path tortuosity, as a function of stress, and delay in breakthrough time. Differently, SLM II undergoes the opposite effect, where the permeability ratio seems to reduce drastically at a depth of 500m and stabilizes after that. We infer this behaviour as due to non-linear behaviour fluid flow as a function of aperture closure or dilation, as seen sometimes in a highly connected system of fractures that are subjected to both normal and shear stresses, characterized by combined closure due to normal stresses and opening of previously closed flow-paths due to shear-dilation effect.

This research provides high resolution data to better optimize results from hydrogeological studies, and their application to the assessments of groundwater flow dynamics within the Viggiano mt. aquifer, especially pertaining to groundwater contamination and remediation. The outcome finds application in similar hydrogeological settings, where the Mesozoic carbonate aquifer is characterized by multiple fracture sets and not heavily karstified.

Appendix: Multiscale structural analyses and DFN modelling of Eocene – Cretaceous shallow-water carbonates, Raparo Mt Southern Italy

This chapter was originally compiled as part of a 6-month internship scientific report to the co-sponsors of the doctoral programme - FEEM Srl and Eni SpA submitted in December 2023 by the PhD student, I.B Abdallah. Analyses was carried out and compiled with support from F. Agosta, C. Manniello, S. Todaro, E. Romaniello and G. Prosser.

This chapter shows results of preliminary structural investigation carried out on Eocene – Lower Cretaceous shallow water carbonates and subsequent multiscale fluid flow and storage analyses to ascertain the contribution of fine to meso scale structural elements. The field of study was the Mesozoic carbonates of the Raparo Mt. south-eastern part of the High Agri Valley (HAV) Basin, Basilicata, southern Italy. Laboratory activity was carried partly at out at the university of Basilicata, Italy (photogrammetry, digital structural analyses, discrete fracture network modelling) and Università of Palermo, Sicily, Italy (Petrographic and microfacies analyses).

The abstract of the appendix is the following:

We investigate the multiscale geometrical and dimensional properties of fracture and fault networks crosscutting Eocene – to Lower Cretaceous shallow-water carbonate rocks. The carbonates are exposed at the Raparo Mt. area, on the south-eastern side of the High Agri Valley Basin (HAV), of southern Italy. The carbonates were initially affected by contractional deformation (reverse faults and overthrusts) during late Miocene compressional regimes and subsequently, transtensional tectonics (high-angle faults) during Plio- Quaternary extensional tectonics.

The shallow water carbonates in the area are quite peculiar relative to the other parts of the HAV basin in that they form gentle folds characterised by interbedded argillaceous clays with multiple sets of calcites filled fractures, relative to the north-east HAV basin with tabular beddings and scarce occurrence of veins. Another interesting feature is the occurrence of syn-sedimentary clasts, some of which consist of hairline veins with bitumen rich infillings within mudstone carbonate beds. Patches of dolomitised carbonates are also observed.

The bedding attitude of these outcrops changes spatially dipping from NNE - NE – E in correspondence with local thrusts and extensional faults that affected these carbonates, corresponding to regions that show onlap, downlap and toplap stratal geometries. The regions of which are denoted accordingly as units/decollements for subsequent modelling purposes. In this area of study, evidence of flexural slip is common, with flat – ramp - flat geometries beautifully exposed along trail cuts, bed-parallel veins and visible kinematic markers.

Firstly, we study deformation related to flexural processes (footwall-flat and hanging wall-ramp damage zones, footwall flat and hanging wall flat) at different scales, then we employ the

results of field and digital structural analyses to derive the input parameters for subsequent Discrete Fracture Network modelling (DFN) of geocellular volumes whose dimension and architecture resemble those of the investigated sites, according to the previous units/decollements. DFN modelling is carried out for geocellular volumes representing the studied bed packages (5m-side volumes), and reservoir scale (50m-side volumes). Since the aperture values collected at the outcrop scale varies proportionally with height/length, modelling at the bed-package scale is carried out using hydraulic aperture values computed from real-field acquired mechanical aperture values. At the 50m scale, we adopt the minimum mechanical aperture value obtained in the field for porosity computations and theoretical values of fracture hydraulic aperture for permeability computations.

Preliminary findings reveal a two-order magnitude of scale-dependent geometry that characterizes the Cretaceous carbonates. After DFN modelling, we show that the contribution to porosity is mainly provided by large scale structural elements (4.7m – 50m height), such as persistent fractured zones and faults captured from digital interpretations, while the equivalent permeability is greater within the SB and NSB fractures (0.1m – 4m height) due to their interconnectivity.

Near isotropic horizontal permeability ellipses are assessed at all scales of observations. At individual outcrops, we note that the permeability ellipses are elongated parallel to dominant WNW–ESE to NW–SE and NNE–SSW to NE–SW fault trend that corresponds to the so-called Apennine and Anti–Apennine fault trends, respectively. Collectively, the occurrence of these fracture – fault sets denote how localized strain affects the directionality of fluid flow.

Abroad - visiting research period

Towards the end of the second year of my PhD work, I spent two months (December 2023 – February 2024), at the University of Maiduguri, Borno State, Nigeria, as part of a reconnaissance survey. Also, my supervisors granted me an opportunity to get acquainted with the geology of Nigeria. There, I visited a quarry that exposes Pindiga Formation. They form a major part of the Gongola Basin, an Upper Cretaceous syn-depositional Basin. They comprise fossiliferous limestones intercalated with shales. However, a report is not compiled as it falls out of the scope of the research.

I spent four months (April 2024 – July 2024) at The University of Manchester, where I collaborated with Professor Cathy Hollis, and virtually with Prof. David Healy from the University of Leeds, UK and Dr. Jeffrey De'Haven from the Los Alamos Laboratory, New Mexico, USA. Here, I spent time getting acquainted with dfnWorks® which allowed to build High-Resolution-Mesh (HRM) DFNs, that are capable of flow and solute transport simulations. Part of the results are the ones shown in Chapter 4. During my stay there, I participated in several training sessions. Amongst them are dynamic modelling sessions on Eclipse®, python coding training for geological applications, and High-Performance Computing (HPC) to mitigate computational resource challenges related to my research.

In total, I performed 160 simulations. These HRM modelling analyses were only performed for the 5m-side scale DFNs due as limited time left on the project. Hence representative models were built for the SLM I, SLM II, ILM and PBC outcrops. Large scale models to be built, hopefully soon.

During the three years spent at the University of Basilicata for the PhD research work, I had the opportunity to present my results at several meetings, seminars, workshops and conferences, as listed below:

1. Meeting with Eni Geoscience team from Milan 24th August 2022
DFN modelling of fractured and faulted platform carbonates (case study: Cretaceous – Jurassic carbonates of Southern Italy)
2. EGU General Assembly, Vienna, Austria, April 2023
From digital outcrops to DFN modelling of fractured platform carbonates
Abdallah Ian, Manniello Canio, Prosser Giacomo, Agosta Fabrizio
3. Meeting with TotalEnergies - Workshop Reservoir Characterization Project, April 2023
DFN modelling of fractured and faulted platform carbonates
4. Departmental Seminar for undergraduate and postgraduate students at Aula 3, university of Basilicata, Italy, 15th May 2023
Reservoir-scale structural architecture of high-angle basin-bounding faults in Mesozoic platform carbonates

5. Meeting with TotalEnergies - First midterm meeting, Reservoir Characterisation Project, October 2nd, 2023
Structural analysis and DFN modelling Outcrop-to-reservoir scale variations of storage and migration fluid properties in faulted Mesozoic shallow-water carbonates (ongoing work)
6. Geoscience workshop with Eni-Shell 8th May 2023
Structural analysis and DFN modelling of the Mesozoic platform carbonates of the Viggiano Mt., Basilicata
7. SGI – SIMP joint Congress, Potenza, September 2023
Reservoir-scale structural architecture of high-angle basin-bounding faults in Mesozoic platform carbonates. Abdallah Ian, Manniello Canio, Prosser Giacomo, Agosta Fabrizio
8. EGU General Assembly, Vienna, Austria, April 2024
Fracture porosity and equivalent horizontal permeability computed for shallow-water carbonates of the southern Apennines fold-and-thrust belt, Italy
Abdallah Ian, Panza Elisa, Manniello Canio, Prosser Giacomo, Agosta Fabrizio
9. IGC conference, Busan, South Korea, August 2024
Multidimensional structural analysis of the reservoir-scale fault damage zones flanking the eastern side of the High-Agri-Valley Basin, south Italy
Abdallah Ian, Manniello Canio, Prosser Giacomo, Agosta Fabrizio
10. SGI – SIMP pre-congress field trip 1 September 2023
Storage and migration fluid properties of carbonate rocks exposed in the Sorrentino peninsula, and High-Agri Valley of southern Italy – organised by Agosta Fabrizio, & Stefani Tavani
11. SGI – SIMP joint Congress Potenza, September 2023
DFN modelling of multiscale geo-cellular volumes after field and digital structural analyses.
Abdallah Ian, Panza Elisa, Prosser Giacomo, Giuseppe Palladino, Agosta, Fabrizio
12. SGI – SIMP joint Congress, September 2024
Multidimensional structural analysis of reservoir-scale fault damage zones flanking the eastern side of the High Agri Valley Basin, southern Italy Ian Abdallah, Cathy Hollis, David Healy, Giacomo Prosser, Fabrizio Agosta

13. University of Manchester/University of Leeds, Uk Professor's Field trip to Basilicata, Italy – organised by Giacomo Prosser, Fabrizio Agosta. Presenters – Giacomo Prosser, Fabrizio Agosta, Fabio Olita and, Ian Abdallah

Furthermore, the PhD research work also included both fieldwork and laboratory analyses whose results are not included in the present PhD thesis dissertation. These activities allowed me to collaborate with many researchers and gain a new knowledge on specific methods and field areas. In particular, during the activities carried out in my study area of the Agri Valley of southern Italy and similar analogues. I had the opportunity to assist the PhD colleague Canio Manniello with digital structural analysis, and another post-doc researcher, Dr. Rocco Novellino with digital and microstructural analysis. I supported the research of two bachelor students, Carmela Taddeo, Eugenia Romaniello, and one Master student, Stefania Dastoli, Some of them are listed below:

1. Pressure solution-assisted diagenesis and thrusting-related deformation of Mesozoic platform carbonates (research article published in June 2023 in the Journal of Structural Geology) C. Manniello, I.B. Abdallah, G. Prosser, F. Agosta
2. Structural architecture and micromechanics of the carbonate-hosted, Marsicovetere low-angle normal fault, southern Apennines, Italy (research article under revision in the Journal of Structural Geology) Novellino R., Prosser G., Bucci F., Tavarnelli E., Abdallah I. and Agosta F.
3. “Fracture stratigraphy of Mesozoic platform carbonates, Agri Valley, southern Italy”, poster presentation presented in 2022 at: AAPG Conference: Carbonate Reservoirs and Sequences... the Challenge Continues, At: Naples, Italy. The author's list is the following: Manniello, C., Agosta, F., Todaro, S., Abdallah, I. B., Prosser, G.
4. “The role of pressure solution in the evolving fracture stratigraphy properties of Mesozoic platform carbonates”, oral presentation at EGU General Assembly 2023, At: Vienna, Austria. The author's list is the following: Manniello, C., Todaro, S., Abdallah, I. B., Prosser, G., Agosta, F.
5. “Origin of bed-parallel mechanical interfaces affecting the fracture stratigraphy properties of Mesozoic platform carbonates, insights from the Viggiano Mt. of southern Italy” oral

presentation held at the SGI conference 2023. The author's list is the following: Manniello C., Todaro S., Abdallah I., Prosser G., Agosta F.

6. “Fault roughness associated to fault growth mechanisms along high-angle normal faults, first results from the field-based structural analysis of the Monte Capo di Serre Fault, Abruzzo”, presentation held at the SGI – SIMP Joint Congress, September 2024” Abdallah I., Dastoli S., Corradetti A., Taddeo C., Mercuri M., Curzi M., Agosta F.
7. BSc. Thesis - Structural analysis of the high angle fault zone outcropping at Monte Capo di Serre, Castel del Monte (AQ) by Carmela Emmanuela Taddeo
8. BSc. Thesis - Analysis of fracturing in carbonate rocks outcropping along the southern sector of Mount Raparo by Eugenia Romanello
9. Article in preparation for Journal of Structural Geology – Structural setting of the Castelsaraceno Area: New insights into the brittle deformation associated to orogenic thrusting and later dissection of the belt by A.M Kyari, I.B. Abdallah, E. Romaniello, S. Todaro, C. Manniello, G. Prosser and F. Agosta.

Workshop/training attendances:

1. Openplot ® training organized by CNR – IGAG cheered by Prof. Stefano Tavani
2. Natural fracture reservoir modelling training organized by Reservoir solutions limited
3. Static and dynamic Modelling training organized by Reservoir solutions limited
4. Well modelling training organized by Reservoir solutions limited
5. EU Project TWINN2SET - Energy transition summer school organised by FORTH/IG and the Technical university of Crete, Greece.
6. Scuola Piali 2024 - Geothermal reservoir modelling summer school - TOUGH2/TOUGH3 organized by the University of Perugia, Italy, cheered by Professors, Roberto Gambini, Alfredo Battistelli, Giorgio Minelli and Cristina Pauselli.

7. dfnWorks ® training organized by Los Alamos Laboratory, New Mexico, USA, cheered by Dr. Jeffrey de'Haven Hyman

CHAPTER 2 - MULTISCALE STRUCTURAL ANALYSES OF MESOZOIC SHALLOW-WATER CARBONATES, VIGGIANO MT., SOUTHERN ITALY

2.1. Introduction

High-angle faults play a critical role in the geometry, distribution, and petrophysical properties of fractured reservoirs (Nelson, 2001; Bense et al., 2013; Rotevatn et al., 2018, 2019). In shallow-water carbonates, these faults are characterized by complex interplays between diagenetic processes and deformation mechanisms (Graham et al., 2003; Aydin et al., 2010; Ferraro et al., 2018, 2019), which provide a difficult puzzle to precisely assess the anatomy of fractured carbonate reservoirs. At an outcrop scale, besides carbonate lithologies these complexities are associated to inherited depositional and diagenetic heterogeneities bounding individual beds and bed packages (Agosta and Aydin, 2006; Antonellini et al., 2008, Agosta et al. 2012, Corradetti et al., 2017; Manniello et al., 2023). At larger scale, the structural architecture of high-angle faults is characterized by heterogeneous carbonate damage zones (Mayolle et al., 2019; Volatili et al., 2021), which in terms of fluid flow are often interpreted as efficient hydraulic conduits for fault-parallel fluid flow (Aydin, 2000; Sagy et al., 2001; Agosta et al., 2010) encompassing lower permeability fault cores (Agosta et al., 2007; Ferraro et al., 2020). In reality, the great variations of carbonate lithofacies, petrophysical properties, and deformation mechanisms do not always allow the application of the aforementioned model to the subsurface shallow-water carbonate rocks (Lucia, 2001).

In this work, we investigate the Mesozoic shallow-water carbonates situated eastward of the Agri Basin, southern Italy, a region of interest for the production of hydrocarbon from subsurface fractured carbonate reservoirs, the occurrence of both natural seismicity, and induced microseismicity due to wastewater reinjection and water table fluctuations (Pantosti and Valensise 1990; Benedetti et al. 1998; Valoroso et al., 2009; Improta et al., 2010; Stabile et al., 2014, 2020; Improta et al., 2017; Rinaldi et al., 2020; Hager et al., 2021; Vadacca et al., 2021; Bello et al., 2022). There, sub-parallel high-angle faults crosscut the carbonates, and juxtapose sheared slope debris against the deformed carbonates (Palladino et al., 2023). We conduct a multiscale study of fault and fracture geometry, distribution, and both density and

intensity by combining field structural analysis with digital outcrop analysis. Results are discussed to unravel the possible control exerted by carbonate units and scales of observation on the afore-mentioned parameters. The outcomes of this work could be of importance to geoscientists and engineers dealing with deformation around basin bounding faults in fields such as hydrocarbon production geothermal energy, CCS, and sustainable use of groundwater within shallow-water carbonates (Philip et al., 2005; Lander et al., 2008; Olson et al., 2009, Giuffrida et al., 2019).

2.2 Geological setting of the study area of the Southern Apennines

The southern Apennines are a NE-verging fold-and-thrust belt (FTB), which formed during the late Oligocene–early Miocene to Pleistocene progressive collision between Africa and Europe plates, and the intervening Adria-Apulia plate (Patacca & Scandone, 1989, 2007). The southern Apennines FTB trends approximately N150 (Figure 2.1a), sub-parallel to the strike of the main thrust faults, and are dissected by Plio-Quaternary, high-angle faults associated with the aperture of the Tyrrhenian Sea and the gravitational collapse of the contractional edifice (Patacca and Scandone 2007; Vezzani et al., 2010). The present-day extensional tectonics is localized along the axial sector of the southern Apennines FTB, whereas thrusting occurs only in its frontal sector (Lavecchia et al., 1994; Montone et al., 1997; Oldow et al., 2002; Ferranti & Oldow 2005). The southern Apennines FTB formed due to the progressive stacking of several thrust sheets (Menardi Noguera & Rea, 2000), which involved the sedimentary cover of deep-water and oceanic basins (along with slices of oceanic crust) such as the Liguride, Sicilide, and Lagonegro basinal units, and the shallow-water Apenninic carbonate platform (Prosser et al., 1996; Piedilato and Prosser, 2005; Patacca and Scandone, 2007; Vezzani et al., 2010). The whole allochthonous units overrode the Apulian shallow-water carbonates along a low-angle decollement made up of a matrix-supported, over-pressurized tectonic melange (Menardi Noguera & Rea, 2000; Shiner et al., 2004; Scrocca et al., 2005; Butler and Mazzoli, 2006; Cippitelli, 2007; Mazzoli et al., 2014; Cavalcante et al., 2023).

Focusing on the shallow-water carbonates of the Apenninic platform, they were over-thrusted by the deep-water, ophiolite-bearing, Ligurian accretionary complex, and by the Sicilide units, and tectonically overrode the Lagonegro deep water unit (Amore et al., 1988; Bonardi et al., 1988a; Palladino et al., 2008; Ciarcia et al., 2009, 2012; Prosser et al., 2021). Then, further shortening was accompanied by a transition from thin-to-thick-skinned tectonics with the involvement of the Apulian Platform (Mazzoli et al., 2000, 2008, 2012; Butler et al., 2012),

which occurred during early Pliocene with the tectonic inversion of Permian-Triassic extensional structures (Mostardini and Merlini, 1986; Shiner et al., 2004; Butler and Mazzoli, 2006). Starting from late Pliocene, low-to-high angle transtensional faulting dissected the whole orogenic wedge, and hence promoted the partial tectonic elision of the Apenninic platform (Bucci et al., 2014; Novellino et al., 2015).

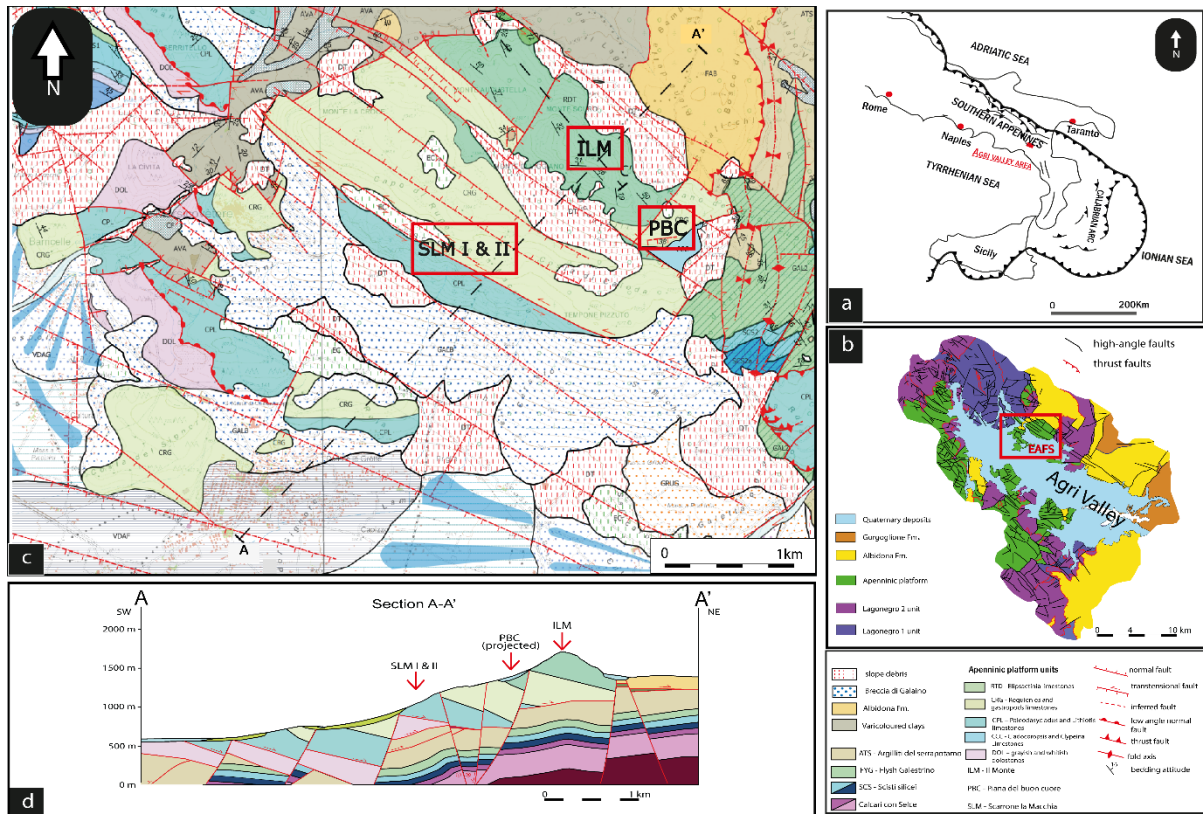


Figure 2. 1 (a) Tectonic map of the Southern Apennines showing NE-verging thrust and the Agri Valley basin (red box). (b) The geological map of Italy showing the Agri valley area and Apenninic platform carbonate of the Viggiano Mt. (shown in green) and EAFS (red box). (c) An expanded view of the highlighted area in figure b showing the study sites (in red) and a cross-section A-A'. Site ILM. Il Monte -Cretaceous carbonates. Site PBC. Piana del Buon Cuore -Lower Cretaceous - Upper Jurassic carbonates. Site SLM I & II. Scarrone la Macchia - Lower Jurassic carbonates (d) The cross-section A-A' running through the Agri valley basin cutting across NW-SE transtensional and antithetic normal faults and showing our study outcrops w.r.t to high-angle basin bounding faults. (Figs 1b-d modified after Palladino et al., 2023)

The study area of the Viggiano Mt. exposes a significant portion of the shallow-water carbonates of the Apenninic platform, spanning approximately 15km², and lying along the eastern flank of the High Agri Valley. The latter is a large intermontane sedimentary basin, whose nucleation started during Early-Middle Pleistocene, when the ancestral Agri Basin was

formed as a result of the N120 striking transtensional faults affecting the deposition of alluvial to lacustrine sediments (Di Niro et al., 1992; Di Niro & Giano 1995; Schiattarella et al., 1998; Giano et al., 2000; Maschio et al., 2005). Presently, the WNW-ESE elongated basin is bounded by high-angle faults pertaining to two different fault systems, which are respectively labelled as East Agri Valley Fault System (EAFS; Figures 2.1b) and Monti della Maddalena Fault System (MMFS) (Cello & Mazzoli, 1998; Cello et al., 2000, 2003; Maschio et al., 2005). The EAFS includes N90-120 trending, left-lateral transtensional faults, N20-30 trending, right-lateral transtensional faults, and N130–150 trending extensional faults (Cello & Mazzoli, 1998; Cello et al., 2000; Manniello et al., 2022; Palladino et al., 2023). Evidence from carbon dating of faulted paleosoils and loose slope deposits present in the study area showed that some fault segments, specifically the NW-SE structural trend have been active in the last 39 -18 ka (Giano et al., 2000; Maschio et al., 2000). The whole Viggiano Mt. is bounded both westward and eastward by WNW–ESE striking, high-angle faults, and both northward and southward by NE–SW-striking, high-angle faults (Figures 2.1c & d). The high-angle faults dissect the buried, NE-verging, low-angle thrust juxtaposing the Viggiano carbonates against the Lagonegro II Unit (Patacca & Scandone, 2007; Bruno et al., 2014), and the associated anticline forelimb (Manniello et al., 2023).

The study sites of the Viggiano Mountain are respectively labelled as Il Monte (ILM), Piano del Buon Cuore (PBC), and Scarrone La Macchia (SLM I and SLM II). ILM marks the culmination of the shallow-water carbonates, lying in close proximity to the thrust front, and exposes Albian-Cenomanian carbonate rudstones and grainstones with gastropods, bivalves, rudists (radiolitidae) and foraminifera originally deposited along the paleo-slope of the carbonate platform (Lechler et al., 2012; Manniello et al., 2022). At the foothills of the ILM outcrop, PBC exposes Lower Cretaceous - Upper Jurassic limestones whose clasts consist of oolites, oncolites and intraclasts. The limestones were likely deposited in a high-energy platform margin environment (Palladino et al., 2023). Both SLM I and SLM II expose Lower Jurassic limestones. The rocks consist of oolitic carbonates (SLM I), and carbonate wackestone-packstones to grainstones arranged in well-layered, discrete bed packages bounded by mm-to-cm thick, clay-rich interfaces (SLM II). The Toarcian oolitic carbonates are characterized by bed amalgamation and were originally deposited in a ramp setting rimmed by oolitic sand shoals. The well-layered carbonate succession is Sinemurian–Pleinsbachian in age and was originally deposited in a low-energy open lagoon environment (Lechler et al., 2012; Manniello et al., 2022).

2.3 Methods

The four sites selected for this work include a variety of carbonate lithofacies and lie at different distances from the main basin-bounding faults of the Agri Basin (Figure 2. 1). The geographic coordinates of the study site are as follow: ILM 40° 22' 42" N - 15° 51' 38" E, PBC 40° 22' 33" N - 15° 52' 02" E, SLM I 40° 22' 29" N - 15° 50' 17" E, and SLM II 40° 22' 30" N - 15° 50' 12" E.

2.3.2 Field structural analysis

The sites crop out away from the outcropping map-scale faults, for this reason, we assume that any possible effect due to stress perturbation and strain localization on the measured fault and fracture properties is avoided. Both linear and circular scanline methods (Priest and Hudson, 1981; Priest, 1993; Mauldon et al., 1999a; Mauldon et al., 1999b; Mauldon et al., 2001; Rohrbaugh et al., 2002) were applied in the field analysis to assess the geometry, distribution, and dimension of single fracture sets. Over 100 fractures were measured per site to attenuate data uncertainty (Ortega et al., 2006).

Linear scanline sampling method

The linear scanline technique was carried out to record fracture attributes such as fracture type, orientation, length/height of fracture, fracture spacing, mechanical aperture, aperture roughness, intensity, nature of possible fracture fill and spacing of each fracture the scanline intersects (Priest and Hudson, 1981; Priest, 1993). True values of fracture spacing were calculated for individual fracture sets applying the Terzaghi correction by considering the trigonometry equations, using both azimuthal and zenith angles formed by the scanline plunge/dip and the main strike/ dip of individual sets, respectively (Figure 2.2) (Terzaghi, 1965). The coefficient of variation for the spacing (C_v) was calculated for clustering analysis by dividing standard deviation of fracture spacing by the mean value of fracture spacing of an individual fracture set (Cox & Lewis, 1966). Bi-logarithmic plots of real fracture spacing and their cumulative number, cn , were made and the best-fit equations calculated for individual fracture sets (Gillespie et al., 1993; Railsback, 1998; Giuffrida et al., 2019).

1D fracture intensity, P_{10} , of every single fracture set was computed by taking a ratio of the number of fractures and the length of the scanline in meters (m) (Priest, 1993). Linear scanline measurements parallel to bedding were performed at single sites. ILM: 13 m-, 15 m-, 19 m-, 20 m-, and 20 m-long. PBC: 8 m-, 9 m-, 10 m-, 10 m-, and 14 m-long. SLM I: 6 m-, 8 m-, and 10 m-long. SLM II: 6 m-, 7 m-, 8 m-, 9 m- and 13 m-long. Data were then plotted for all the

surveyed sites by using equal-area, lower hemisphere projection using the Stereonet® software (Allmendinger et. al., 2012; Cardozo et. al., 2013). In this work, the attitude data are reported in the right-and-rule format strike/dip (RHR), unless otherwise stated.

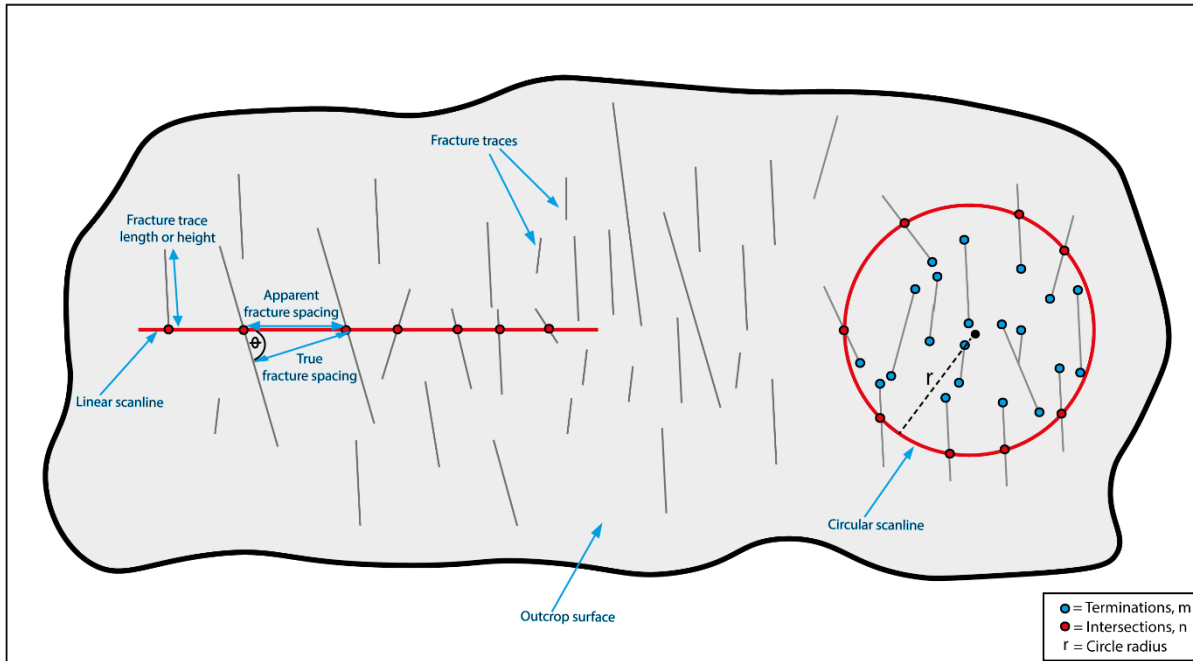


Figure 2. 2 An overview of the Linear scanline and Circular scanline overlain on an outcrop surface (light grey). The linear scanline (in red) intersecting fractures (dark grey), showing several fracture attributes along the scanline. The Circular scanline (also in red) with m , number of fracture terminations within the scanline (in blue) and n , number of fracture intersections with the scanline (in red), r , represents the radius of the circular scanline, which could vary according to user preference. Shown on the right are linear and circular scanlines applied in the field.

Circular scanline sampling method

The circular scanline method is a technique originally proposed by Mauldon (1999), Mauldon et al. (2001) and Rohrbaugh et al. (2002) and involves the counting of the number of fracture intersections (n) with the edge of a circular line placed on an outcrop, and of the number of fracture terminations (m) within the circle (Figure 2. 2). The measured values of m and n were employed for 2D fracture density, P20, and fracture intensity, P21, computations (Eqn. 1 & Eqn. 2). The use of this method eliminates orientation bias of layer parallel fractures in 2D (Watkins et al., 2015). P20 represents the number of fracture traces per unit area ($1/m^2$), and is obtained by applying the following equation:

$$P20 = \frac{m}{2\pi r} \quad (1)$$

where, m is the number of fracture terminations within the sampling circle, r is the radius of the circular scanline. $P21$ represents the mean total trace length of fractures per unit area (m/m^2), and is obtained by applying the following equation:

$$P21 = \frac{n}{4r} \quad (2)$$

where, n is the number of fracture intersections with the sampling circle and, r is the radius of the circular scanline. For a representative estimate of $P20$ and $P21$, Rohrbaugh et al. (2002) suggested a sampling circle large enough to contain a minimum of 30 end points. 45 circular scanline surveys were carried out at the ILM site, 19 at PBC, 5 at SLM I, and 35 at SLM II. The outcrops were chosen based on accessibility, and distance from outcropping faults. The diameters of the circular scanlines range from 20 cm to 50 cm. Only fracture traces longer than 3 cm were considered.

2.3.2 Digital structural analysis

High resolution images were acquired digitally using a DJi Mavic II zoom drone (Figure 2. 3a) with its generic camera model FC2204 (fixed focal length of 25mm, ISO -100, diaphragm opening of F/2.8, shutter speed of 1/200s). The digital images were collected with >75% overlap for the four sites and then processed using the Agisoft Metashape® software (Agisoft Metashape Professional, 2021; Figure 2. 3b). Specifically, 839 high resolutions images were used to build a 3D digital photogrammetry model with dimensions of 200m x 140m x 100m of ILM, 616 to build a 170m x 65m x 25m model of PBC, 139 to build a 77m x 45m x 20m model of SLM I, and 283 to build a 90m x 50m x 56m model of SLM II. The images were captured manually both nadir and oblique at 5-10m distance from the exposed rock surface.

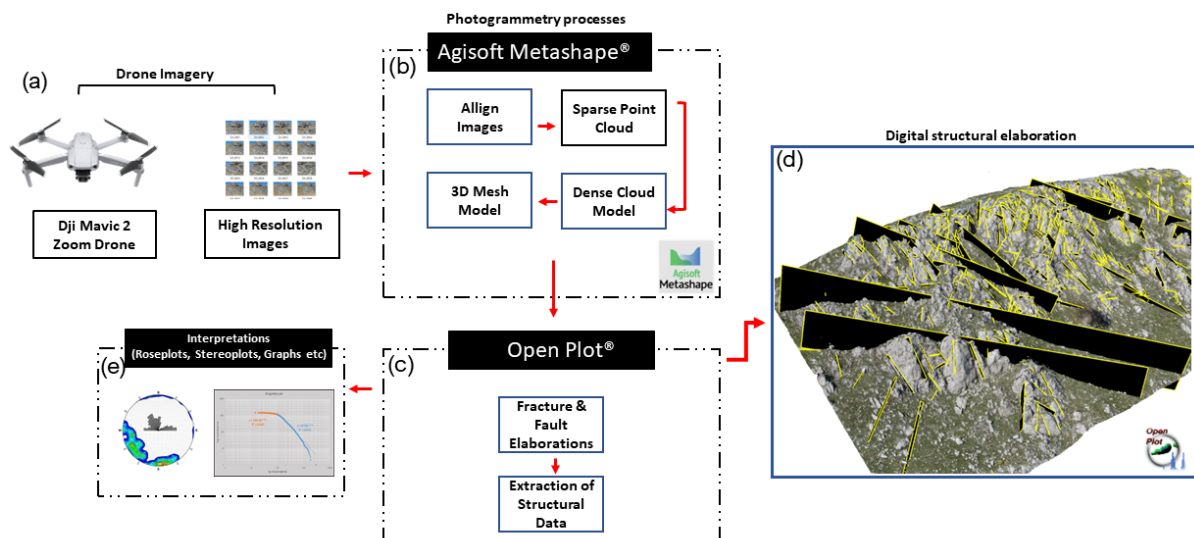


Figure 2. 3 Schematic diagram showing workflow for: (a) drone acquisition by means of Unmanned Aerial Vehicle (UAV) - drone (b) 3D digital photogrammetry process (c), (d) and (e) Digital structural elaboration.

According to the resolution of the digital outcrop models, structural data pertaining to small faults (throw < 1 m) and medium faults (throw > 1 m) were extracted by exporting Open plot® files (Tavani et al., 2011) as vector graphics files (SVG format) into FracPaQ® (Healy et al., 2017; Figures 2.3c to e). Since the outputs of the OpenPlot ® were in pixels, we converted 1 pixel to an average value of 1.5m in the FracPaQ ® environment. Regarding this operation, it was conducted on specific 2D surfaces of the 3D models. The 2D surfaces were chosen perpendicularly oriented with respect to the main digital planes. The FracPaQ® software permitted the calculation of both P20 (number of fractures/area of exposure) and P21 (sum of fracture traces/area of exposure), whose values are presented in map forms as well as average numerical values computed for the single digital outcrops.

2.4 Results

We first present the results of field structural investigations, which include the geometry of the outcropping fracture network, and the density, intensity, and multiscale distribution of the single fracture sets. Then, we show the results of digital structural analyses in terms of geometry and multiscale dimensional properties of both small and medium-sized faults.

2.4.1 Field fracture analyses

Il Monte (ILM)

The Cretaceous carbonates include massive and amalgamated limestone beds ranging in thickness from 30 cm to 100 cm. Results after circular scanlines are consistent with P20 values ranging from 35m^{-2} to 428m^{-2} , and P21 values between 7m^{-1} and 35m^{-1} . Results after linear scanline of diffuse deformation reveal the presence of four major sets of fractures (Figure 2.4a), whose best fit planes are oriented as follows:

- WNW-ESE set - N300/72
- NW-SE set - N329/72
- N-S set - N358/79
- E-W set - N260/88

The computed P10 values are shown in Figure 2.4a. There, we note that the WSW-ENE set exhibits the highest value P10 value of 2.15m^{-1} , whereas the WNW-ESE set the lowest one, 0.25m^{-1} . The values for coefficient of variation, C_v , are 1.15 (WNW-ESE set), 0.87 (NW-SE set), 1.25 (N-S set), and 1.05 (E-W set). All fracture sets are characterised by negative exponential fracture height distributions (Figure 2.6a). Differently, while the NW-SE, N-S, and E-W sets are also characterized by negative exponential spacing distributions, the WNW-ESE set displays a power-law spacing distribution, with a fractal dimension, D -value of 0.58 (Figure 2.6a). The relations among the four fracture sets in terms of abutting and crosscutting geometries are shown in Figure 2.5a. We document that the N-S set (red) crosscuts and displaces the WNW-ESE (purple) and the E-W (green) sets of fracture. Also, shown in light grey, we show that the NW-SE set cut across all previous fracture sets.

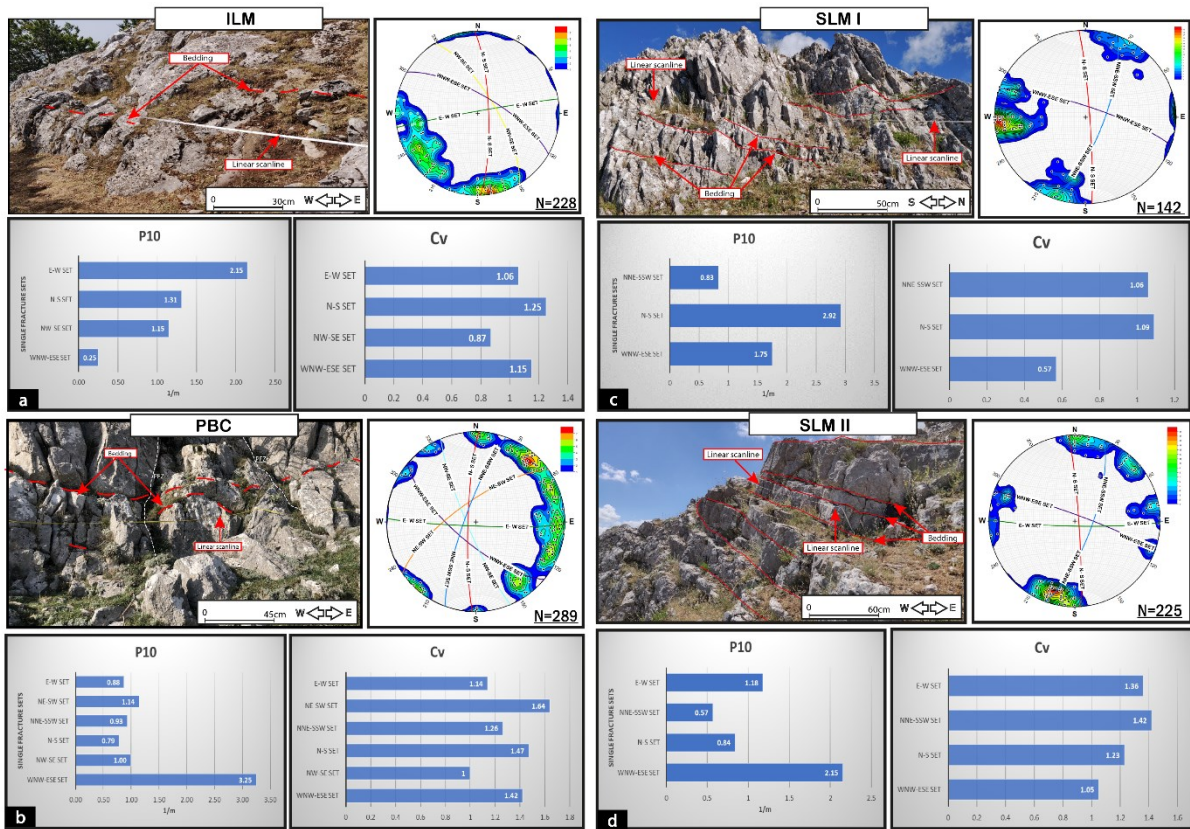


Figure 2. 4 Field data: (a) ILM outcrop with linear scanline applied. A stereonet (lower-hemisphere, equal area) and best-fits for all the single fracture sets. A graph showing P10 values for the four single fracture sets. A graph showing coefficient of variation (C_v) for the four single fracture sets. (b) PBC outcrop with linear scanline applied. A stereonet (lower-hemisphere, equal area) and best-fits for all the single fracture sets. A graph showing P10 values for the six single fracture sets. A graph showing coefficient of variation (C_v) for the six single fracture sets. (c) SLM I outcrop with linear scanline applied. A stereonet (lower-hemisphere, equal area) and best-fits for all the single fracture sets. A graph showing P10 values for the three single fracture sets. A graph showing coefficient of variation (C_v) for the three single fracture sets. (d) SLM II outcrop with linear scanline applied. A stereonet (lower-

hemisphere, equal area) and best-fits for all the single fracture sets. A graph showing P10 values for the four single fracture sets. A graph showing coefficient of variation (Cv) for the four single fracture sets.

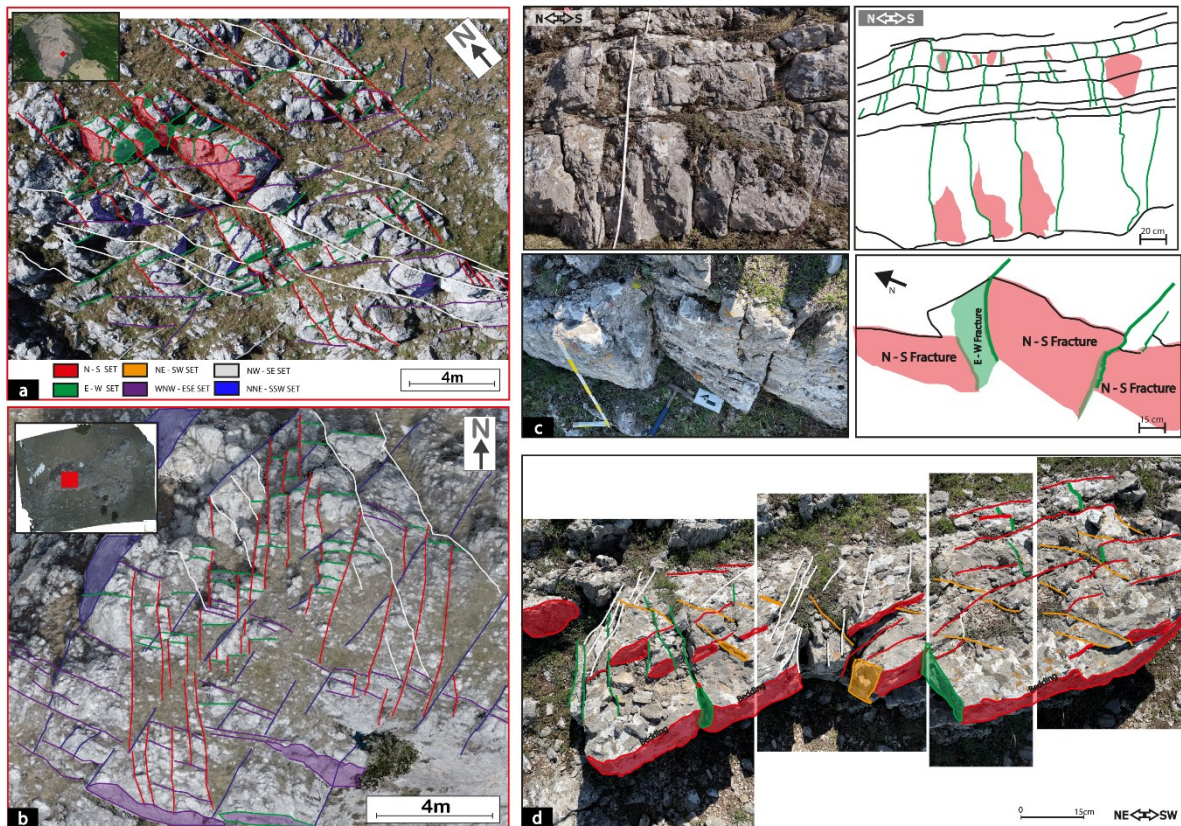


Figure 2. 5 Field data: qualitative analyses of background and localized fractures wrt. equivalent units showing crosscutting relationship between fracture sets for (a) relating to ILM & PBC (b) SLM I shown from an aerial-view (c) & (d) fractures relating to SLM II shown on vertical cliffs. Legend shown in the figure.

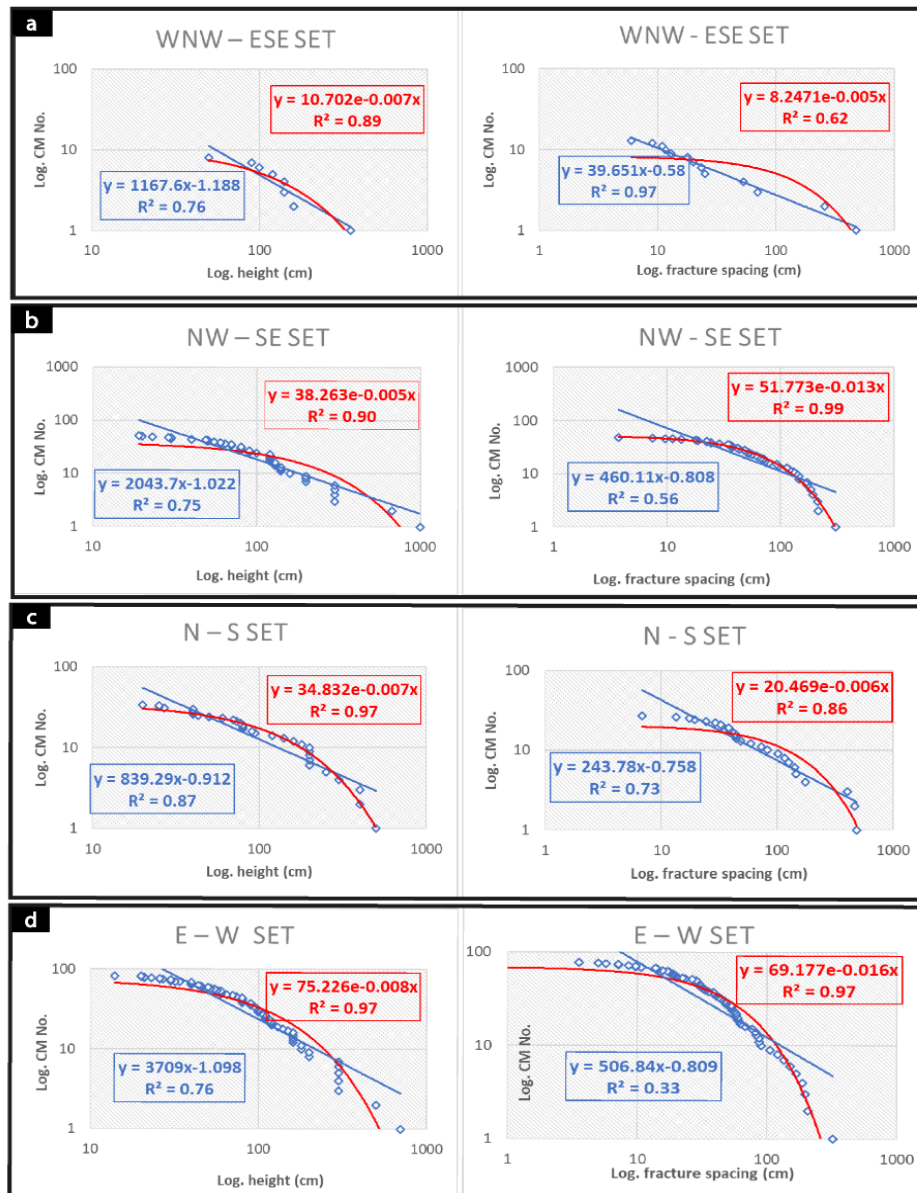
Piana del Buon Cuore (PBC)

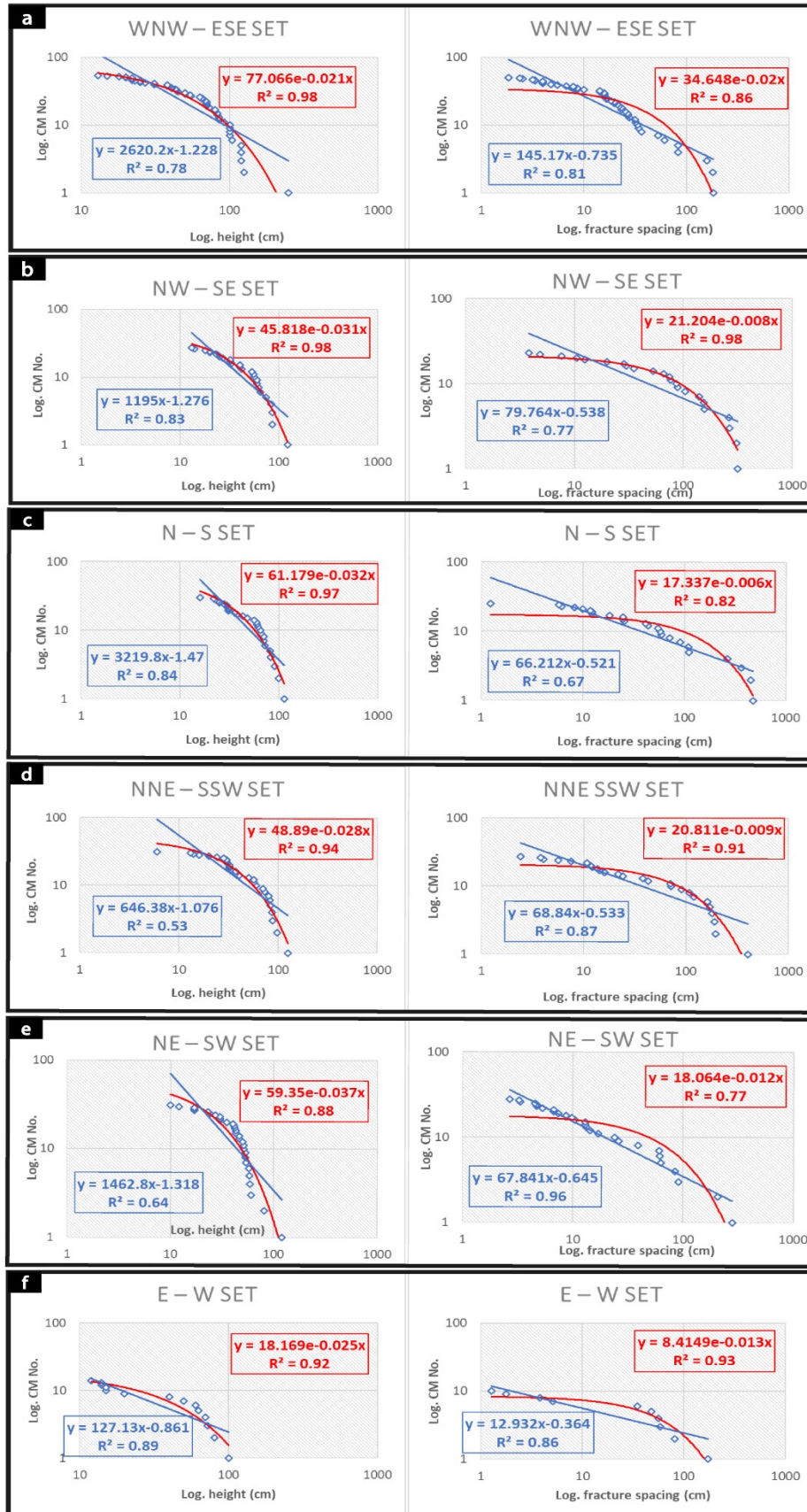
The Lower Cretaceous - Upper Jurassic carbonates consist of amalgamated -massive limestones with bed thickness ranging from ca. 25 cm to ca. 180 cm. Results after circular scanlines are consistent with P20 values ranging from 120 m⁻² to 362 m⁻², and with P21 values from 19 m⁻¹ to 43 m⁻¹. Results after linear scanline reveal the presence of six major sets (Figure 2.4b), whose best-fit planes are oriented as follows:

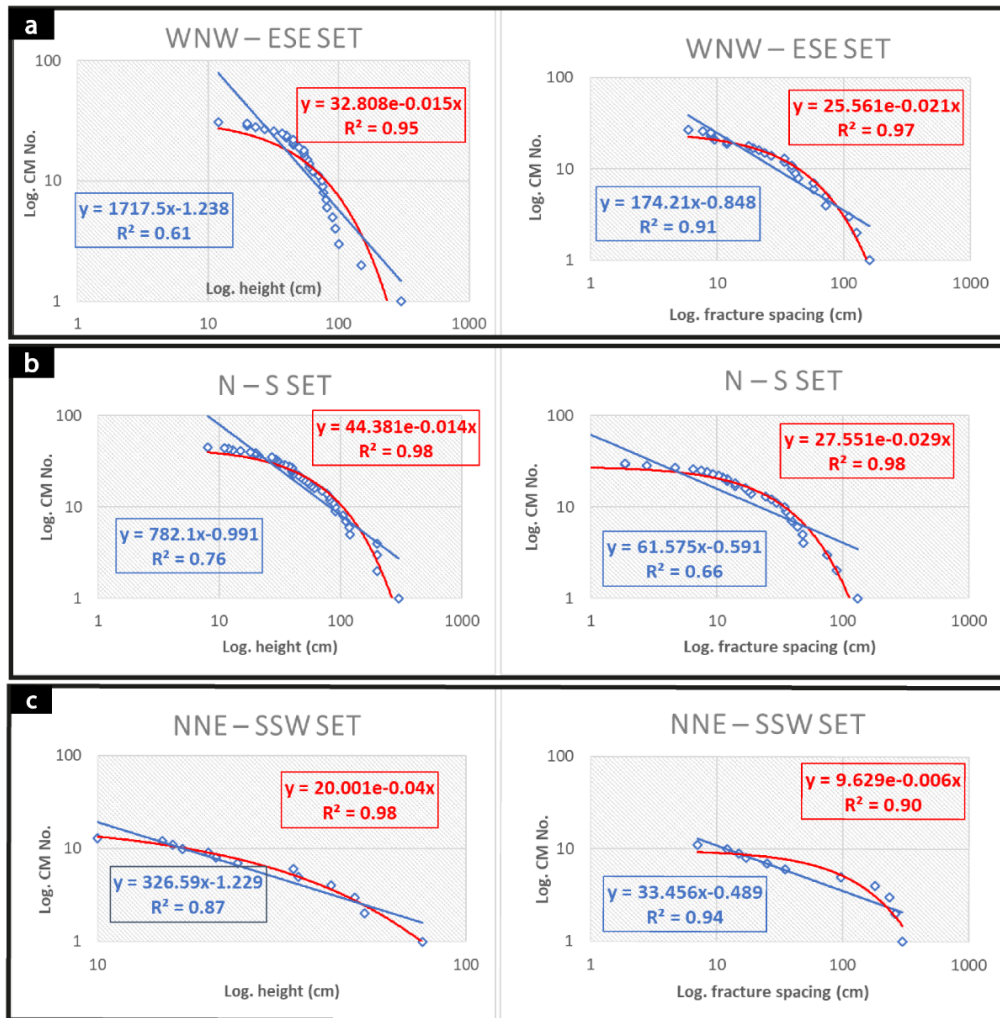
- WNW-ESE set – N130/71
- NW-SE set – N157/82
- N-S set - N182/83
- NNE-SSW set - N200/83
- NE-SW set - N235/72

■ E-W set - N92/86

The Computed P10 are shown in Figure 2.4b. There, the WNW–ESE set shows the highest value, 3.25 m^{-1} , and the N–S set by the lowest one, 0.79 m^{-1} . The Cv values (Figure 2.4b) are 1.42 (WNW–ESE set), 1.00 (NW–SE set), 1.47 (N – S set), 1.26 (NNE–SSW set), 1.64 (NE–SW set), and 1.14 (E–W set). All sets show negative exponential height distributions (Figure 2.6b). All fracture sets but the NE-SW are also characterized by a negative exponential fracture spacing distribution, whereas the latter set shows a power-law spacing distribution with a D-value of 0.65.







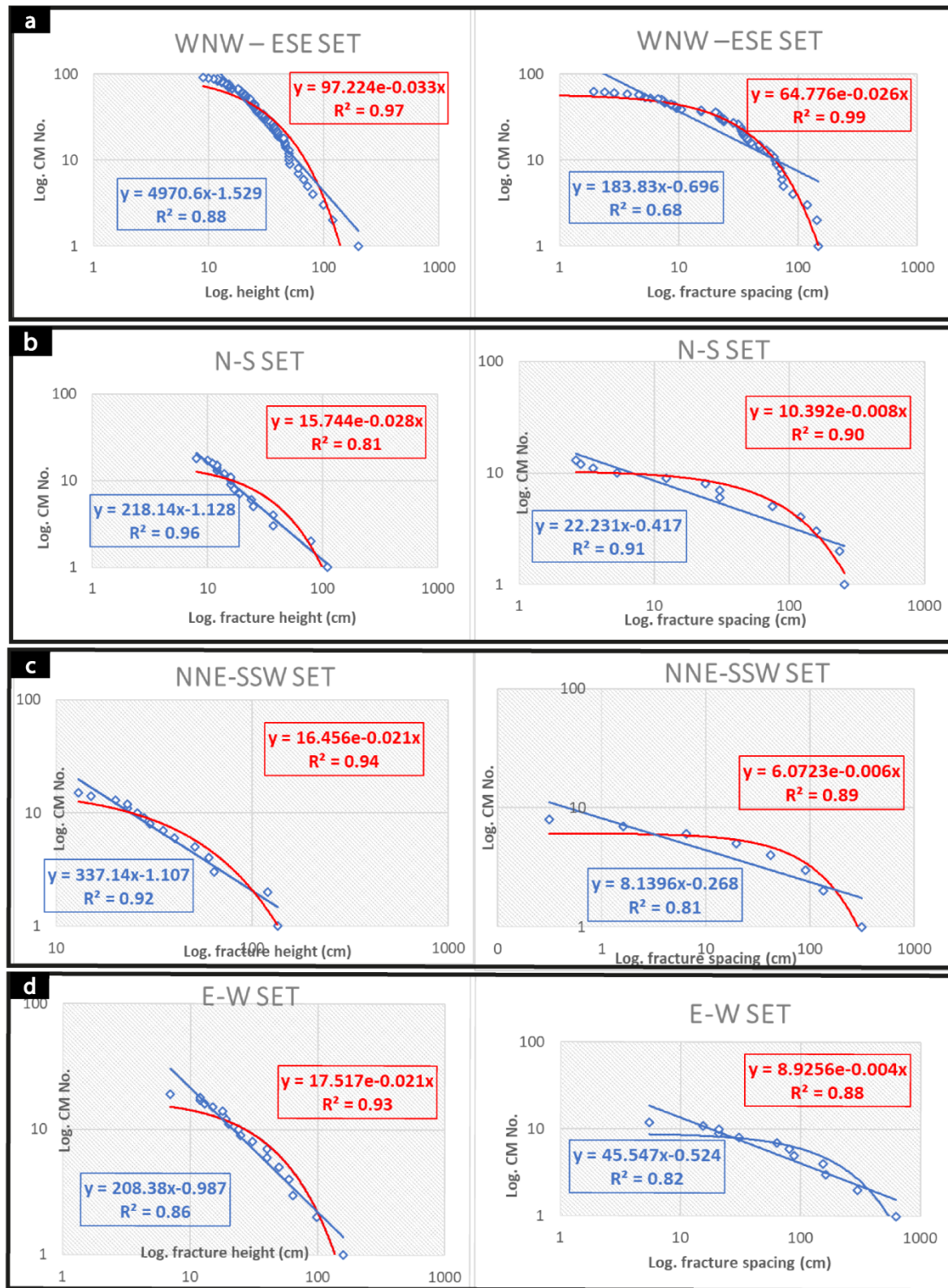


Figure 2.6 Field data: multiscale fracture properties for the study sites showing a log-log plot of cumulative No. Vs. fracture height and cumulative No. Vs. fracture spacing. Annotations for fracture sets are shown within the graph. Best-fit equations are shown for all the fracture sets; (1) Showing ILM

study site with all sets best-fit negative by exponential plot, except WNW-ESE fracture set in the fracture spacing graph which show power-law distribution; (2) PBC study site with all sets best-fit by negative exponential plots, except NE-SW fracture set in the fracture spacing graph which show power-law distribution; (3) SLM I study site with all sets best-fit by negative exponential plots, except NNE-SSW fracture set in the fracture spacing graph which show power-law distribution; (4) SLM II with the N-S fracture set showing power-law distribution in both fracture height and fracture spacing plots.

Scarrone La Macchia I (SLM I)

The oolitic Lower Jurassic carbonates include massive and amalgamated limestone beds ranging in thickness from ca. 55 cm to ca. 90cm. Results after circular scanlines show P20 values ranging from 87 m^{-2} to 488 m^{-2} , and P21 values comprised between 10 m^{-1} and 33 m^{-1} . Results after linear scanline measurements reveal the presence of three major sets of fractures (Figure 2.4c), whose best fit planes are oriented as follows:

- WNW-ESE set – N289E/80
- N-S set – N356E/86
- NNE-SSW set – N20E/73

The P10 values (Figure 2.4c) vary from 2.92 m^{-1} (N-S set) to 0.83 m^{-1} (WNW-ESE set), whereas the Cv values are 0.57 (WNW–ESE set), 1.09 (N–S set), and 1.06 (NNE–SSW set). All sets are characterized by a negative exponential height distribution (Figure 2.6c). Differentially, both WNW–ESE and N–S sets also show a negative exponential fracture spacing distribution, whereas the NNE–SSW set is characterized by a power law fracture spacing distribution, with a D-value of 0.49 (Figure 2.6c).

In Figure 2.5b we show that the N-S set of fractures (red) crosscuts and displaces the E-W (green) set. Both sets displace the WNW-ESE (purple) and are crosscut by NNE-SSW (blue) trending fractures. Note that the E-W set of fractures do not form a dense pole cluster in the stereoplot of Figure 2.4c, and hence they are not reported in the list of main sets above.

Scarrone La Macchia II (SLM II)

The lower Jurassic carbonates are arranged into 12 different bed packages, which range in thickness from ca. 1 m to ca. 13 m. The single carbonate beds are 5 to 40 cm-thick and are delimited by mm to cm thick bed interfaces including bed-parallel stylolites and pressure solution seams (Manniello et al., 2022). Results after circular scanlines are consistent with P20 values ranging from 91 m^{-2} to 552 m^{-2} , and with P21 values comprised between 11 m^{-1} and 46 m^{-1} . Results after linear scanlines highlight the presence of four major sets (Figure 2.4d), whose best fit planes are oriented as follows:

- WNW-ESE set – N290/84
- N-S set – N356/86
- NNE-SSW set – N20/73
- E-W set – N91/85

The P10 values are shown in Figure 2.4d, with the WNW-ESE set showing the highest value of 2.15 m^{-1} , and the NNE-SSW set the lowest one, 0.57 m^{-1} . The computed C_v values are 1.05 (WNW-ESE set), 1.23 (N-S set), 1.42 (NNE-SSW set), and 1.36 (E – W set). Regarding the multiscale fracture height distribution, the WNW-ESE, NNE-SSW, and E-W sets are characterized by negative exponential best fits (Figure 2.6d), while the N-S set shows a power law best fit with a D-value of 1.13. The N-S set is also characterised by a power law multiscale spacing distribution, with a D-value of 0.42. Differently, the WNW-ESE, NNE-SSW, and E-W sets show a negative exponential multiscale fracture spacing distribution.

A qualitative description of relative timing for the fracture sets is shown on vertical cliffs. The E-W fractures (green) cut across the N-S ones (red), whereas the NE-SW fractures (orange) abut against the N-S sets (Figure 2.5c & d). The NW-SE fractures (grey) form clusters crosscutting all the aforementioned fracture sets (Figure 2.5d).

2.4.2 Digital structural analyses

Results of digital structural interpretations after 3D digital photogrammetry modelling of the four carbonate outcrops show the geometry of the networks comprised of small and medium-scale faults. We also show the values of density, intensity and multiscale length/height distribution computed for single sets.

Il Monte (ILM)

The 1127 measured planes form five major sets, whose best fit planes are oriented as follows (Figure 2.7a):

- NW-SE set - N320/75
- NNE-SSW set - N210/75
- NE-SW set - N40/44
- ENE-WSW set - N60/52
- E-W set - N271/89

Two synthetic scanlines, A-A' and B-B' are drawn across the structurally interpreted model to assess the spatial variation of the measured planes (Figure 2.7a). The results are reported, with plots showing regions with isolated clusters of fault planes striking nearly parallel to each other. The computed values of P20 and P21 are respectively up to 1.2 m^{-2} and 1.4 m^{-1} (Figure 2.8a). Regarding the multiscale length distribution, the NW-SE, NE-SW, E-W, and ENE-WSW sets show power-law best fits, with D values respectively of 1.42 (NW-SE), 1.53 (NE-SW), 2.02 (E-W), and 1.79 (ENE-WSW). On the contrary, the NNE-SSW set is characterized by a negative exponential best fit (Figure 2.11a).

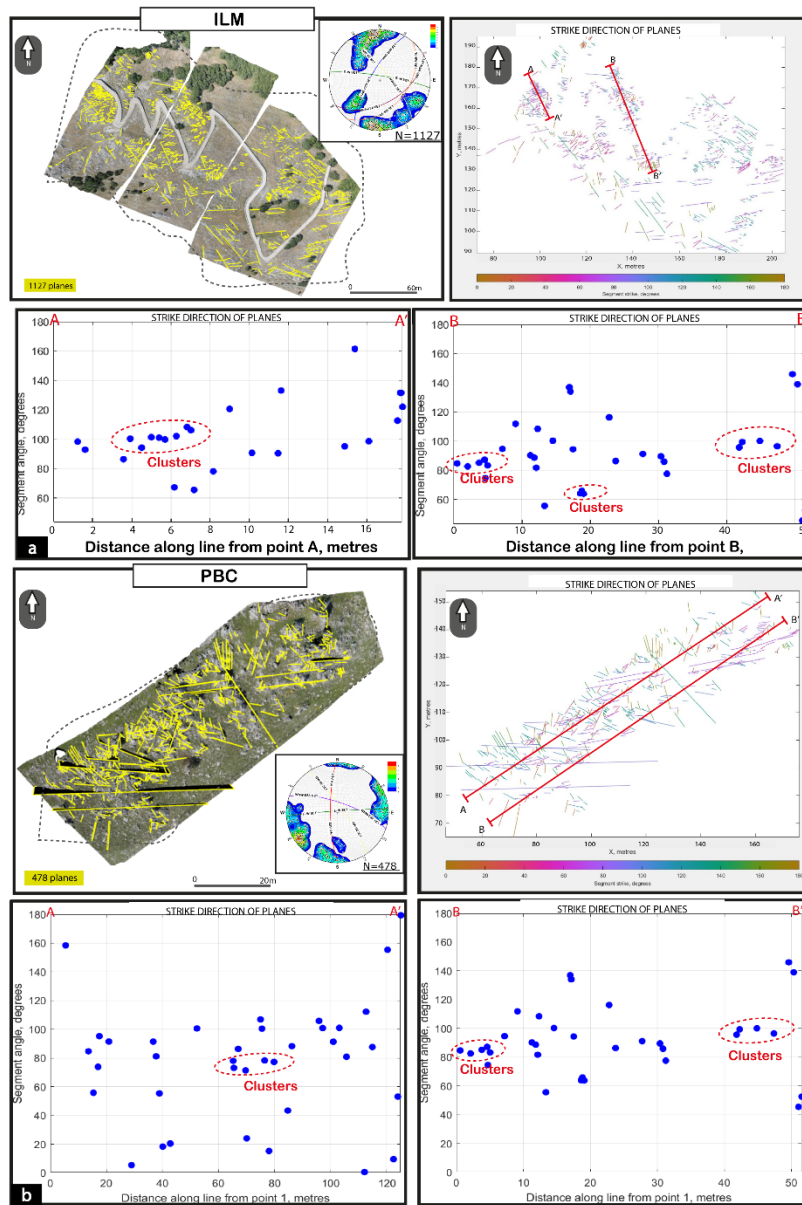


Figure 2. 7 Digital data: (a) The top-view is shown of 3D photogrammetric model with 1127 digitized planes from ILM outcrop. inset: stereoplot for the digitized. Output from FracPaQ® showing strike direction for high-angle planes from digital structural elaboration. Two transects A-A' & B – B' drawn to assess variation in fracture & fault properties along each transect. Plots showing fracture and fault

properties along transect A – A' & B – B'. Lateral variation for geometry of planes and spacing along each transect is shown. (b) The top-view is shown of 3D photogrammetric model with 478 digitized planes from PBC outcrop. inset: stereoplot for the digitized planes. Output from FracPaQ® showing strike direction for high angle planes from digital structural elaboration. Two transects A-A' & B – B' drawn to assess variation in fracture & fault properties along each transect. A plot showing fracture and fault properties along transect A – A' & B – B'. Lateral variation for geometry of planes and spacing along each transect is shown. Isolated fault clusters (red circles) representing fluid corridors likely to yield anisotropic flows. Grey dotted outlines around outcrop to ease viewing of P20-P21 results (see Figure 2.8).

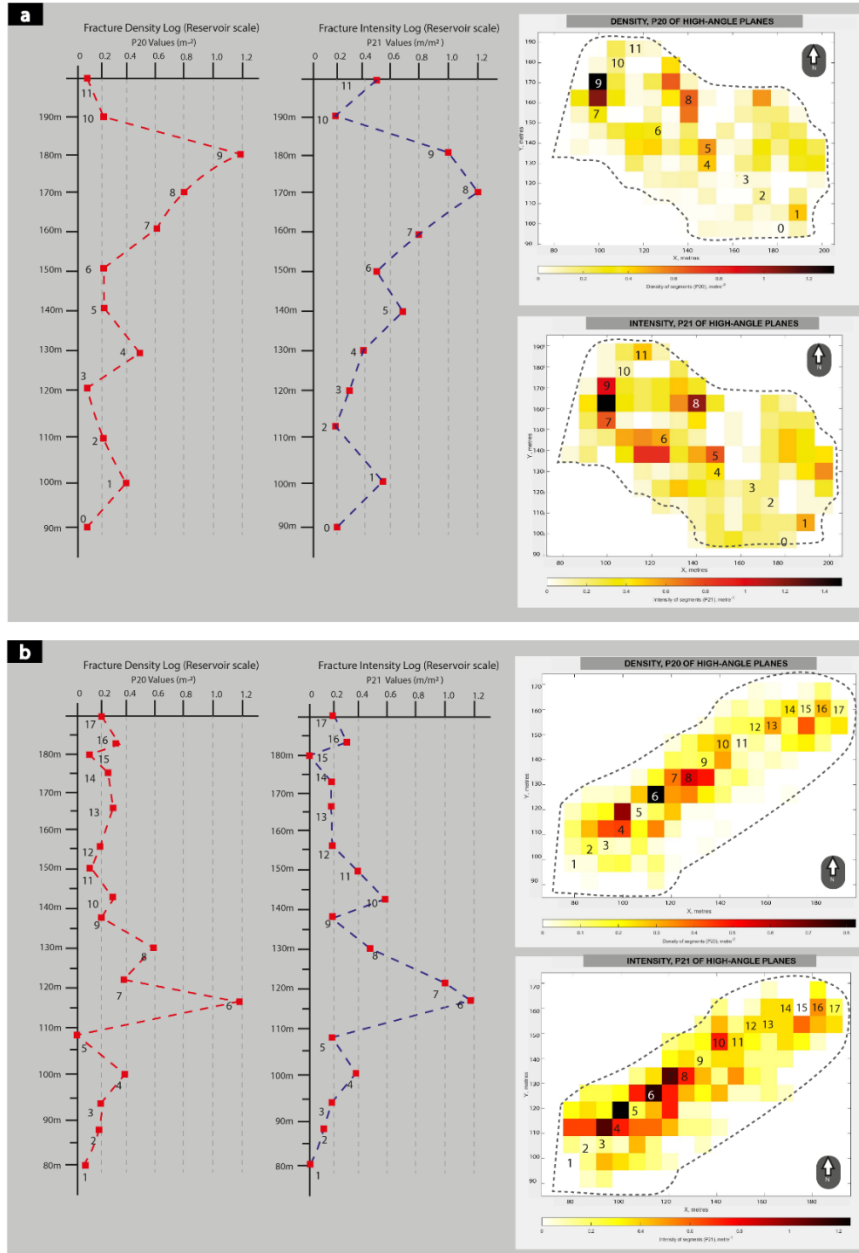


Figure 2. 8 Digital data: FracPaQ® output showing P20 - P21 variation across the outcrop. From right – left, P20 & P21 distribution shown in aerial view (plane defined in the FracPaQ software). Fracture density & intensity log acquired from random points in the aerial view & shown by the numbers indicated, to assess the similarity or variation of the P20 & P21 across the entire outcrop surface: (a) ILM (b) PBC.

Piana del Buon Cuore (PBC)

The 478 measured planes form four major sets, whose best fit planes are oriented as follows (Figure 2.7b):

- WNW-ESE set - N289/73
- NW-SE set - N325/81
- N-S set - N179/79
- E-W set - N266/87

Two synthetic scanlines, A-A' and B-B' are drawn across the structurally interpreted model to assess the spatial variation in properties of the measured planes (Figure 2.7b). Results of P20 and P21 evaluations are shown with values respectively up to 0.8 m^{-2} and 1.2 m^{-1} (Figure 2.8b). Regarding their multiscale height values (highly steeped outcrop), all sets are fit by negative exponential distributions (Figure 2.11b), except the E-W set which has a D-fractal value of 0.9.

Scarrone La Macchia I (SLM I)

The 402 measured planes form three major sets, whose best fit planes are oriented as follows (Figure 2.9a):

- WNW-ESE set - N303/88
- NNE-SSW set - N196/88
- NE-SW set - N38/87

Two synthetic scanlines, A - A', and B - B' are drawn across the structurally interpreted model to assess the spatial variation in properties of the measured planes (Figure 2.9a). The results of P20 and P21 (Figure 2.10a) show values respectively up to 1.8 m^{-2} and 1.6 m^{-1} . Regarding their multiscale length distribution, the WNW-ESE and NE-SW sets are characterised by a power-law best fits, with D-values respectively of 1.11 and 1.09 (Figure 2.11c).

Scarrone La Macchia II (SLM II)

The 1238 measured planes form four major sets, whose best fit planes are oriented as follows (Figure 2.9b):

- N-S set - N178E/87
- NNE-SSW set - N197E/88
- NE-SW set - N40E/87

- ENE–WSW set - N62E/87

Two synthetic scanlines, A-A' and B-B' are drawn across the structurally interpreted model to assess the spatial variation in properties of the measured planes (Figure 2.9b). The results of P20 and P21 (Figure 2.10b) show values respectively up to 6 m⁻² (P20) and 3.5 m⁻¹ (P21). Regarding the multiscale height distributions, all sets are characterized by negative exponential best fits (Figure 2.11d).

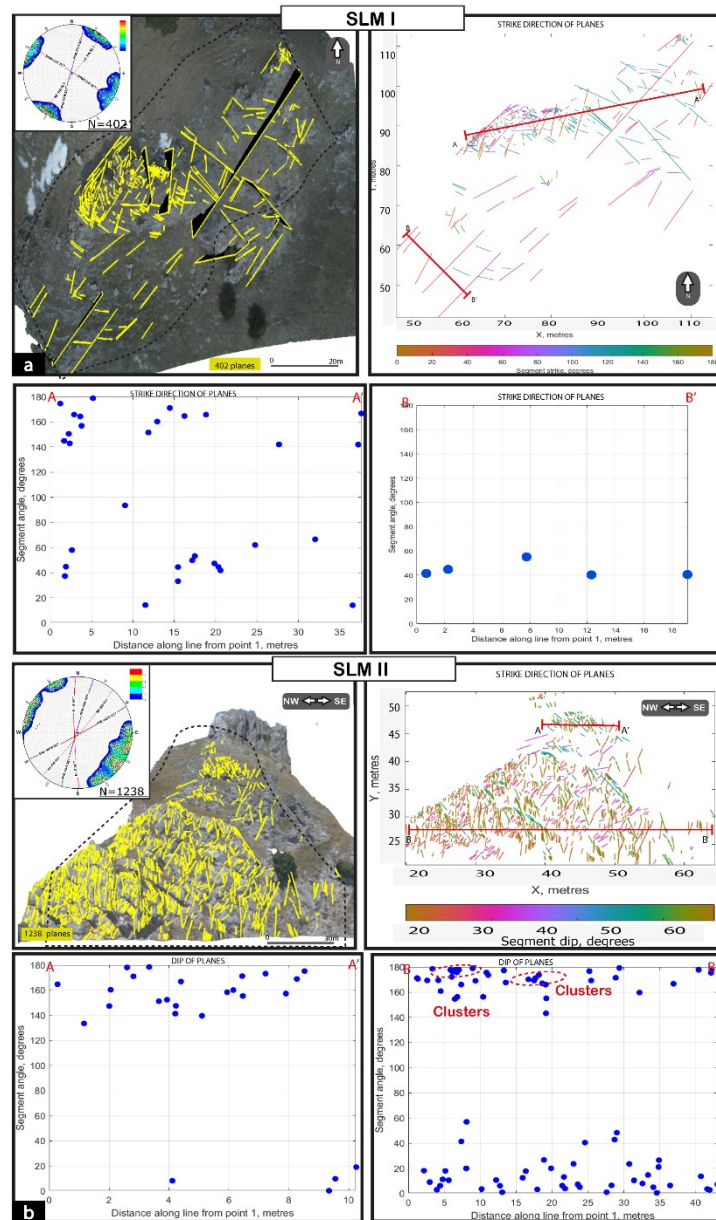


Figure 2. 9 Digital data: (a) 402 digitized planes from SLM I outcrop. inset: stereoplot for the digitized planes showing best-fit of major sets. Output from FracPaQ® showing strike direction for high angle planes from digital structural elaboration. Two transects A-A' & B – B' drawn to assess variation in fracture & fault properties along each transect. Plots showing fracture and fault properties along transect A – A' & B – B'. Lateral variation for geometry of planes and spacing along each transect is shown. (b) 1238 digitized planes from SLM II outcrop. inset: stereoplot for the digitized planes showing best-fit of major sets. Output from FracPaQ® showing strike direction for high angle planes from digital

structural elaboration. Output from FracPaQ® showing strike direction for high angle planes from digital structural elaboration. Two transects A-A' & B-B' drawn to assess variation in fracture & fault properties along each transect. A plot showing fracture and fault properties along transect A – A' & B – B'. Lateral variation for geometry of planes and spacing along each transect is shown. Isolated fault clusters (red circles) representing fluid corridors likely to yield anisotropic flows.

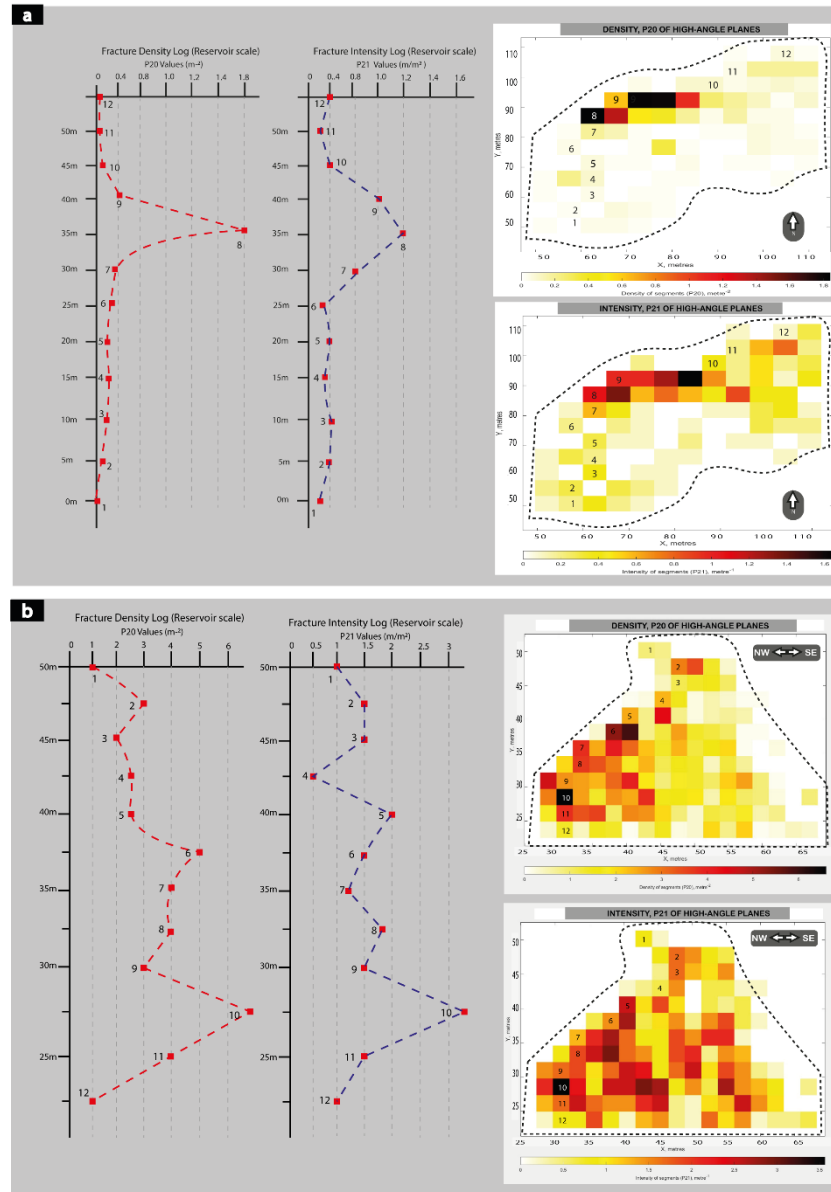
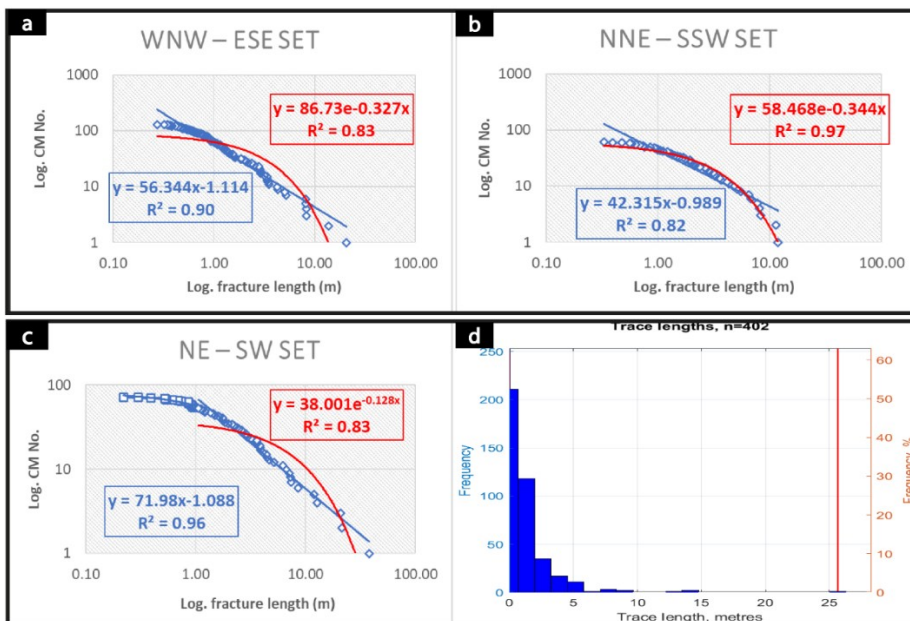
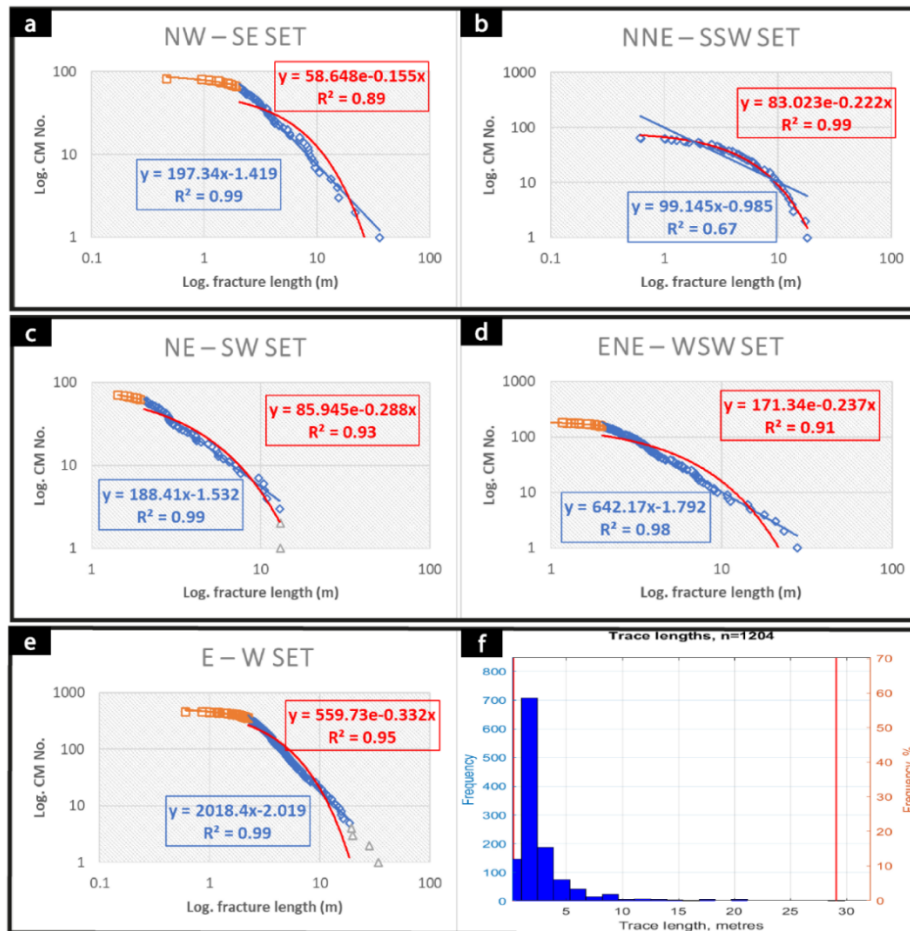


Figure 2. 10 Digital data: FracPaQ® output showing P20 - P21 variation across the outcrop. From right – left, P20 & P21 distribution shown in aerial view. Fracture density & intensity log acquired from random points in the aerial view & shown by the numbers indicated, to assess the similarity or variation of the P20 & P21 across the entire outcrop surface: (a) SLM I (b) SLM II.



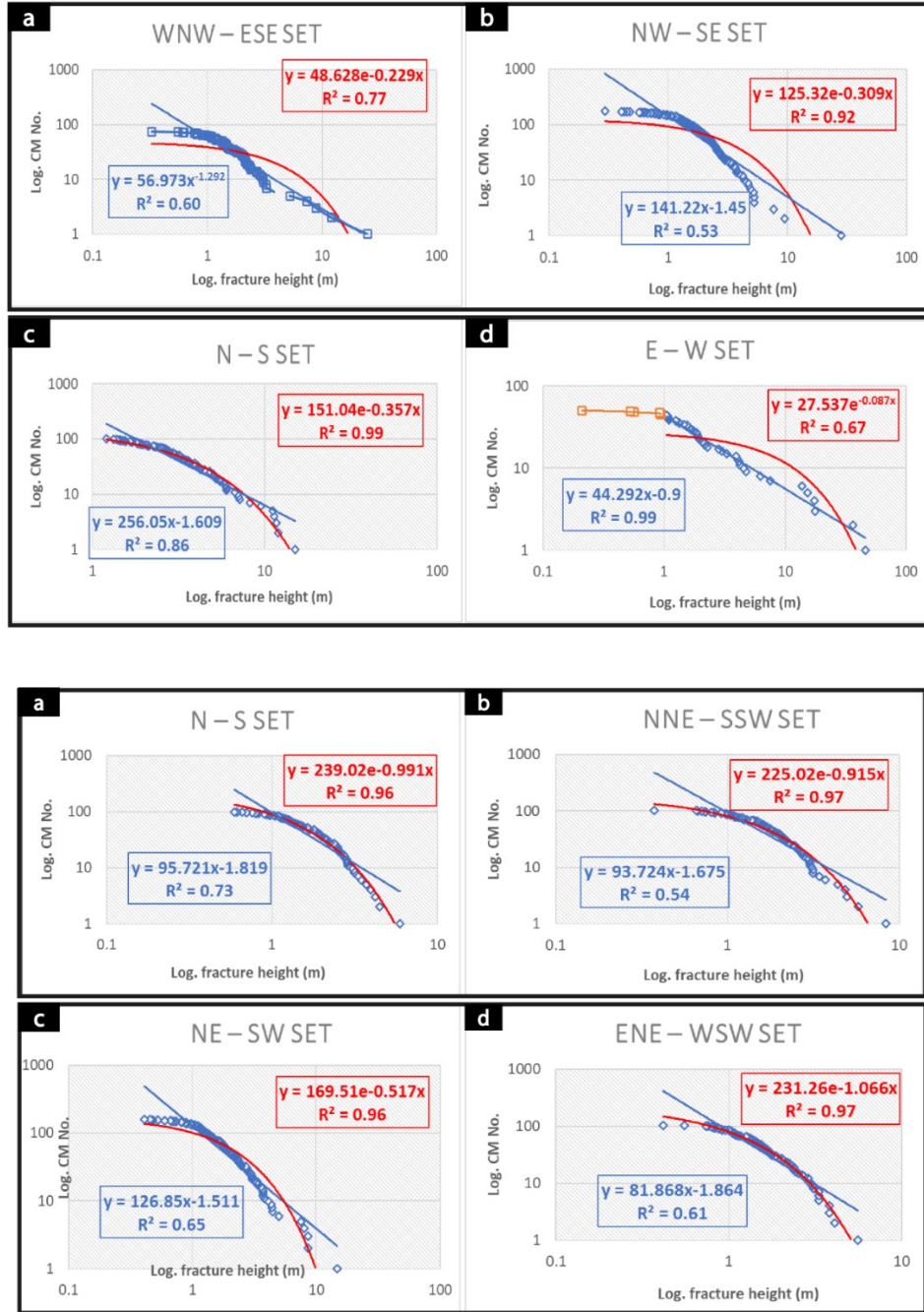


Figure 2.11 Digital data: multiscale fracture properties for the study outcrops showing (1) to (4) a log-log plot of cumulative No. Vs. fracture height.

2.5 Discussion

We discuss the results of our structural analyses to assess the multiscale structural architecture of high-angle faults and fractures crosscutting the Mesozoic shallow-water carbonates. First, we discuss the role of diffuse vs localized deformation. Then, we decipher the possible control

exerted by rock lithologies on the computed fracture properties. Finally, we focus on the variation of our data sets according to the scales of observation.

2.5.1 Diffuse vs localized deformation

After field analyses, the fracture spacing distribution shows exponential best fits for the sets NW-SE, N-S and E-W (ILM), WNW-ESE, NW-SE, N-S, NNE-SSW and E-W (PBC), WNW-ESE and N-S (SLM I), and WNW-ESE (SLM II). A similar distribution was reported by Manniello et al. (2022) for the N292, N284 (WNW-ESE) and N206 (NNE-SSW) striking fracture sets exposed at SLM II. The aforementioned fracture sets hence formed under remote stress fields (Dershowitz & Einstein, 1988; Bonnet, 1997), and their distribution due to Poissonian processes (Cruden, 1977) representative of diffuse deformation in shallow-water carbonates (Korneva et al., 2014). Differently, a power-law spacing distribution (Mandelbrot, 1983) is documented for the WNW-ESE set (ILM, D-value=0.58), NE-SW set (PBC, D-value=0.65), NNE-SSW set (SLM I, D-value=0.49), and N-S set (SLM II, D-value=0.42). These results, similar to the D-values > 0.4 reported by Panza et al. (2016) and Giuffrida et al. (2019) for localized fracture sets in shallow-water carbonates, lie within the proposed range 0.4 – 1 of D-values for power law spacing distribution proposed by Gillespie et al. (1993; 2001) for fault-related fractures. We note that some of these fracture sets pertain to either diffuse (negative exponential spacing distribution) or localized deformation (power law spacing distribution) depending upon the site of measurement. These results could be effect of re-activation of pre-existing diffuse fractures during faulting of the carbonates (Agosta et al., 2006, 2009), and/or bias due to sampling procedures (Marret & Allmendinger, 1991; Bonnet et al., 2001), and/or a different degree of finite state of deformation (Sornette et al., 1993; Cowie et al., 1993).

Considering the multiscale fault height distribution obtained after digital structural analysis, we document both power-law and negative exponential best fits for single fault sets. Accordingly, we propose that the transition from negative exponential to power-law properties (Cowie et al., 1993; Cladouhos & Marrett, 1996) supports the model envisioning fault growth due to linkage of pre-existing heterogeneities (Agosta and Aydin, 2006; Aydin et al., 2010), as highlighted by the data shown in Figure 2.13a for the study area of the Viggiano Mt. (Manniello et al., 2022). According to Sornette et al. (1993), who proposed that the exponent of fracture length/height distribution depends on the degree of fault maturation, all D-values (aside from the ILM E-W set, D=2.02), correspond to poorly to fairly-developed fault sets (Gillespie et al.,

1993; Cowie et al., 1993). Focusing on the multiscale height distribution of fractures after outcrop structural analysis, we note that only the SLM II N-S fault set shows a power-law best fit ($D\text{-value}=1.13$) similar to the results obtained for the multiscale fracture spacing distribution.

2.5.2 Deformation of single carbonate units

Fracture geometry

Considering a scattering up to $\sim 20^\circ$, the diffuse network is made up of high-angle fractures mainly striking WNW-ESE, N-S, NNE-SSW, and E-W with minor sets striking NW-SE and NE-SW (Fig. 5). At a large scale, we note that both fractures and small to medium faults do not show a similar geometry. In fact, the moving average rose diagrams (Munro & Blenkinsop, 2012) obtained for fractures and faults documented in the four sedimentary units show a scale-dependent geometry (Figure 2.12). Similar data were reported by Ceccato et al. (2022) for fractured crystalline basement rocks of SW Norway (Bomlo Island), by Martinelli et al. (2020) for normal faults in shallow-water carbonates of the Maltese islands, and by Villarreal et al. (2020) for the Lower Cretaceous Los Santos Formation sandstones of Colombia. The scale dependency of fault and fracture might be due to a number of factors, the most important of which is related to the relatively larger digital dataset (McQuillan, 1974; Wu and Pollard, 1995; Mercuri et al., 2023). We hence document that the larger-scale digital analysis could be more efficient in terms of geometry representativeness than the field analysis, which was conducted at specific outcrops. Other factors affecting the results deal with the source image resolution during digital acquisition (Patruno et al., 2021; Abdallah et al., 2021), and with the orientation bias (Zeeb et al., 2013) related to the analysis of vertical digital outcrop walls. In fact, the fault sets striking $< 30^\circ$ to the outcrop face directions fall in the blind zone (Fowler, 2013; Panara et al., 2022) and produce a bias effect that is observed in the roughly trending WNW-ESE digital outcrop of SLM II (Figure 2.9b). There, the ENE-WSW to E-W sets are completely obliterated for the larger scale results (Figure 2.12).

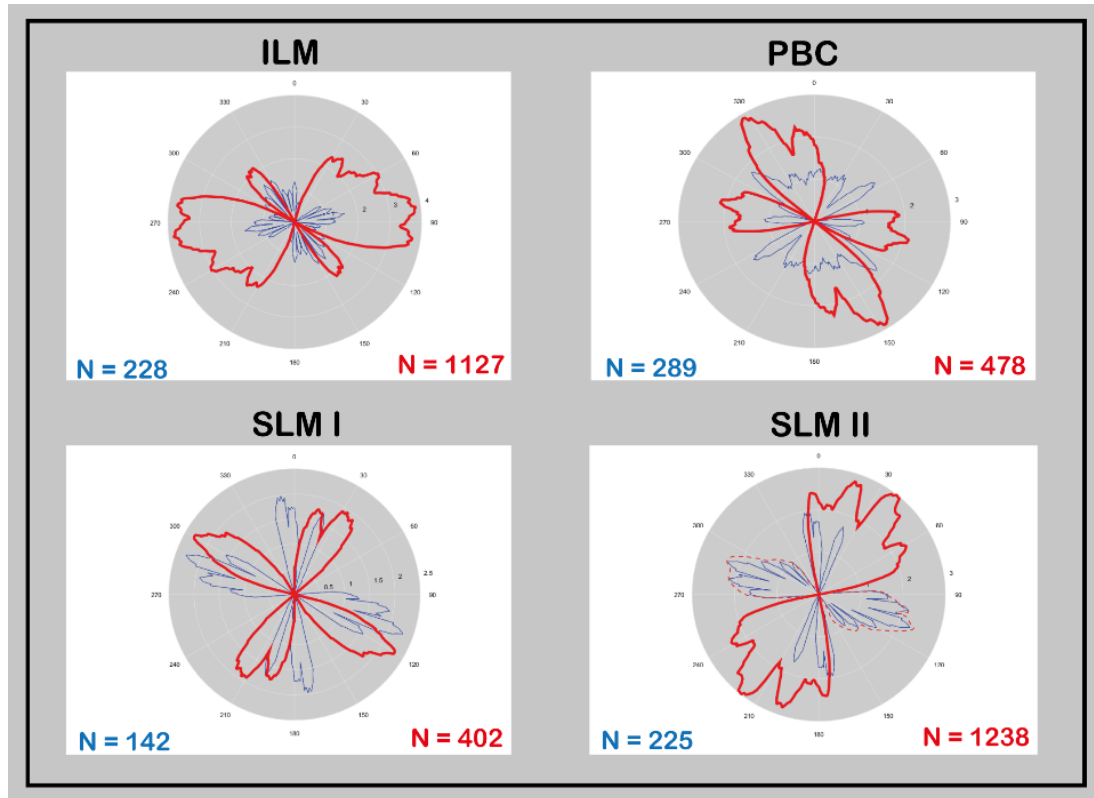


Figure 2.12 Moving average diagram for the four study outcrops. (Equal area, aperture of 9° and weighting factor 0.9). Blue indicating field data and Red, data acquired digitally (reservoir scale). A scale-variant geometry is shown. Red dotted lines in SLM II indicating a possible set of faults oriented in that direction but absent due to orientation bias since the outcrop itself is oriented NW-SE.

Fracture density and intensity

Away from the outcropping faults, the fractures are characterized by spacing distributions with a coefficient of variation, C_v , ranging between 0.87 and 1.25 (ILM), 0.99 and 1.65 (PBC), 0.57 and 1.09 (SLM I), and 1.05 and 1.42 (SLM II) for all surveyed sets. Most of the C_v values are smaller than 1, and hence consistent with a network of diffuse deformation localized away from the major faults (Gillespie et al., 1993; Odling et al., 1999; Giuffrida et al., 2019). However, as shown by the C_v values greater than 1, clusters of localized deformation are documented at ILM (NW-SE fractures, Figure 2.5a), PBC (NE-SW fractures) and SLM II units (N-S fractures, Figures 2.5c and d).

The P10 values range from $1.85\text{--}3.35\text{m}^{-1}$ (ILM), to $4.8\text{--}7.25\text{m}^{-1}$ (PBC), $5.21\text{--}7.25\text{m}^{-1}$ (SLM I), and $3.98\text{--}7.4\text{m}^{-1}$ (SLM II). Results show that the great variability of diffuse fracture intensity, similar to what La Bruna et al. (2020) documented for the tight platform Apulian carbonates exposed at the nearby site of Monte-Alpi, southern Italy, and by Al-Fahmi et al. (2020) for the Upper Jurassic shallow-water carbonates at the Arabian shelf. The values of P20 and P21 from field analyses (Figure 2.13a) respectively range $36\text{--}428\text{m}^{-2}$ and $7\text{--}35\text{m}^{-1}$ (ILM), $120\text{--}362\text{m}^{-2}$ and

19-43m⁻¹ (PBC), 61-488m⁻² and 10-33m⁻¹ (SLM I), and 71-552m⁻² and 10-47m⁻¹ (SLM II). As already reported by Manniello et al. (2022), we document that both fracture density and intensity are not controlled by the bed thickness at the outcrop scale (Gross et al., 1997, Bai & Pollard, 2000).

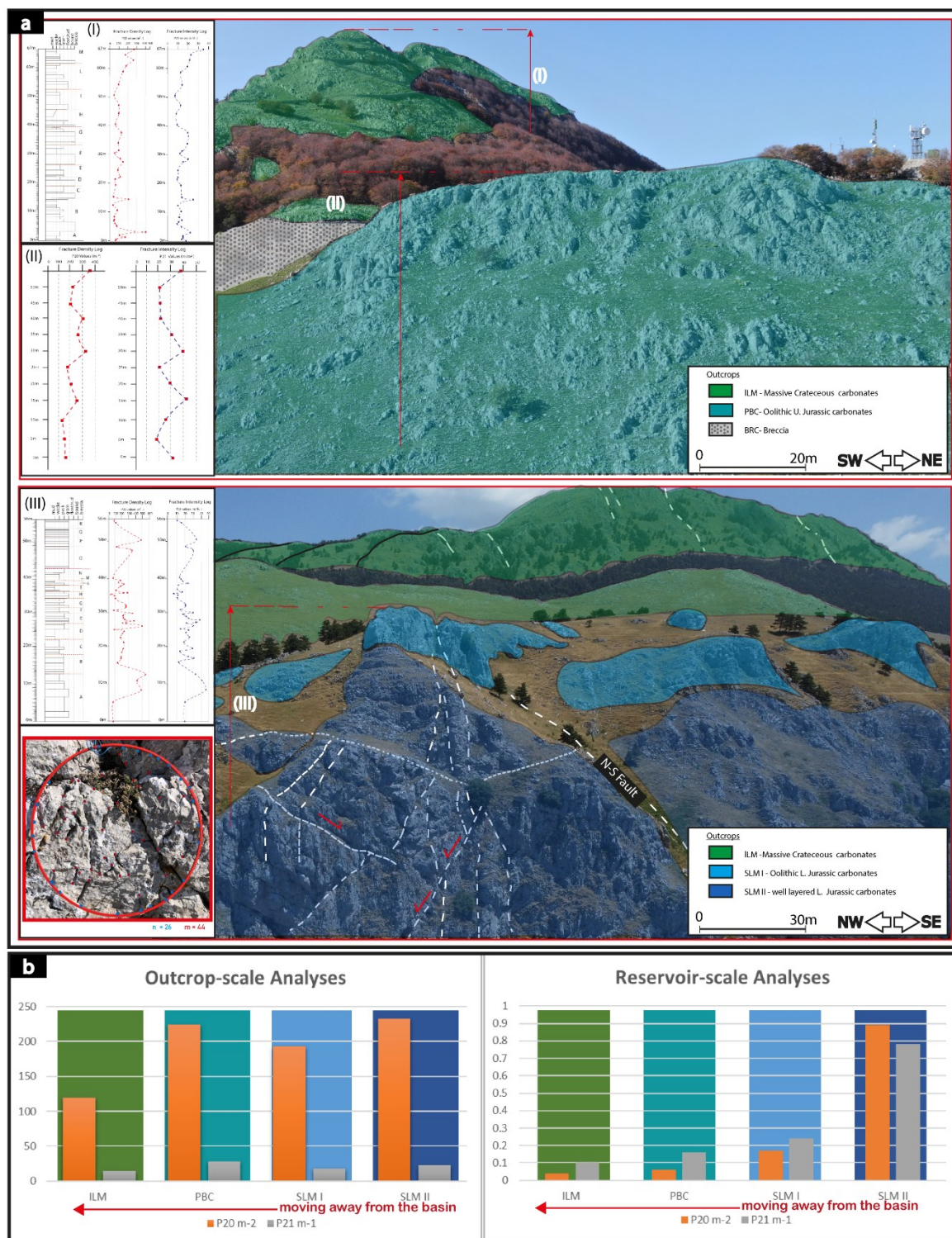


Figure 2. 13 - An overview of the study outcrops showing: (a) fracture stratigraphy analysis shown with P20 - P21 variation within the sedimentary units, (i) and (iii) modified from Manniello et al., 2022 (ii)

P20 - P21 variation trend for PBC; (b) A histogram comparing average results of P20 (orange) and P21 (grey) for the study outcrops according to the scales of observation.

2.5.3 Outcrop-to-reservoir scale fault and fracture properties

We now compare the results of data collection from field ($6\text{ cm} < \text{fracture heights} < 3\text{ m}$, cf. section 5.2) and digital analyses ($2.5\text{ m} < \text{fault heights} < 45\text{ m}$). Considering the scale-dependent geometry discussed in section 5.2.1, we note that the greatest P20 and P21 field values (Manniello et al. 2022, Figure 2.13a) correspond to those after digital analyses computed for the same carbonate outcrops (Figures 2.8a, 2.8b, 2.10a, 2.10b). Accordingly, we calculate the ratio of the peak P20 and P21 values from outcrop (field) to reservoir (digital) scales for each carbonate unit. Results show that the P20 yields inconsistent results, while the outcome of P21 ratio are similar throughout the whole study area of the Viggiano Mt. and are consistent with an average value ~ 20 of the P21 ratio.

The inconsistent P20 ratio means that the number of structural elements documented at larger scales does not increase proportionally with decreasing lengths or heights. Such a result could be due to either a more pronounced effect of fault linkage relative to formation of new fractures, as mentioned above, and/or to a truncation bias due to loss of resolution at larger scales (Zeeb et al., 2013; Mercuri et al., 2023). The latter effect would more profoundly affect the density values, therefore producing greater discrepancies among the different scales of observation. The P21 scaling factor close to 20 from outcrop-to-reservoir scales suggests that digital structural modelling can be employed to fully characterize the intensity of the structural elements. However, we highlight the importance of traditional field structural analysis to precisely document the amount of fracture density both away and within the fault damage zones crosscutting the shallow-water carbonates. Finally, the similar P20 and P21 variation patterns after field and digital analyses (Figure 2.8, 2.10, and 2.13a) is interpreted as due to the scale-invariant fault growth processes, which took place by mean of coalescence of pre-existing fractures and formation of new fractures within the evolving processes zones. As already suggested by Manniello et al. (2022), these processes would then increase the number of fractures, P20, with increasing cumulative fracture length, P21.

2.6 Conclusions

This work focused on the multiscale structural analyses of Mesozoic shallow-water carbonates flanking eastern side of High Agri Valley Basin, southern Italy. The studied carbonate units included: (i) Il Monte, ILM, massive, amalgamated, Cretaceous carbonate rudstones and

grainstones originally deposited along the paleo-slope of the carbonate platform; (ii) Piana del Buon Cuore, PBC, Lower Cretaceous - Upper Jurassic limestones whose clasts consist of oolites, oncolites and intraclasts deposited in a high-energy platform margin environment; (iii) Scarrone la Macchia I, SLM I, Toarcian oolitic carbonates characterized by bed amalgamation originally formed in a ramp setting rimmed by oolitic sand shoals; (iv) Scarrone La Macchia II, SLM II, well-layered, Sinemurian–Pleinsbachian carbonate succession of wackestone-packstones to grainstones arranged in discrete bed packages originally deposited in a low-energy, open lagoon environment. Taking advantage of the exposures, we conducted integrated field and digital structural analyses to fully assess the nature, geometry, and multiscale distribution of high-angle fractures and faults dissecting the shallow-water carbonates. The results of this work were discussed to decipher the possible control exerted by carbonate lithologies and scales of observation on the afore-mentioned structural elements. The conclusions of this work are hence summarized as follows:

1. In terms of fracture geometry, via field investigation we identified a diffuse network of high-angle fractures majorly comprised of WNW-ESE, N-S, NNE-SSW, and E-W striking sets whose multiscale spacing distributions were negative exponential. Two minor sets striking NW-SE and NE-SW were also documented. At specific outcrops, we also computed power law spacing distributions, with D-values ranging from 0.42 (N-S set at SLM II) and 0.49 (NNE-SSW set at SLM I) to 0.58 (WNW-ESE set at ILM), and 0.65 (NE-SW set at PBC). The latter data were interpreted as due to fault-related deformation, in which the D-values were consistent with poorly to fairly developed fault zones.
2. When we considered data collected both in the field ($6\text{ cm} < \text{fracture heights} < 3\text{ m}$) and from digital models ($2.5\text{ m} < \text{fault heights} < 45\text{ m}$), all studied carbonate units showed a geometry-scale dependency. We documented a higher degree of anisotropy at larger scales and interpreted this occurrence as due to strain localization and bias due to source image resolution during digital acquisition along vertical digital outcrop walls. We concluded that the larger-scale digital analysis is more efficient to portray the occurrence of fracture corridors and localized deformation.
3. In terms of any possible control exerted by carbonate lithologies on the fracture properties, the results of field analyses showed a great variation of 1D (P10) and 2D fracture intensity (P21), as well as of 2D fracture density (P20). We noted that the values did not vary with the bed thickness; they were interpreted as due to presence of

fracture clusters ($C_v > 1$). Fault growth by shearing along pre-existing fractures, linkage across bed and bed packages interfaces, and formation of new fractures at releasing jogs were invoked as specific deformation mechanisms.

- Comparing and contrasting the results achieved after field and digital structural analyses, we computed a P21 scaling factor close to 20. Differently, inconsistent results were gotten for P20 variations. Such a discrepancy was interpreted as due to the deformation mechanism described above and the associated truncation effects (missing fault-related fractures localized at releasing jogs).

The results of this work highlighted the importance of traditional field structural analysis to precisely document the amount of fracture density both away and within the carbonate fault damage zones, with important implications for the characterization of the amount of fluid storage within fractured rock volumes. In conclusion, we documented that the fracture properties change according to the original depositional setting of the shallow-water carbonates, and also to the scales of observation.

		OUTCROP SCALE DATA							RESERVOIR SCALE DATA						
		WNW-ESE	NW-SE	NNW-SSE	N-S	NNE-SSW	NE-SW	E-W	WNW-ESE	NW-SE	N-S	NNE-SSW	NE-SW	E-W	ENE-WSW
ILM	Total No. of fractures/surveyed	228							1127						
	Strike/dip - RHR	300/72	329/72	***	358/79	***	***	260/88	***	320/75	***	210/75	40/44	271/89	60/52
	Cv	1.15	0.87	***	1.25	***	***	1.05	***	***	***	***	***	***	***
	P10 (m ⁻¹)	0.25	1.15	***	1.31	***	***	2.05	***	***	***	***	***	***	***
	*MSP-Best fit (Height/Length)	exp	exp	***	exp	***	***	exp	***	Power	***	exp	Power	Power	Power
	Power law exponent, D	***	***	***	***	***	***	***	***	1.42	***	***	1.53	2.02	1.79
	MSP-Best fit (Spacing)	power	exp	***	exp	***	***	exp	***	***	***	***	***	***	***
	Power law exponent, D	0.58	***	***	***	***	***	***	***	***	***	***	***	***	***
	P20 m ⁻² (range)	35 - 428							upto 1.2						
	P21 m ⁻¹ (range)	7 - 35							upto 1.4						
For the entire outcrop-mean P20/P21		119.2/14.4							0.04/0.099						
PBC		OUTCROP SCALE DATA							RESERVOIR SCALE DATA						
		WNW-ESE	NW-SE	NNW-SSE	N-S	NNE-SSW	NE-SW	E-W	WNW-ESE	NW-SE	N-S	NNE-SSW	NE-SW	E-W	ENE-WSW
	Total No. of fractures/surveyed	289							428						
	Strike/dip - RHR	130/71	***	157/82	182/83	200/83	235/72	92/86	289/81	325/81	179/79	***	***	266/87	***
	Cv	1.42	***	0.99	1.47	1.26	1.65	1.14	***	***	***	***	***	***	***
	P10 (m ⁻¹)	3.25	***	1	0.79	0.93	1.14	0.88	***	***	***	***	***	***	***
	*MSP-Best fit (Height/Length)	exp	***	exp	exp	exp	exp	exp	exp	exp	exp	***	***	power	***
	Power law exponent, D	***	***	***	***	***	***	***	***	***	***	***	***	0.90	***
	MSP-Best fit (Spacing)	exp	***	exp	exp	exp	power	exp	***	***	***	***	***	***	***
	Power law exponent, D	***	***	***	***	***	0.65	***	***	***	***	***	***	***	***
P20 m ⁻² (range)	120 - 362							upto 0.8							
P21 m ⁻¹ (range)	19 - 43							upto 1.2							
For the entire outcrop-mean P20/P21		224.1/28.7							0.056/0.159						
SLM I		OUTCROP SCALE DATA							RESERVOIR SCALE DATA						
		WNW-ESE	NW-SE	NNW-SSE	N-S	NNE-SSW	NE-SW	E-W	WNW-ESE	NW-SE	N-S	NNE-SSW	NE-SW	E-W	ENE-WSW
	Total No. of fractures/surveyed	142							402						
	Strike/dip - RHR	289/80	***	***	356/86	20/73	***	***	303/88	***	***	196/88	38/87	***	***
	Cv	0.57	***	***	1.09	1.06	***	***	***	***	***	***	***	***	***
	P10 (m ⁻¹)	1.75	***	***	***	***	***	***	***	***	***	***	***	***	***
	*MSP-Best fit (Height/Length)	exp	***	***	exp	exp	***	***	power	***	***	exp	power	***	***
	Power law exponent, D	***	***	***	***	***	***	***	1.11	***	***	***	1.09	***	***
	MSP-Best fit (Spacing)	exp	***	***	exp	power	***	***	***	***	***	***	***	***	***
	Power law exponent, D	***	***	***	***	0.49	***	***	***	***	***	***	***	***	***
P20 m ⁻² (range)	87 - 488							upto 1.8							
P21 m ⁻¹ (range)	10 - 33							upto 1.6							
For the entire outcrop-mean P20/P21		197.5/18.9							0.175/0.238						
SLM II		OUTCROP SCALE DATA							RESERVOIR SCALE DATA						
		WNW-ESE	NW-SE	NNW-SSE	N-S	NNE-SSW	NE-SW	E-W	WNW-ESE	NW-SE	N-S	NNE-SSW	NE-SW	E-W	ENE-WSW
	Total No. of fractures/surveyed	225							1238						
	Strike/dip - RHR	290/84	***	***	356/86	20/73	***	91/85	***	***	178/88	197/88	40/87	***	62/87
	Cv	1.05	***	***	1.23	1.42	***	1.36	***	***	***	***	***	***	***
	P10 (m ⁻¹)	2.15	***	***	0.84	1.92	***	1.18	***	***	***	***	***	***	***
	*MSP-Best fit (Height/Length)	exp	***	***	power	exp	***	exp	***	***	exp	exp	exp	***	exp
	Power law exponent, D	***	***	***	1.13	***	***	***	***	***	***	***	***	***	***
	MSP-Best fit (Spacing)	exp	***	***	power	***	***	exp	***	***	***	***	***	***	***
	Power law exponent, D	***	***	***	0.42	***	***	***	***	***	***	***	***	***	***
P20 m ⁻² (range)	91 - 552							upto 6							
P21 m ⁻¹ (range)	11 - 46							upto 3.5							
For the entire outcrop-mean P20/P21		233.2/22.3							0.888/0.776						

*MSP - multiscale properties

CHAPTER 3 - MULTISCALE DISCRETE FRACTURE NETWORK MODELLING OF SHALLOW-WATER CARBONATES: EAST AGRI VALLEY BASIN, SOUTHERN ITALY.

3.1 Introduction

Both fractures and faults often affect the directionality of fluid flow (Gillespie et al., 1993; Bonnet et al., 2001; Agosta et al., 2010; Ceccato et al., 2022), and possibly lead to permeability anisotropies within rock masses (Lorenz et al., 1988, 1989; Garzic et al., 2011; Holdsworth et al., 2019). To quantify the control exerted by structural heterogeneities on the petrophysical properties of rock volumes, Discrete Fracture Network (DFN) modelling has emerged as a powerful tool to quantify the amounts of fracture porosity and equivalent permeability of geocellular volumes populated by digital fractures (Wilson et al., 2011; Panza et al., 2016). This tool, commonly employed in petroleum geology, hydrogeology, and geothermal studies (Meyer & Einstein, 2002; Doonechaly & Rahman, 2012; Viswanathan et al., 2022), also find applications for the analysis of surface analogues of fractured reservoirs buried at depth (Korneva et al., 2015; Zambrano et al., 2016; Casini et al., 2016; Panza et al., 2018, 2019; Giuffrida et al., 2019; Romano et al., 2020; Smeraglia et al., 2021), and the integration of DFN models with reservoir simulation software for an accurate reservoir management (Moinfar et al., 2014; Jiang and Younis., 2016; Dershowitz et al., 2020). In hydrogeology, DFN modelling is carried out to better constrain the directionality of groundwater flow and contaminant transport in fractured aquifers (Makedonska et al., 2015; Du et al., 2023; Masciopinto et al., 2021, 2024).

Within layered carbonates, such as those investigated in the present study, fractures are often compartmentalized within single beds and are hence named as Strata Bound (SB) fractures. On the contrary, those that cut across multiple beds but do not solve any significant amount of slip are named as Non-Strata Bound (NSB) fractures. The former ones are seen as fractures whose vertical growth was somehow impeded by the bed interfaces or any other traction-free heterogeneity (*sensu* Helgeson & Aydin, 1991; Gross & Engelder, 1995), whereas NSB fractures as incipient faults that might result from the linkage of pre-existing SB fractures (Sornette et al., 1993; Cooke & Underwood, 2001; Graham et al., 2003; Crider and Peacock, 2004). The linkage processes typically result in vertically persistent discontinuities crosscutting and displacing multiple beds, and in the formation of new fractures within the narrow rock volumes bounding the mechanical interfaces (Peacock et al., 1997; Graham et al., 2003; Agosta et al., 2009, 2015; Antonellini et al., 2008; Aydin et al., 2010).

Some models tend to overlook fracture data of certain scales, ignoring the immense contribution mesoscale fractures have on overall reservoir properties. The effect of such biases is observed when aerial fracture density (P_{20}) expressed as the number of fractures per unit area (L^{-2}), and aerial fracture intensity (P_{21}), expressed as length of fracture traces per unit area (L^{-1}) are gathered from integrated field and digital studies, and the results vary with scale, which is due to loss in resolution (Zeeb et al., 2013; Mercuri et al., 2023; Abdallah et al., 2023).

Hence, our study provides evidence of the non-negligible contribution on fracture porosity and equivalent permeability by mesoscale faults and fractures dissecting Mesozoic shallow-water carbonates exposed along the axial zone of the southern Apennines fold-and-thrust belt. The investigation is conducted at m-to-km scales by integrating field and digital structural analysis of the carbonates, and then running multiple DFN models of nine different geocellular volumes whose dimensions are equivalent of the study exposures.

In fact, by computing the dimensional properties of single sets of SB fractures, NSB fractures, small (cm-offset) and medium faults (10's of cm-offset), the geocellular volumes are populated by the structural elements documented at any given scale of observation. The original data are discussed in terms of fluid storage and migration properties of the studied rock volumes, and the main outcomes are summarized in a conceptual model showing the horizontal permeability ellipses computed at m-to-km scales.

The model reports the control exerted by faults and fractures on subsurface fluid flow under vadose and phreatic conditions, and hence provides valuable information for geoscientists dealing with groundwater protection, pollutant dispersion in the subsurface, and insights for those involved in hydrocarbon recovery, geothermal energy production, and Carbon Capture and Storage (CCS) activities.

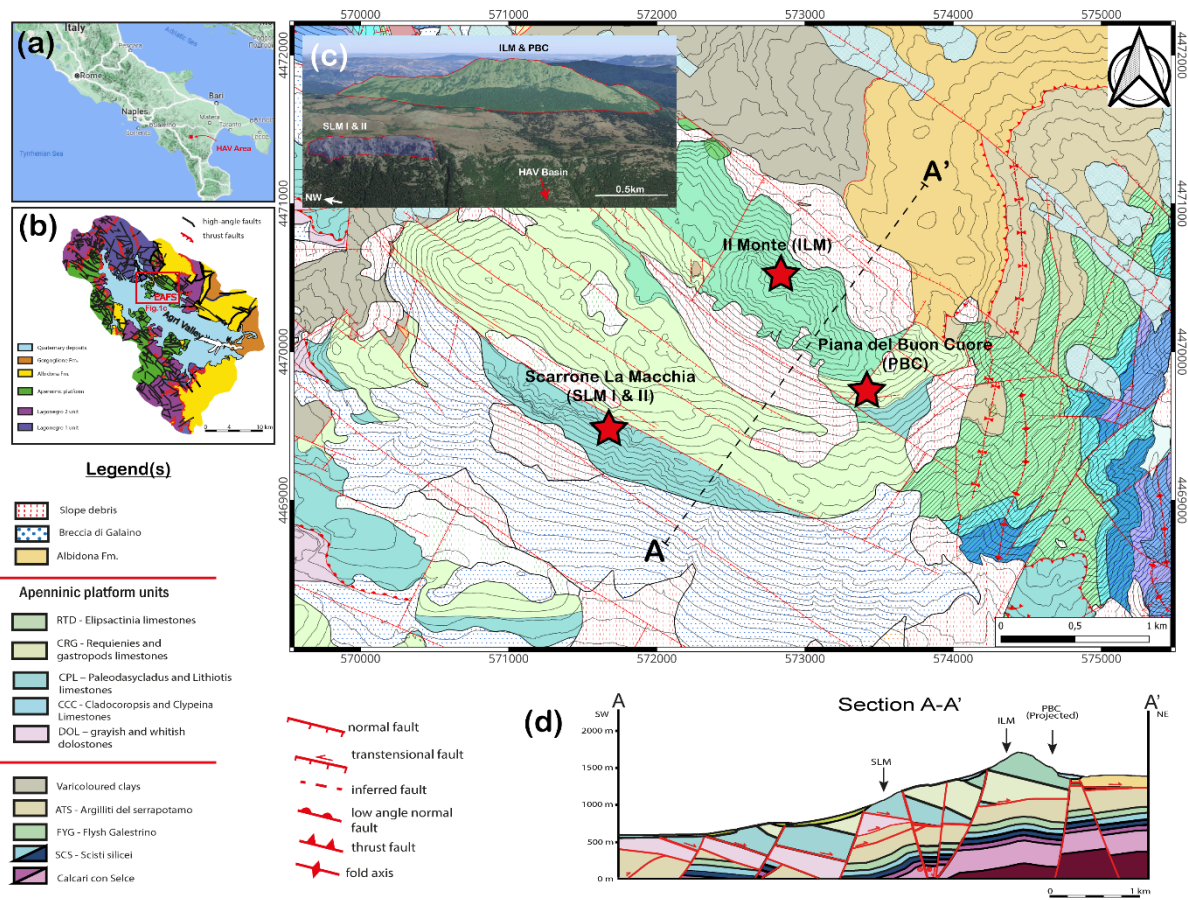


Figure 3. 1 (a) Map of Italy showing the location of the High Agri Valley, HAV. (b) Geologic map of the High Agri Valley area showing the East Agri Fault System (EAFS). (c) Geologic map of Viggiano Mt. area showing an expanded view of the EAFS faults from 1b. and showing the studied locations, U. Cretaceous Il monte (ILM), L-Cretaceous – U. Jurassic Piana del Buon Cuore (PBC), L. Jurassic Scarrone La Macchia 1, and Jurassic Scarrone La Macchia 2 (SLM I & II) (d) A cross section from A to A' showing the high – angle basin bounding faults and the studied sites.(Figs. 1b – d modified after Palladino et al., 2023)

3.2 Geological setting

3.2.1 Southern Apennines

The southern Apennines (Figure 3.1a) is a E-verging fold-and-thrust belt (FTB) formed since Oligocene times after W-directed subduction of the Tethyan oceanic domain and consequent collision of the African and Eurasian tectonic plates. Tectonic units forming the FTB consist of Meso–Cenozoic sedimentary covers scraped off from different paleogeographic domains of the Tethys Ocean and the western margin of the African plate (Piedilato and Prosser, 2005; Patacca and Scandone 2007). From W to E, the main tectonic units are: i) the Tethyan-derived

Liguride and Sicilide Units and ii) the Africa-derived Apenninic Platform and Lagonegro Units. Eastward, the Apulian Platform represents the foreland area of the FTB.

In detail, the studied shallow-water carbonates of the Viggiano Mt. (Figure 3.1b) pertain to the Apenninic Platform. During Miocene, this was first over-thrusted by the deep-sea Ligurian and Sicilide tectonic units and then, it overrode the Lagonegro unit during eastward propagation of the contractional deformation (Bonardi et al., 1988; Palladino et al., 2008; Ciarcia et al., 2009, 2012; Prosser et al., 2021). Finally, the whole FTB overrode the Apulian Platform along a basal decollement outlined by a *mélange* zone (Shiner et al., 2004), separating the Lagonegro Unit at the hanging wall from early Pliocene turbidites at the footwall. Continued crustal shortening during Pliocene led to the formation of deep-seated reverse faults involving the crystalline basement and the Mesozoic carbonates of the Apulian Platform. This was responsible for the transition from thin-to-thick-skinned deformation in the FTB (Mazzoli et al., 2008, Butler et al., 2012). Thick-skinned reverse faults formed by positive inversion of pre-existing, Permian-Triassic in age extensional faults, under contractional stress field (Mostardini and Merlini, 1986; Shiner et al., 2004; Butler and Mazzoli, 2006). During the Late Pliocene, the overthickened FTB was affected by low-angle normal faults due to gravitational collapse of the Apennines, promoting the partial tectonic removal of the Apenninic platform and the Liguride units (Ferranti et al., 1996; Bucci et al., 2014; Mazzoli et al., 2014; Novellino et al., 2015). The central and western sectors of the FTB were then downfaulted by high-angle normal and strike-slip faults of Plio-Quaternary age, connected to the opening of the Tyrrhenian Sea (Hippolyte et al., 1995; Noguera & Rea, 2000; Vezzani et al., 2010).

3.2.2 High Agri Valley Basin

The intra-mountain High Agri Valley (HAV) Basin trends NNW-SSE to WNW-ESE and lies in the axial portion of the southern Apennines (Figure 3.1). This 30 km-long and 12 km-wide basin formed as a result of transtensional faulting, which generated accommodation space allowing the deposition of alluvial to lacustrine sediments of Quaternary age (Di Niro et al., 1992; Di Niro & Giano 1995; Schiattarella et al., 1998; Giano et al., 2000; Maschio et al., 2005). Presently, the basin is bound eastward by high-angle faults pertaining to the East Agri Valley Fault System, EAFS (Figure 3.1b), and westward by the high-angle faults of the Monti della Maddalena Fault System, MMFS (Cello & Mazzoli, 1998; Cello et al., 2000, 2003; Maschio et al., 2005). The EAFS includes N90-120 trending, left-lateral transtensional faults, N20-30 trending, right-lateral transtensional faults, and N130–150 trending extensional faults

(Cello & Mazzoli, 1998; Cello et al., 2000; Palladino et al., 2023; Abdallah et al., 2023). The HAV area is tectonically active, and loci of the devastating 1875 Basilicata earthquake (Mallet, 1868; Branno et al. 1985; Maschio et al., 2005). Evidence from dating of paleosoils has confirmed the recent activity of the high-angle faults (Giano et al., 2000). The area hosts the largest onshore hydrocarbon field in West Europe that produces from fractured carbonate reservoir (Mosca & Mavrek, 2002; Stabile et al., 2021) and forms potent aquifers providing water for both domestic and industrial usages.

3.2.3 Viggiano Mt.

Viggiano Mountain lies on the eastern side of the HAV (Fig.1c). It exposes fractured and faulted Mesozoic shallow-water carbonates of the Apenninic Platform (D' Argenio et al., 1975. With an area $\approx 15\text{km}^2$, these carbonate rocks differ in properties according to their depositional setting and structural position away from the main basin-bounding faults (Burchette & Wright, 1992; Lechler et al., 2012; Manniello et al., 2022, 2023; Abdallah et al., 2023; Todaro et al., 2024). The three study sites are respectively named as Il Monte, ILM, Piana del Buon Cuore, PBC, and Scarrone La Macchia, SLM (Figure 3.1c). At the latter site, two specific areas are investigated, and accordingly labelled as SLM I and SLM II. ILM marks the culmination of the shallow-water carbonates, lying in close proximity to the thrust front which juxtaposes the Apenninic platform on the Lagonegro Unit (Figure 3.1d). It exposes Albian-Cenomanian carbonate rudstones and grainstones with gastropods, bivalves, rudists (Radiolitidae) and foraminifera originally deposited along the paleo-slope of the carbonate platform. These carbonates are massive and characterised by bed amalgamation. There, through-going fractures and faults across bedding are common (Figure 3.2a). At the foothills of the ILM outcrop, PBC exposes Lower Cretaceous - Upper Jurassic limestones whose clasts consist of oolites, oncolites and intraclasts. The PBC also shares similar features of bed amalgamation as the ILM. The limestones were likely deposited in a high-energy platform margin environment (Palladino et al., 2023). SLM I and SLM II expose Lower Jurassic limestones. The rocks consist of oolitic limestones with amalgamated beds on its upper part (SLM I; Figure 3.2b), overlying carbonate wackestone, packstones to grainstones arranged in well-layered, discrete bed packages bounded by 5–10 cm-thick, clay-rich interfaces (SLM II). The single beds (5–40 cm-thick) are delimited by mm to cm-thick interfaces, in some instances marked by the presence of pressure solution seams. The oolitic carbonates are Toarcian in age and were originally deposited in a ramp setting rimmed by oolitic sand shoals, while the well-layered carbonate succession is Sinemurian– Pleinsbachian in age and was originally deposited in a low-energy open lagoonal environment (Lechler et al., 2012; Manniello et al., 2022; Todaro et al., 2024).

These carbonates, affected by Upper Miocene thrusting tectonics and subsequently exhumed from depths of around 4.5 km, offer excellent exposures (lateral continuity for over 100s of meter, not covered by vegetations and also accessibility for field scale analysis as well as 3 dimensional exposures for representative 3D photogrammetry models), for studying the impact of structural elements on hydraulic properties (Patacca & Scandone, 2007; Manniello et al., 2023)

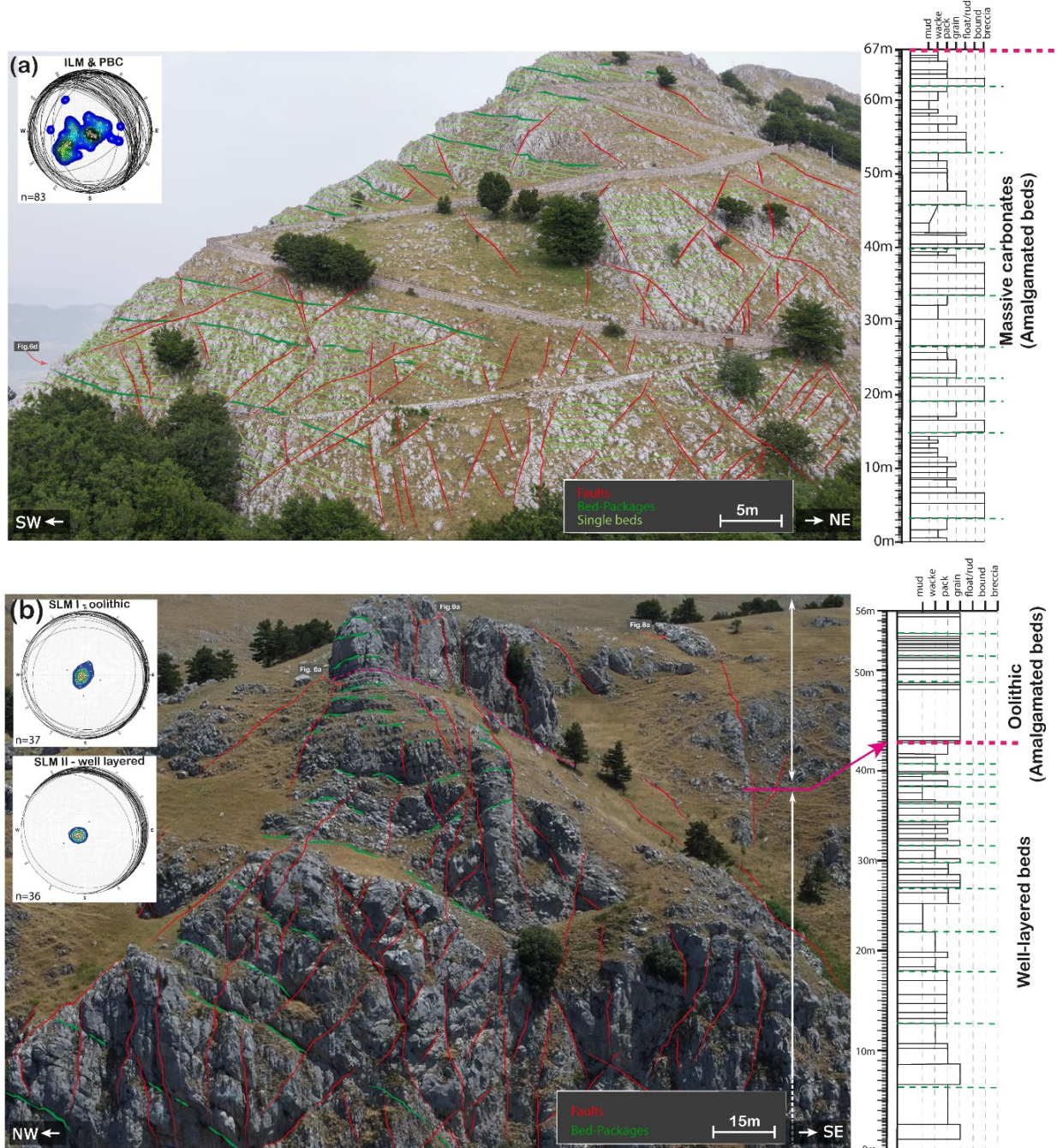


Figure 3. 2 (a) SW-NE view of the ILM outcrop showing the massive, amalgamated carbonate beds and bed packages that are crosscut by through going fractures and small faults. The lithostratigraphic log is shown alongside. At the foot of this outcrop lies the PBC outcrop, quite similar to the ILM hence, it is not shown here. Inset (a) shows contour plots for which is bedding poles of the respective outcrops (Fig

3.2a. modified after Manniello et al., 2023). (b) NW–SE view of the SLM outcrops (amalgamated beds oolitic carbonates, SLM I and well-layered beds carbonates, SLM II) showing the bed packages and series of outcrop scale high-angle faults crosscutting these carbonates. The lithostratigraphic logs and contoured bedding poles are also shown alongside.

3.3 Methods

3.3.1 Photo lineament interpretation

Photo lineament interpretation was conducted at the scale of 10s of metres-to-few-kilometres to cover the entire Viggiano Mt area. This was carried out to map 1st order structural elements and other faults ranging from > 30m and up to few kilometres-scale in length. Orthorectified aerial photos and satellites images were employed, sourced from the Military Geological Institute (1: 33, 000: Sheet 199 – Potenza – swiping N34°, frames 24 – 36) and from Google Earth ® with scale of up to 1: 3,000.

Other data employed were orthophotos from the Geoportal of Basilicata Region (<https://rsdi.regione.basilicata.it>) at variable scales (maximum scale used 1: 3,000). Structural interpretation was carried out using the QGIS open-source software (version 3.6.2). Traces were made on the basis of the recognised first-order tectonic features as reported in the geological map of the region and other structural elements were later added from ortho-rectified photo interpretations. A minimum threshold for efficient structural interpretation based on the limitation posed by resolution was set at 30m, and hence, all structural traces shorter than that were discarded. The traced structures (without map) were extracted as a .svg file and analysed with FracPaQ2D (Healy et al., 2017). There, the data was statistically and geometrically processed. A rose diagram was generated that allowed the recognition of different sets of features, according to their strike directions. Statistical processing of the data involved the extraction of lengths for individual structural elements (FracPaQ), assigning them according to their respective sets, and assessment of their multiscale length distribution (Log-Log graph of Cumulative No. plotted against Length).

3.3.2 Field acquisition

For centimeter-to-meter scale data inputs required an efficient 5m bed-package sized DFN modelling, we collected data in the field on geometry (attitude) and dimensions (height, spacing, mechanical aperture, roughness) of SB-NSB fractures with height values comprised between 6 cm and 3 m height (Pickering et al., 1997; Figure 3.4). Using the linear scanline method (Priest and Hudson, 1981; Priest, 1993), at single outcrops we oriented the measuring

tapes perpendicular to the main fracture sets (localized deformation) or parallel to bedding interfaces (diffuse deformation) as widely reported in the literature (i.e., Watkins et al., 2015). Over 100 fractures were measured at each site to attenuate data uncertainty (Ortega et al., 2006).

Five scanline measurements were each conducted at each ILM, PBC and SLM II. Their lengths varied from 6 m to 20 m. Three scanlines' measurements were conducted at SLM I, whose lengths were comprised between 6 and 10 m. All chosen sites lie away from the large-scale faults reported by Manniello et al. (2022) and Abdallah et al. (2023). The measured fractures consisted of joints, veins, sheared fractures, and small faults with few centimetres of displacement. The acquired data on fracture geometry was processed in the Stereonet® software (Allmendinger et. al., 2012; Cardozo et. al., 2013), and then reported using equal-area, lower hemisphere projections to distinguish the mean fracture sets (Fisher, 1953). Data regarding fracture heights were plotted against cumulative number, CN, in a log-log graph, and data regarding their best-fit regressions, R, were extracted. All fracture sets were fit by a power-law distribution to extract the exponent of its equation, which corresponds to the Fractal D-value for DFN input. This is based on assertion that natural fracture exhibits self-similar (fractal) behaviours over a range of scale (Mandelbrot, 1982; Sornette et al., 1993; Bonnet et al., 2001). Fracture aperture values, one of the essential parameters in fluid modelling (Gong and Rossen, 2017; Zambrano et al., 2019) were collected as mechanical aperture, E, and Joint Roughness Coefficient, JRC, for single barren fractures. The afore-mentioned values were measured along the scanline by using a comparator following the approach suggested in the literature (Barton & Choubey, 1977; Ortega et al., 2006; Rustichelli et al., 2013, 2015; Guerriero et al., 2015; Giuffrida et al., 2019). However, it is important to note that the aperture values collected in the field did not vary proportionally with height, hence we adopted the minimum value as input for all fracture sets during the modelling phase.

3.3.3 Digital structural data acquisition and analysis

A digital structural survey was conducted that allowed for the extraction of faults up to 100s meter in fault height to the 50m bed package association, and 500m large cliff DFN model computations using the generated 3D photogrammetry models. This is especially important since some of the outcrops (i.e., large cliff at SLM and SLM II) were mostly inaccessible by foot, and large-scale structures could be better appreciated aurally and away from the study outcrops.

An unmanned aerial vehicle (UAV) survey was conducted by using a DJI Mavic II zoom drone (generic camera model FC2204, fixed focal length of 25 mm, ISO -100, diaphragm opening of F/2.8, shutter speed of 1/200s. High-resolution images were captured manually with > 75% overlap, in both nadir and oblique camera inclinations, at 5-10m distance from the exposed rock surface at each of the study sites. 3D virtual outcrop models were built using structure-from-motion (SfM) and Multiview-stereo (MVS) algorithms within the Agisoft Metashape software following the workflow proposed by Tavani et al (2014). For proper georeferencing, orientation of the models was provided from by the Global Navigation Satellite System (GNSS) coordinates written within the metadata of each photo by the drone and no additional ground control points (GCPs) were required (James & Robinson, 2012; Corradetti et al., 2022). Georeferenced 3D outcrop models were later exported as .obj files to the OpenPlot software (Tavani et al., 2011), which allowed the extraction of geometry and dimensions of multiple fracture – fault planes from 2.5m to 500m (fracture – fault height; Figure 3.3). The number of structural planes extracted were reported for each figure. A total of the following six photogrammetry models were generated for digital structural analyses. At the Il Monte site, the following three models were built up:

1. ILM (200 m × 140 m x 100 m).
2. PBC (170 m × 65 m x 25 m).
3. Top Viggiano Mt., (combined ILM & PBC outcrops, 1800 m x 600 m x 700 m).

At the Scarrone la Macchia site, the following three models were constructed:

1. SLM I (77 m × 45 m x 20 m).
2. SLM II (90 m × 50 m x 56 m).
3. combined SLM (combined SLM I and II outcrops, 710 m x 200 m x 150 m).

3.3.4 Discrete Fracture Network modelling

The multiple Discrete Fracture Network, DFN, models of the multiscale fractured carbonates were built using the stochastic approach in Move ® software (Petroleum Experts) using data collected from the field for the smallest 5m bed-package-scale sized model, and data extracted from the digital outcrop models for the intermediate 50m bed-package association and 500m large-cliff scales (Figure 3.3). The data input for the models were: minimum and maximum values of fracture length, power-law D fractal values for the length (Mandelbrot, 1982; Sornette et al., 1993; Bonnet et al., 2001), aspect ratio applying 1:2 for SBs and 1:4 for NSBs (Odling et al., 1997; Olson, 2003; Panza et al., 2015, 2016; Giuffrida et al., 2019; 2020), mean orientations of fracture sets in dip direction and dip format (default settings), and their fisher

distribution values (Fisher, 1953). For the smallest sized model that required field data input, we used the geo-mechanical parameter, joint volumetric count, J_v (Eqn 1; Palmstrom, 2001; Panza et al., 2016), which is the same as fracture density, P_{30} (Dershowitz and Herda, 1992). It is expressed as number of joints per m^3 as:

$$J_v = \left(\frac{n}{L} \right)^3 \quad (1)$$

Where n is number of fracture and L is the length of the scanline. In our case, a division of number of fractures of the same fracture sets by the length of that scanline from which they are recognized.

Fracture distribution inputs for the intermediate (50m) and larger sized (500m) models were volumetric fracture intensity values, P_{32} , is the division of the fractures area by their volumes (L^{-1}). This value was computed by dividing the computed sum total area of digitally extracted planes of each set by the estimated volume of the 3D outcrop.

Fracture parameters modelled stochastically are treated as random variables with given probability distributions. An example is the fracture length parameter, which in our study adopts Power-law distribution. Fractures are populated within individual cells on the basis of their length until the intensity values are reached. As regards to porosity and permeability, firstly, fracture porosity, ϕ , is calculated as the ratio of total fracture volume in a cell, per cell volume, whereas the fracture permeability tensor is based on the Oda's methodology (Oda, 1985) derived from both Darcy's law and Navier-stokes equation for incompressible fluid flow between two smooth parallel plates (Snow, 1965; Long et al., 1996; Eqn. 2):

$$\frac{Q}{A} = \frac{e^3}{12D} \frac{dh}{dl} \frac{\rho g}{\mu} \quad (2)$$

where Q is the flow rate, A the cross-sectional area of the modelled volume, e is the fracture hydraulic aperture, D is the fracture spacing, h/l is the pressure head, ρ is the fluid density and μ is the fluid dynamic viscosity. The result is a 'geometric permeability', which depends on the cumulative fracture area, or 'void' spaces, of each cell and on fracture aperture. The permeability is presented as a tensor (K_{xx} , K_{yy} , K_{zz} , K_{xy} , K_{xz} , and K_{yz}). However, only the K_{xx} , and K_{yy} are considered in this study for 2D horizontal permeability assessments, since the Move[®] software doesn't allow modelling of bed and bed package interfaces within DFN models.

The constant value of 0.1mm corresponding to the minimum aperture collected in the field was applied for all fracture sets during porosity computation. This value is within the range reported for fractured carbonates at shallow crustal depths (Davaranah and Hemat, 2017; Stadtmuller

et al., 2021) and according to the method adopted by Larssen et al., (2020). The value was applied in order to provide a major focus on the contribution of SB and NSB fractures. Another possible option was the employment of the average vein thickness (Vermilye & Scholz, 1994). However, since veins were rarely visible in the outcrop, this option was not taken. Differently, fracture permeability computations were performed only considering theoretical values. We ran models inputting both “hydraulic aperture proportional to fracture length” and “hydraulic aperture proportional to the square root of fracture length” as most favourable and least favourable options for fluid flow, respectively, acknowledging therefore the contribution played by large scale structural elements to overall permeability (Olson, 2003; Mayrhofer et al., 2019).

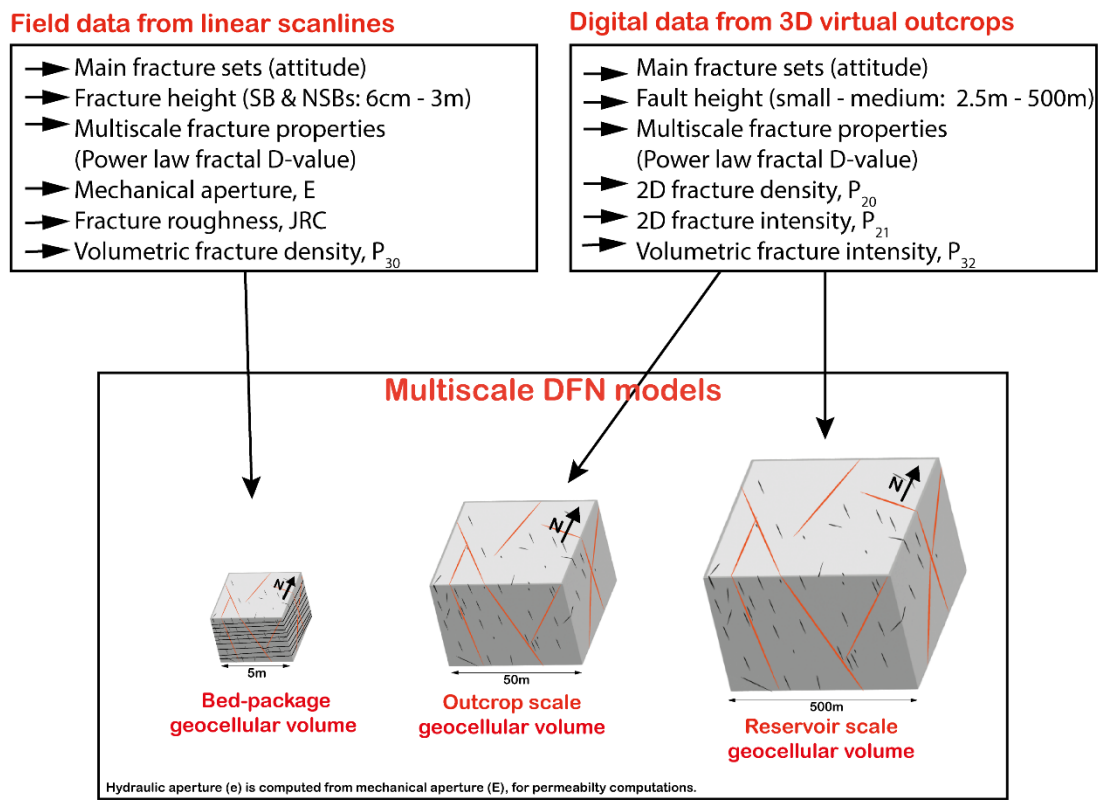


Figure 2.3 (a) Schematic diagram of the methodology applied for multiscale DFN modelling this study. The field data are used as inputs for the 5m bed package scale DFN modelling while the digital structural data from 3D virtual outcrops are inputs for the 50m outcrop scale model and 500m reservoir scale model.

A total of nine multiscale DFN models were built (Figure 3.4). The Il Monte site, ILM, the 5 m-sized geocellular volume (no sub-volumes, representative of the amalgamated bed packages) included 10 cm-sized cells, the 50 m-sized volume (no sub-volumes, representative

of the ILM digital outcrop model) included 1 m-sized cells. At Piana del Buon Cuore site, PBC, the 5 m-sized geocellular volume (no sub-volumes) included 10 cm-sized cells, and the 50 m-sized volume (no sub-volumes, representative of the PBC digital outcrop model) with 1m-sized cells. A large 500 m-sized geocellular volume (no sub-volumes, which incorporated both ILM and PBC sites and represented the large Top Viggiano Mt. digital outcrop model) included 10 m-sized cells. At Scarrone la Macchia, SLM, two different 5 m-sized geocellular volume were built. Both SLM I (no sub-volumes, representative of the amalgamated oolitic bed packages) and SLM II (10, 50 cm-thick, geocellular sub-volumes representative of single carbonate beds) were built with 10 cm-sized cells. Then, a 50m geocellular volume was built combining both SLM I and SLM II (13 sub-volumes, a 14 m-thick top sub-volume representative of oolitic carbonates, and 12 sub-volumes, each one 3 m-thick, representative of single bed packages) included 1 m-sized cells. Finally, a large 500 m-sized geocellular volume (no sub-volumes) was built with 10 m-sized cells. Input for this large-scale model derived from the results of large SLM digital outcrop analysis.

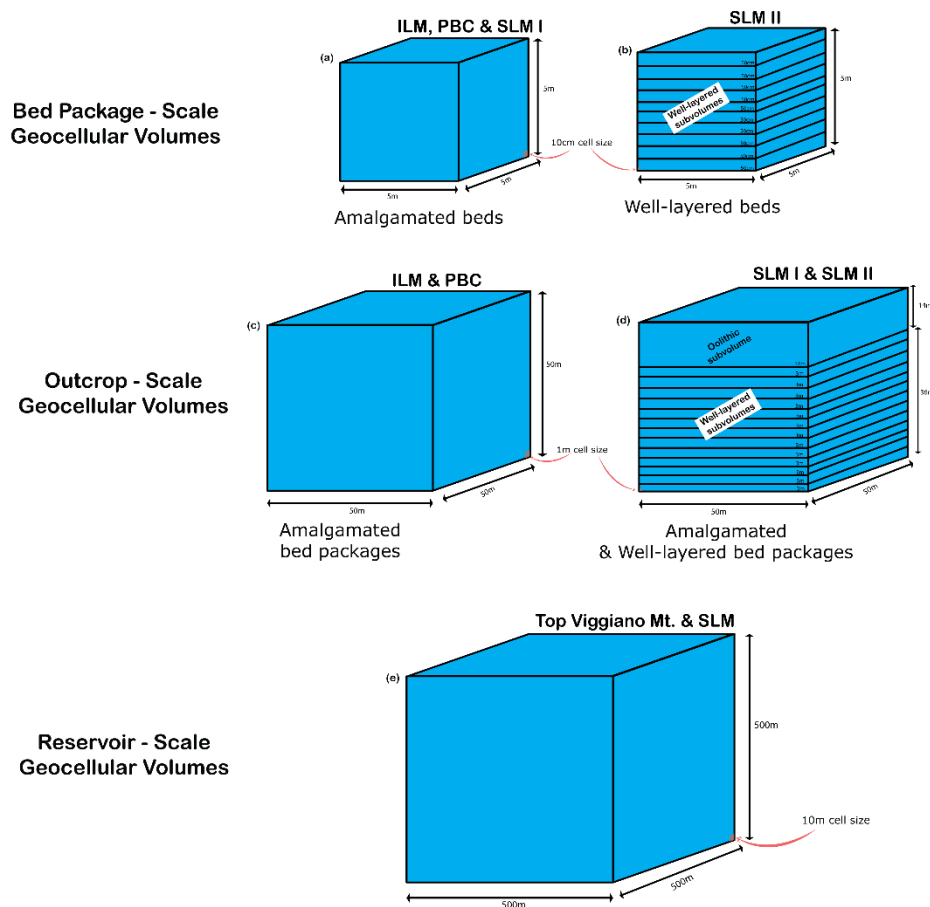


Figure 3. 4 Geocellular volumes according to the scale of observation and DFN computations. (a) Three 5m-bed package scale geocellular volumes (no sub-volumes) built to represent ILM, PBC and SLM I at that scale. (b) One 5m bed-package scale geocellular volume built with ten, 50cm sub-volumes representing single beds, for the well-layered SLM II carbonate outcrop. (c) Two 50m outcrop scale

geocellular volumes (no sub-volumes) built to represent the amalgamated beds carbonates of ILM and PBC. (d) One 50m outcrop scale geocellular volume subdivided into 13 sub-volumes, one 14m sub-volume represents the portion with oolitic carbonate as observed during field investigation, the others are twelve sub-volumes, 3m each representing the bed-packages of SLM II. (e) Two 500m reservoir scale geocellular volume (no sub-volumes) for Top Viggiano Mt. model and large Scarrone la Macchia cliff.

3.4 Results

We first report the results from aerial photointerpretation of the Viggiano Mt. area, and then those after field investigation and subsequent 3D outcrop analysis. The original data are presented together with those previously published by Abdallah et al. (2023) for the same outcrops studied.

3.4.1 Morphological lineaments

Altogether, 3,728 lineaments are recognised. First order features, which are the reported in the geological map of the area (Palladino et al., 2023) are shown in white, whereas the smaller scale features are coloured according to their strike direction (Figure 3.5a). The rose diagram of the strike direction of the lineaments (Figure 3.5b) shows five main sets respectively striking WNW-ESE, NW-SE, N-S, NE-SW and ENE-WSW. The multiscale length properties of the single sets are fit by power law distributions (R^2 , 0.86 – 0.99). The computed D- values are 1.59 (WNW-ESE), 1.24 (NW-SE), 1.53 (NE-SW), and 1.62 (ENE-WSW). The N-S set shows evident bi-fractal distribution with D-values of 0.42 and 3.22 (Fig. 5c).

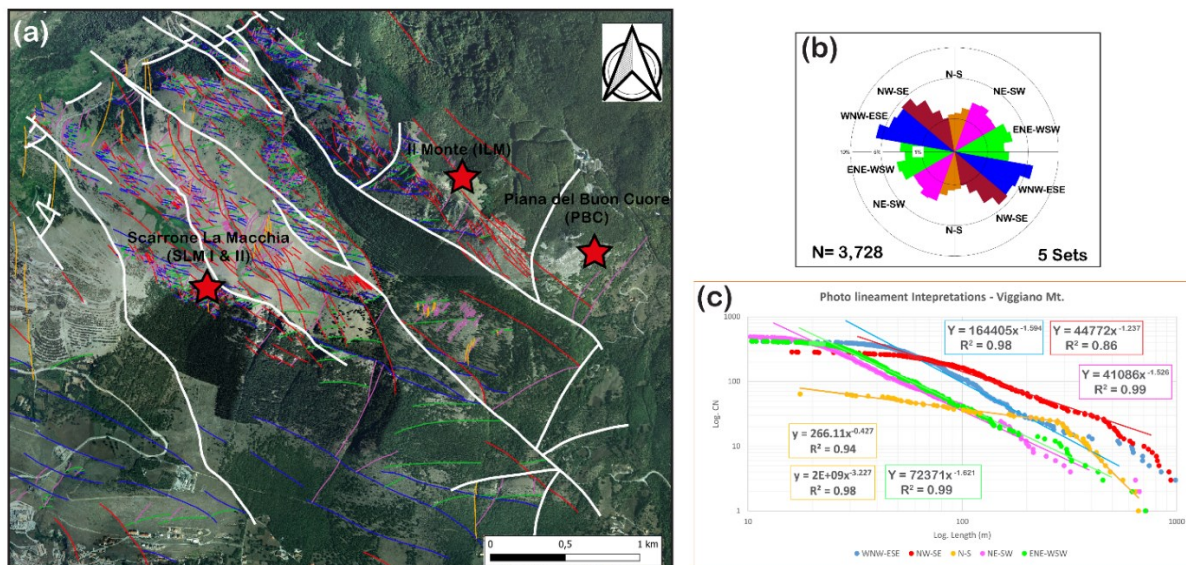


Figure 3.5 Morphological traces coloured according to their respective sets (b) Rose diagram of equal area showing five main sets-oriented WNW-ESE, NW-SE, N-S, NE-SW and N-S. (c) Statistical analyses in terms of length used to compute multiscale length property distribution for the individual

sets of traces. A graph of Log cumulative Number (CN) vs. Log Length (in meters), shown in the Y axis and X axis, respectively. Graphs contain Power-law best-fit equations.

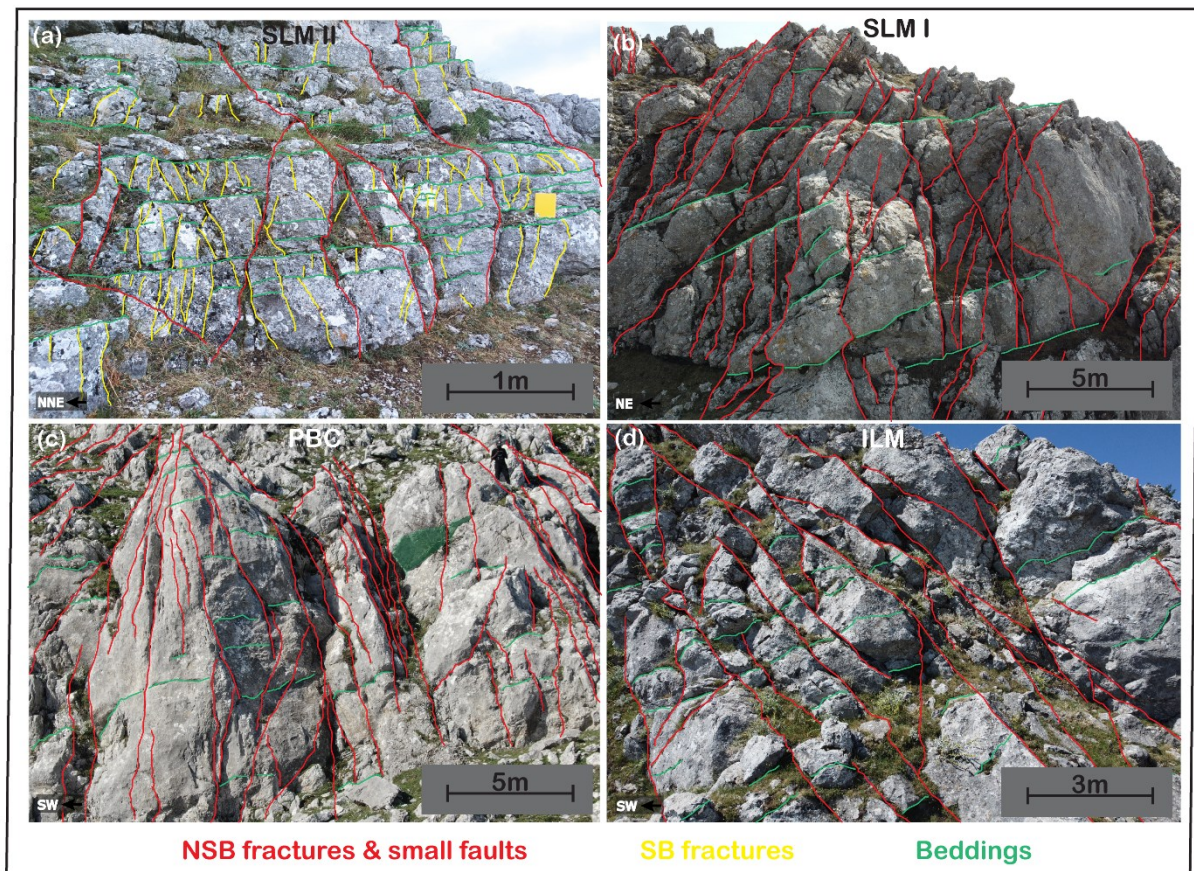


Figure 3. 6(a) SLM II, well-layered carbonates characterised by beds and bed packages that localise strata bound fractures, SBs, some few NSBs and small faults. NSBs and small faults are shown in red, SBs in yellow and bedding is shown in green (small faults: throw few centimetres to < 1 meter). . (b) SLM I, oolitic carbonates with amalgamation of the beds, characterised by through going NSBs and small faults. (c) PBC, massive, amalgamated bed carbonates similar to ILM with throughgoing NSB fractures and small faults that cut across single beds and bed package interfaces (d) ILM, massive, amalgamated bed carbonates crosscut by non-strata bound fractures, NSBs, and small faults that crosscut the entire carbonate beds.

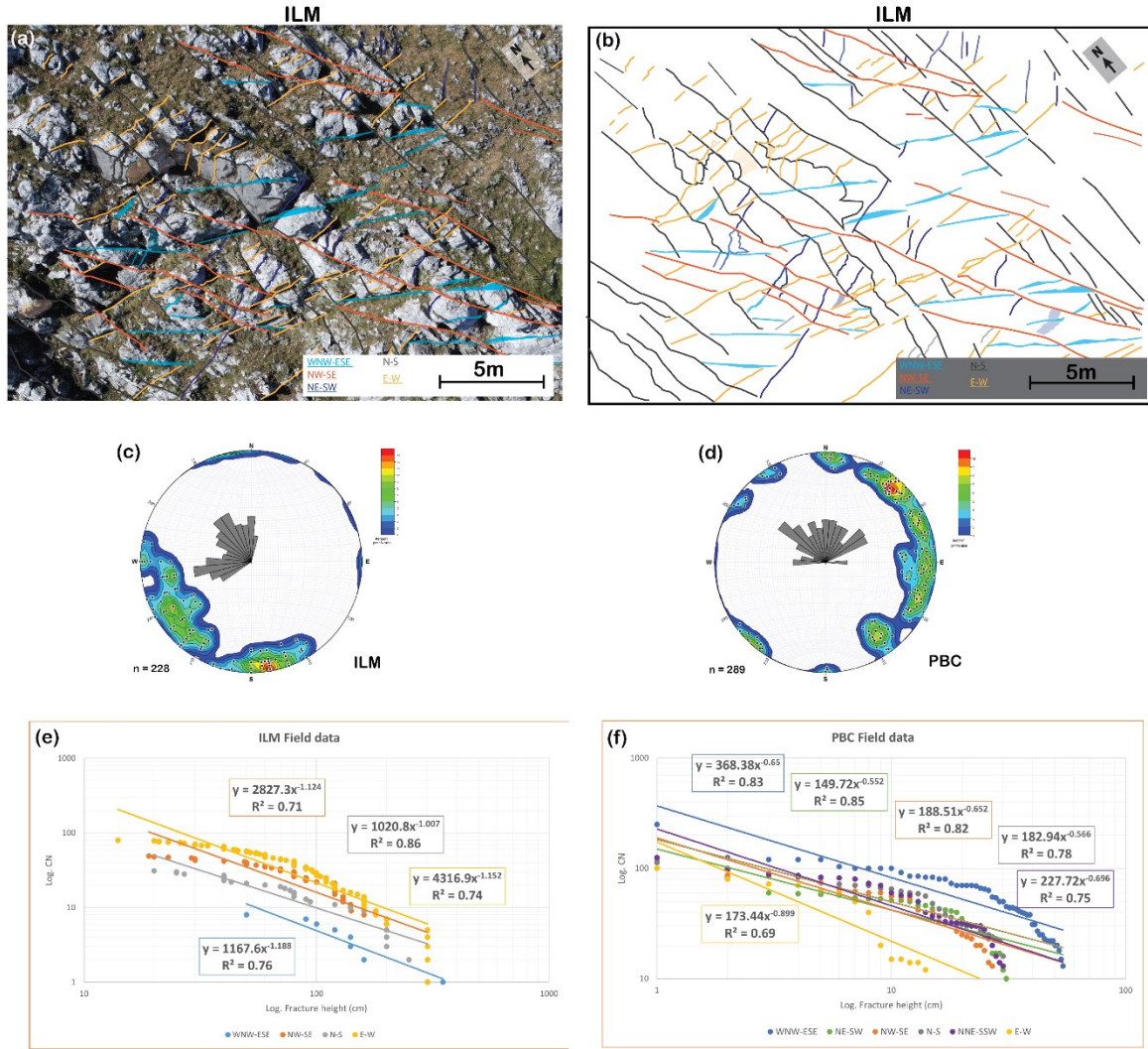


Figure 3. 7 (a) Top Viggiano in aerial view showing crosscutting and abutting relations amongst several fractures and small fault sets. NW-SE set, in dark orange, which is probably the most recent set, the WNW-ESE set of fractures cuts all other sets. (b) fractures traces from 7a are shown (without photo). (c) Stereoplot with contour and Rose diagram is shown, (lower hemisphere, equal area) of 228 fractures collected at the ILM study site during field investigation. Clusters of poles defined by fisher statistics form four major sets of fractures, oriented WNW-ESE, NW-SE, N-S and E-W. (d) Stereo plot with contour and Rose diagram, (lower hemisphere, equal area) of 228 fractures collected at the PBC study site during field investigation Clusters of poles defined by fisher statistics form six major sets of fractures, oriented WNW-ESE, NW-SE, N-S, NNE-SSW, NE-SW and E-W. (e) Multiscale fracture height distribution plot for the ILM field data. (f) Multiscale fracture height distribution plot for the PBC field data. Graphs contain Power-law best-fit equations. Exponents of the Power-law Eqn. are the D-fractal values used as input for DFN modelling of 5m bed package scale geocellular volumes.

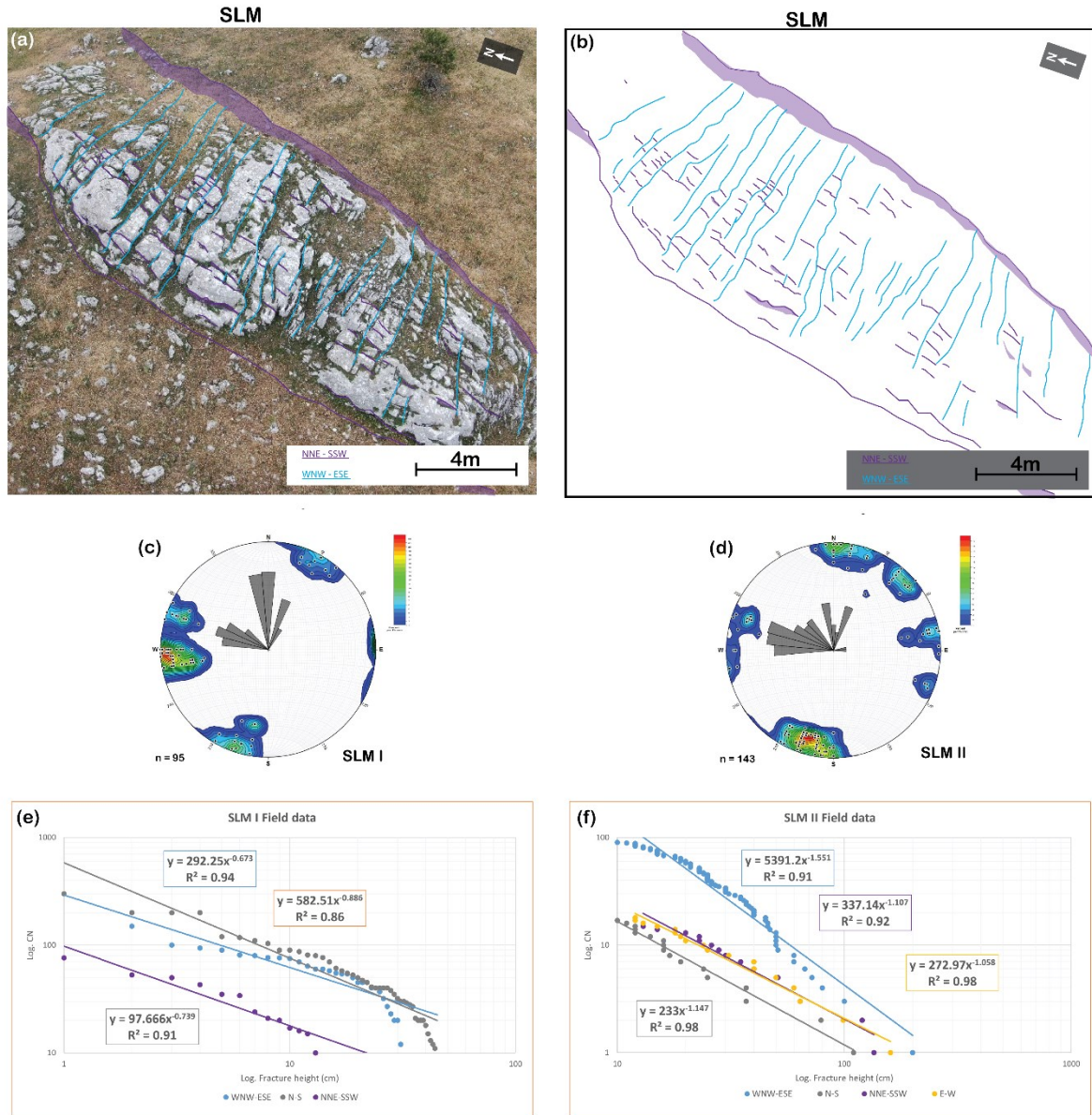


Figure 3. 8 (a) Scarrone la Macchia in aerial view showing crosscutting and abutting relations amongst some fractures and faults. The NNE-SSW sets confined between a relatively larger WNW-ESE sets of fractures. Large NNE-SSW oriented faults bound them all (b) fractures traces from 8a are shown (without photo). (c) Stereo plot with contour and Rose diagram is shown, (lower hemisphere, equal area) of 95 fractures collected at the SLM I site. Fisher clusters form three major sets of fractures, oriented WNW-ESE, N-S and NNE-SSW. (d) Stereo plot with contour and Rose diagram is shown, (lower hemisphere, equal area) of 143 fractures collected at the SLM II site. Clusters of poles defined by fisher statistics form four major sets of fractures, oriented WNW-ESE, N-S, N-S, NNE-SSW, and E-W. (e) Multiscale fracture height distribution plot for the SLM I field data. (f) Multiscale fracture height distribution plot for the SLM II field data.

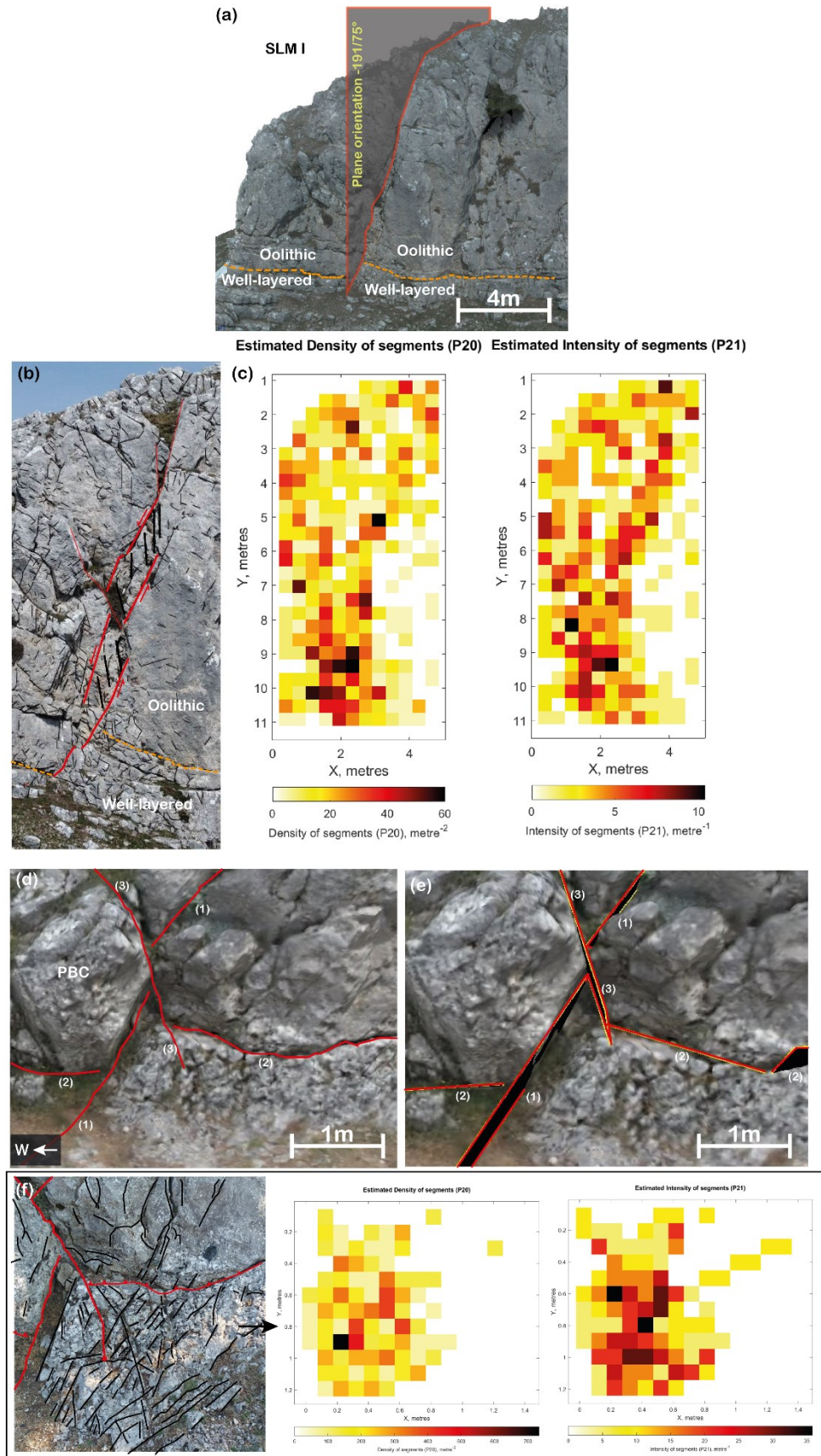


Figure 3.9 Strain localization within fault zones. (a) At the boundary between SLM I and SLM II, digitised small fault plane that disrupts mechanical interfaces, i.e., the contact between the oolitic limestone and the well layered succession, oriented N191 striking, 75°- west-dipping fault, obtained.

(b) Close examination of this fault zone in the field shows the small fault comprised of main slip segments (red), and a cluster of fractures (black) that mainly localize within the releasing jogs and at the extensional quadrants of the single slip surfaces. (c) 2D fracture density, P_{20} and fracture intensity, P_{21} results within the fault zone showing areas; PBC: (d) high-angle fault oriented N190 – N200 striking, 75°- west-dipping fault (1) that disrupts mechanical interface of a N240 striking, 35° NW-dipping back thrust (2) with a displacement of ~1m. Both the previous high-angle fault and back thrust are offset by a N150 striking, 82° NE-dipping high-angle normal fault (3). (e) A relation between the 3 faults (in red) is shown, as analysed in Openplot (Tavani et al., 2011). (f) P_{20} and P_{21} results showing the localised deformation (cluster of fractures) related to the earlier faults.

3.4.2 Field Structural Data

Field structural data are mainly related to background fractures and small faults, which are exposed away from major fault zones. Stratabound (SB) fractures mainly consist of joints confined within single carbonate beds (Figure 3.6a). The spacing distribution of SB fractures does not vary proportional to the bed thickness, and the less-spaced sets are documented within grain-supported carbonates (Manniello et al., 2022). Non stratabound (NSB) fractures cut across single beds, and arrest against the mm-cm thick bed package interfaces (Figure 3.6b). These fractures are made up of sheared, pre-existing SB fractures which coalesced together across bed interfaces (Manniello et al., 2022; Abdallah et al., 2023). Small faults are those with cm-offset. They are very common in massive and oolitic carbonates (Figures 3.6b, c & d), forming clusters of localized deformation.

In terms of single fault and fracture sets, hereafter the results obtained for single sites are reported. At the Il Monte site, ILM, five sets of high-angle fractures and small faults are documented. There, the WNW-ESE and NW-SE sets cut and displace the other sets, among which the N-S set forms well-defined corridors (Figures 3.7a, b & c). At the Piana del Buon Cuore site, PBC, six sets of high-angle fractures and small faults are present (Fig. 7d). The multiscale fracture height properties computed for the single sets are reported in Figures 3.7e & f. At the Scarrone La Macchia site exposing oolitic carbonates, SLM I, the WNW-ESE high-angle fractures crosscut the NNE – SSW set (Figures 3.8a & b). There, the N-S set is the most common (Figure 3.8c). Underneath the oolitic carbonates, the well-layered carbonates, SLM II, are crosscut by four main sets of high-angle fractures and small faults (Figure 3.8d). The multiscale fracture height properties computed for the single sets are reported in Figure 3.8e & f.

At a larger scale, the architecture of medium-sized faults is shown in Figure 3.9. At the Scarrone la Macchia site, a ca. N-S striking high-angle fault displaces the oolitic – well-layered contact including a ca. 10 cm-thick mixed carbonate-terrigenous material (Manniello et al., 2022). The N190 striking, 75°- west-dipping fault shows a ca. 1 m-throw (Figure 3.9a),

and it is comprised of multiple slip segments (Figure 3.9b) surrounded by fracture clusters that localize at their extensional quadrants (cf. the computed values of fracture density, P_{20} and fracture intensity, P_{21} in Figure 3.9c). Similarly, at the Il Monte site, a ca. NNE-SSW striking high-angle fault cuts and displaces of ca. 1 meter a N240 striking, 35° NW-dipping thrust fault (Figure 3.9d). In turn, the N220E, 75° - west-dipping fault is offset by a N150E, 82° NE-dipping normal fault (Figures 3.9d, 9e). As a result, the whole outcrop is characterized by fracture clusters associated with these crosscutting relations, as shown by variations of the computed P_{20} and P_{21} values (Figure 3.9f).

The result of field measurement of fracture mechanical aperture, E , conducted along single SB and NSB fractures exposed along the surveyed outcrops is reported in Figure 3.10. The E values are plotted with respect to the fracture height (Figures 3.10a & 3.10b) in order to evaluate the possible correlation factor for these two parameters. Unfortunately, the E values of the surveyed SB and NSB fractures do not show any correlation with the fracture height, and a minimum value of 0.1 mm characterizes a wide range of fracture heights.

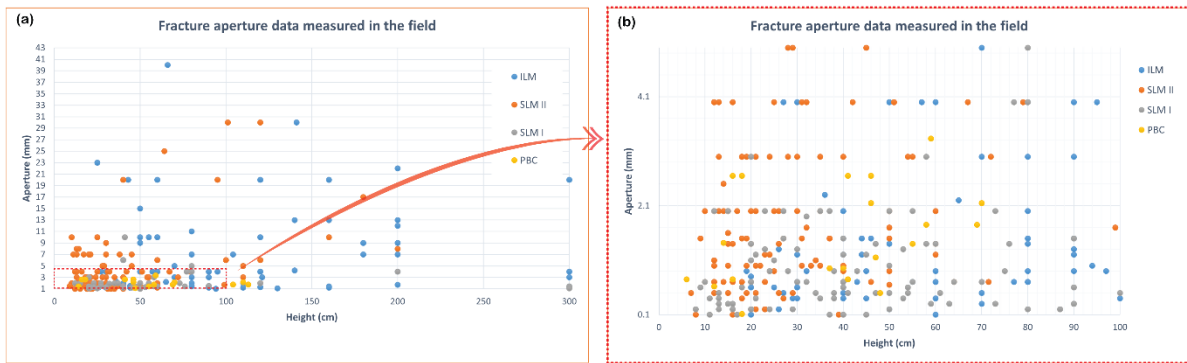


Figure 3.10 (a) Fracture aperture (in mm) Vs. fracture height (in cm). (b) Zoomed portion of the graph from Fig. 3.10a is zoomed in to show more details.

3.4.3 Digital Structural Data

From the Cretaceous – U. Jurassic Top Viggiano digital outcrop model (1800 m x 600 m x 700 m; Figure 3.11a), we extract 108 fault planes, whose attitude are reported in Figure 3.11d. The main fault sets strike WNW-ESE, NNE-SSW, ENE-WSW and E-W. For each set, the fractal D-values computed for the fault length, and the 3D intensity, P_{32} , of the fault planes respectively are 1.05 and 0.15m^{-1} (WNW-ESE), 1.00 and 0.02m^{-1} (NNE-SSW), 0.79 and 0.02m^{-1} (ENE-WSW) and 0.99 and 0.02m^{-1} (E-W) (Figure 3.11e, Table 2 for P_{32} values).

Considering the L. Jurassic Scarrone la Macchia digital outcrop model (1800 m x 600 m x 700 m; Figure 3.12a), we extract 292 fault planes (Figure 3.12d). The main sets strike WNW-ESE, NNW-SSE, N-S and NE-SW sets. For each set, the fractal D-values computed for the fault length, and the 3D intensity, P_{32} of the fault planes respectively are 0.8 and 0.16m^{-1} (WNW-

ESE), 1.0 and 20.15 m^{-1} (NNW-SSE), 1.22 and 0.009 m^{-1} (N-S), and 1.34 and 0.06 m^{-1} (NE-SW) (Figure 3.12e).

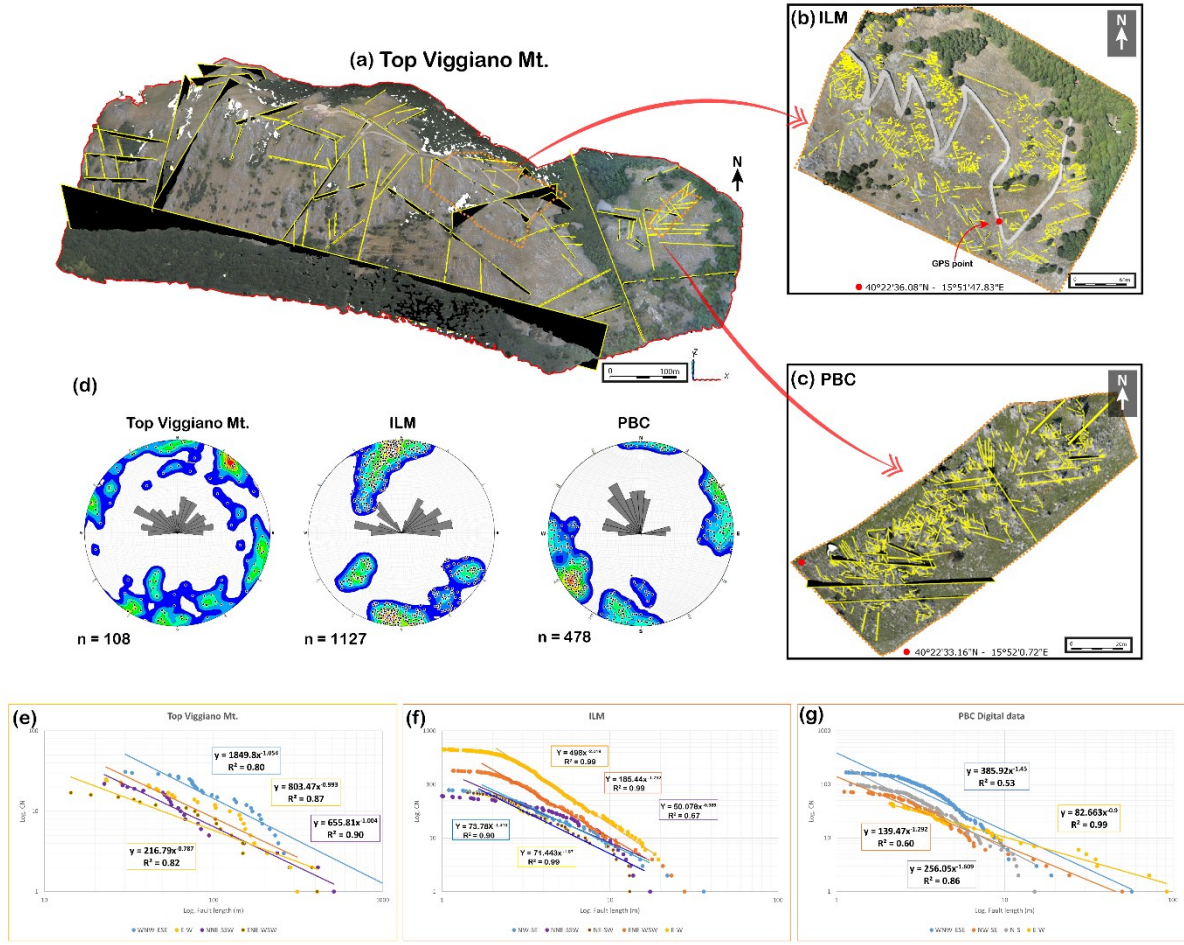


Figure 3.11 (a) 3D photogrammetric model of the ILM and the PBC. Locations are indicated with orange dotted lines. 108 main fault planes were digitized. Geometrical and dimensional results were extracted for further analysis. (b) Aerial view of the ILM model with 1127 digitized fault planes, results are extracted for further analysis. (c) Aerial view of the PBC model with 478 digitized fault planes, results were extracted for further analysis. (d) Stereo plots with contour (lower hemisphere, equal area) and Rose diagrams are shown for Top Viggiano Mt., ILM and PBC models. For the Top Viggiano Mt., Clusters of poles form four major sets of faults. (e) Multiscale fracture length distribution plot for the Top Viggiano Mt. (f) Multiscale fracture length distribution plot for the ILM. Graph of Log. (g) Multiscale fracture length distribution plot for the PBC. (Fig. 3.11b & c. modified after Abdallah et al., 2023)

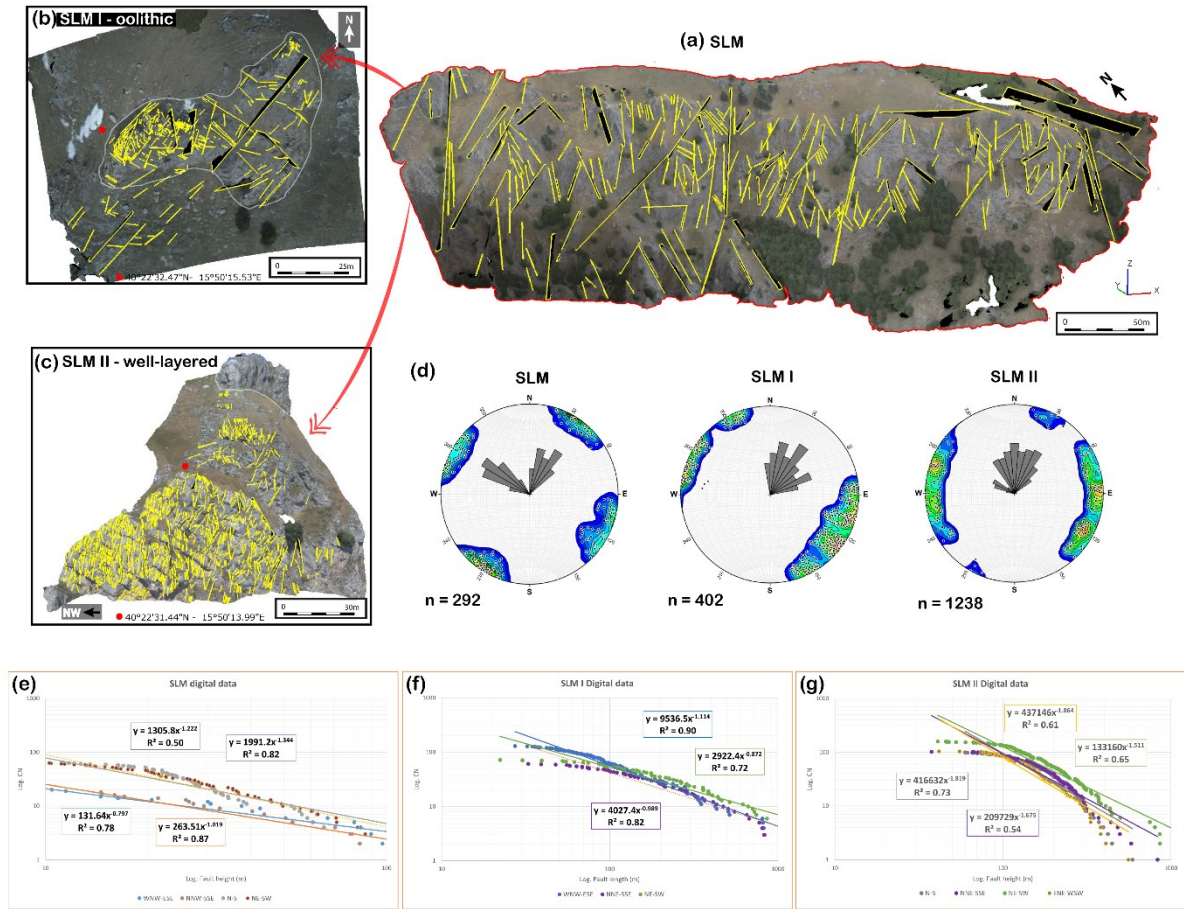


Figure 3.12 (a) 3D photogrammetric model of the large SLM cliff, which comprises the SLM I and the SLM II carbonate outcrops. Locations are indicated with orange arrows. 292 main fault planes were digitized. Geometrical and dimensional results were extracted for further analysis. (b) Aerial view of the SLM I model with 402 digitized fault planes. (c) NW-SE view of the SLM II model with 1238 digitized fault planes. (d) Stereo plots and Rose diagrams are shown for large SLM cliff, SLM I and SLM II outcrop models. For the large SLM, Clusters of poles form four major sets of faults, the SLM I showed three major sets of faults, while the SLM II showed four major sets of faults. (e) Multiscale fracture height distribution plot for the large SLM is shown. (f) Multiscale fracture length distribution plot for the SLM I. (g) Multiscale fracture height distribution plot for the SLM II. (Figure 3.12b & c. modified after Abdallah et al., 2023)

3.4.4 Input data for DFN Modelling

By considering the results of field measurements and digital structural analysis, we derive the input data for DFN modelling (Tables 3.1 and Table 3.2). As reported in section 3, we use a constant 0.1 mm mechanical aperture value for fracture porosity computation, and theoretical hydraulic aperture values for the computation of equivalent permeability. For the latter operation, both the most favourable fluid flow conditions (hydraulic aperture proportional to

fracture length) and least favourable conditions (hydraulic aperture proportional to the square root of fracture length) are considered.

Also, our model is inferred fracture-controlled fluid-flow since very low values of matrix porosity (average porosity of 3 % at both atmospheric condition and high-confining pressure of 600 Psi) within the same study area (Manniello et al., unpublished results).

Results of DFN modelling are hereafter presented according to single sites (Figure 3.13 – 3.15, Table 3.3).

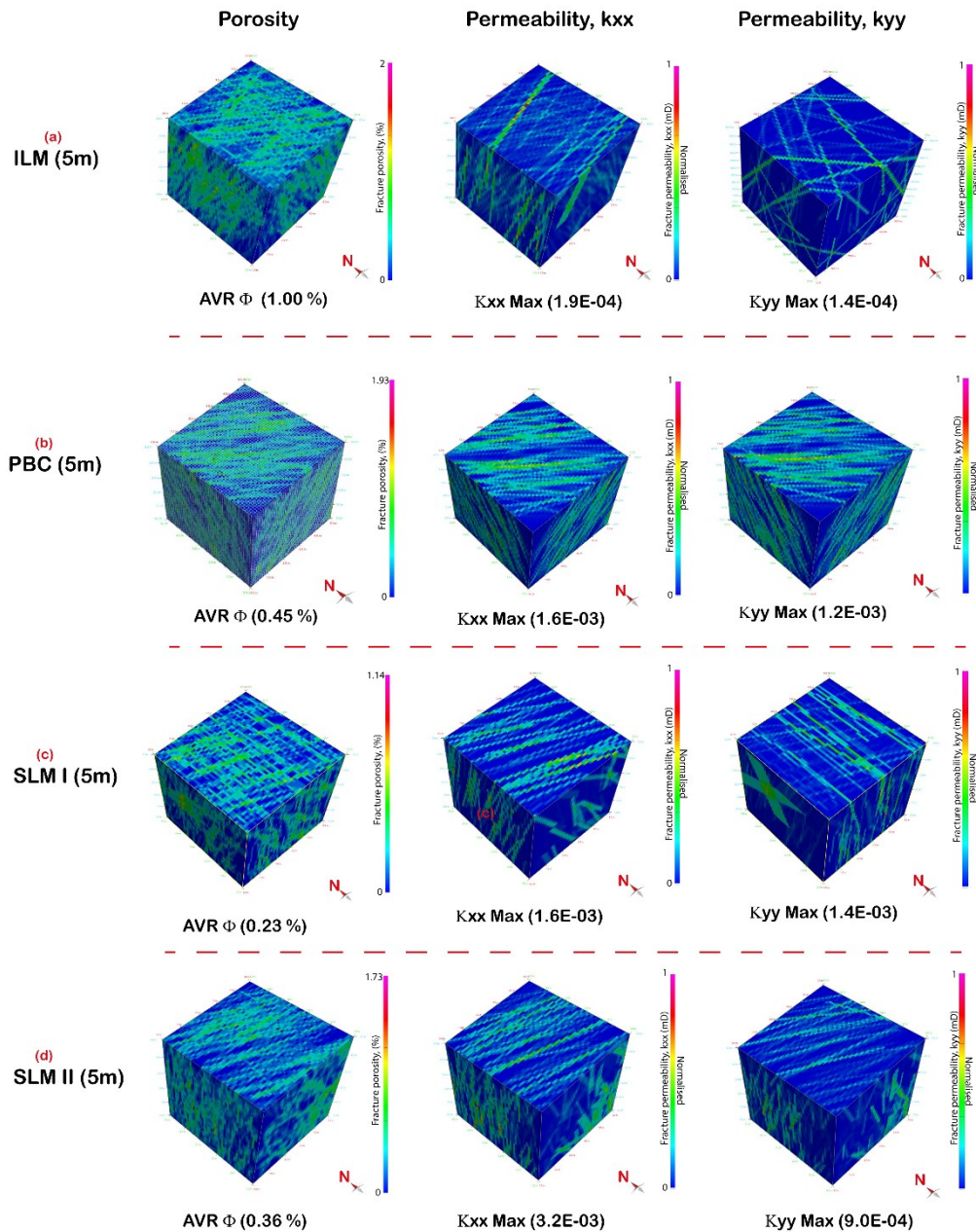


Figure 3.13 DFN results for the 5m bed-package scale configurations according to the sites investigated. Average porosity and maximum equivalent permeability (Kxx, Kyy) values are shown. (a) ILM (b) PBC (c) SLM I (d) SLM II

Table 1**Table reporting DFN inputs for 5m bed-package scale models (field data)**

Study Area		ILM										PBC										SLM I										SLM II			
Input Parameters		SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET	SET		
Best-fit (strike, dip) RHR		N300/72	N329/72	N358/79	N260/88	N130/71	N157/82	N182/83	N200/80	N235/72	N 92/86	N289/80	N356/86	N207/73	N290/84	N356/86	N207/73	N290/84	N356/86	N207/73	N290/84	N356/86	N207/73	N290/84	N356/86	N207/73	N290/84	N356/86	N207/73	N290/84	N356/86	N207/73	N290/84		
Fisher Distribution		151	36.2	31	61.5	52.1	25.3	86.4	48.7	73.4	129.2	72.6	147.8	48.8	50.5	36.4	32.8	115.4	48	52	48	52	48	52	48	52	48	52	48	52	48	52	48		
Min Length (cm)		100	38	40	28	26	26	32	26	20	24	24	22	20	800	440	540	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640		
Max Length (cm)		700	600	1000	1000	500	244	226	250	240	200	600	600	152	800	440	540	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640		
Fractal D-value		-1.12	-1.12	-0.91	-1.13	-1.23	-1.28	-1.47	-1.28	-1.32	-0.86	-1.24	-1.04	-1.23	-1.55	-1.15	-1.11	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06	-1.06		
Aspect Ratio		1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4		
Mechanical Aperture, E (mm)		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1		
Hydraulic Aperture, e (mm)		1.00E-05	1.00E-05	1.00E-05	1.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05		
Average JRC		12.5	12.5	12.5	12.5	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	
P30 (l/m ³)		9.94	1.52	2.24	2.46	35.6	1	0.8	0.84	1.56	0.7	8.35	6.16	0.9	33.8	0.64	0.18	1.72																	

Table 2**Table reporting DFN inputs for 50m and 500m scale models (digital data)**

Study Area		ILM												PBC												ILM & PBC																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
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Table 3.1 Table reporting DFN inputs for the 5m bed-package scale geocellular volumes

Table 3.2 Table reporting DFN inputs for the 50m outcrop scale and 500m reservoir scale geocellular volumes.

3.4.5 Results of DFN Modelling

Cretaceous – U. Jurassic Top Viggiano Mt. (ILM and PBC sites)

The ILM 5 m-side (bed-package scale) DFN model includes 1,936 fractures, with an average DFN P_{32} of 55.3 m^{-1} , a maximum porosity of 2.00 %, and an average porosity of 1.00 % (Figure 3.13a; Table 3.3; Appendix 3.1 & Appendix 3. 2). Considering a fracture aperture proportional to fracture length, the average permeability is $2.12 \times 10^{-4} \text{ mD}$, and the maximum K_{xx} and K_{yy} permeability values respectively are 1.85×10^{-4} and $1.38 \times 10^{-4} \text{ mD}$ (Figure 3.13a; Appendices 3.3a & 3.3b). Applying a fracture aperture proportional to root of fracture length, the computed average permeability is $6.13 \times 10^{-5} \text{ mD}$, and the cumulative maximum K_{xx} and K_{yy} permeability values are 4.78×10^{-5} and $3.63 \times 10^{-5} \text{ mD}$, respectively (Appendix 3.4a & 3.4b).

The ILM 50 m-side outcrop scale DFN model includes 148 faults, with an average DFN P_{32} of 0.03 m^{-1} , a maximum porosity of 0.05 %, a cumulative maximum porosity of 2.05 %, an average porosity of 0.0003 %, and a cumulative average porosity of 1.00 % (Figure 3.14a, Table 3.3, Appendix 3.1 & Appendix 3.2). Considering a fracture aperture proportional to fracture length, cumulative average permeability is $3.43 \times 10^{-4} \text{ mD}$ and the cumulative maximum K_{xx} and K_{yy} permeability values respectively are 1.88×10^{-3} and $1.39 \times 10^{-3} \text{ mD}$ (Appendices 3.3a & 3.3b). Inputting a fracture aperture proportional to root of fracture length, the cumulative average permeability is $2.79 \times 10^{-6} \text{ mD}$, and the cumulative maximum K_{xx} and K_{yy} permeability values are 4.8×10^{-4} and $3.65 \times 10^{-4} \text{ mD}$, respectively (Appendices 3.4a & 3.3b). The word “Cumulative” in this context means the 50m-outcrop scale model incorporates results from the bed package scale 5m-scale models.

The PBC 5 m-side, bed-package scale DFN model includes 5069 fractures, with an average DFN P_{32} of 44.9 m^{-1} , a maximum porosity of 1.93 %, and an average porosity of 0.45 % (Figure 3.13b, Table 3.3, Appendix 3.1 & Appendix 3. 2). Taking into account a fracture aperture proportional to fracture length, the average permeability is $2.3 \times 10^{-3} \text{ mD}$, and the maximum K_{xx} and K_{yy} permeability values respectively are 1.64×10^{-3} and $1.18 \times 10^{-3} \text{ mD}$ (Table 3.3; Appendix 3.3a & 3.3b). Considering a fracture aperture proportional to root of fracture length, the average permeability is $5.76 \times 10^{-4} \text{ mD}$, and the maximum K_{xx} and K_{yy} permeability values are 3.99×10^{-4} and $2.86 \times 10^{-4} \text{ mD}$, respectively (Appendices 3.4a & 3.4b).

The PBC 50 m-side outcrop scale DFN model includes 585 faults, with an average DFN P_{32} of 44.9 m^{-1} , a maximum porosity of 0.057 %, a cumulative maximum porosity of 1.99 %, an average porosity of 0.004 %, and a cumulative average porosity of 0.45 % (Figure 3.14b; Table 3.3, Appendix 3.1 & Appendix 3.2). Applying a fracture aperture proportional to fracture length, the computed average permeability is $3.07 \times 10^{-4} \text{ mD}$, the cumulative average

permeability is 2.34×10^{-2} mD, and the cumulative maximum K_{xx} and K_{yy} permeability values respectively are 1.66×10^{-2} and 1.2×10^{-2} mD (Appendices 3.3a & 3.3b). Inputting a fracture aperture proportional to root of fracture length, the computed average permeability is 3.72×10^{-5} mD, cumulative average permeability is 5.8×10^{-3} mD, and cumulative maximum K_{xx} and K_{yy} permeability values are 4.03×10^{-3} and 2.89×10^{-3} mD, respectively (Appendices 3.4a & 3.4b).

The large Top Viggiano Mt. 500m scale DFN model includes 793 faults, with an average DFN P_{32} of 0.11 m^{-1} , maximum porosity is 0.009 %, a cumulative maximum porosity is 2.03 %, an average porosity is 0.001 %, and a cumulative average porosity of 0.73 % (Fig. 3.15a; Table 3.3, Appendix 3.1 & Appendix 3.2). Considering a fracture aperture proportional to fracture length, the average permeability is 2.32×10^{-6} mD, a cumulative average permeability is 1.2×10^{-1} mD, and the cumulative maximum K_{xx} and K_{yy} permeability values respectively are 9.24×10^{-2} and 6.72×10^{-2} mD (Appendices 3.3a & 3.3b). With a fracture aperture proportional to root of fracture length, the computed average permeability is 3.22×10^{-2} mD, and the maximum K_{xx} and K_{yy} permeability values are 2.25×10^{-2} and 1.63×10^{-2} mD, respectively (Appendices 3.4a & 3.4b). The word “Cumulative” in this context means the 500m-reservoir scale model incorporates results from both the 50m-outcrop scale model and the 5m-bed package scale model.

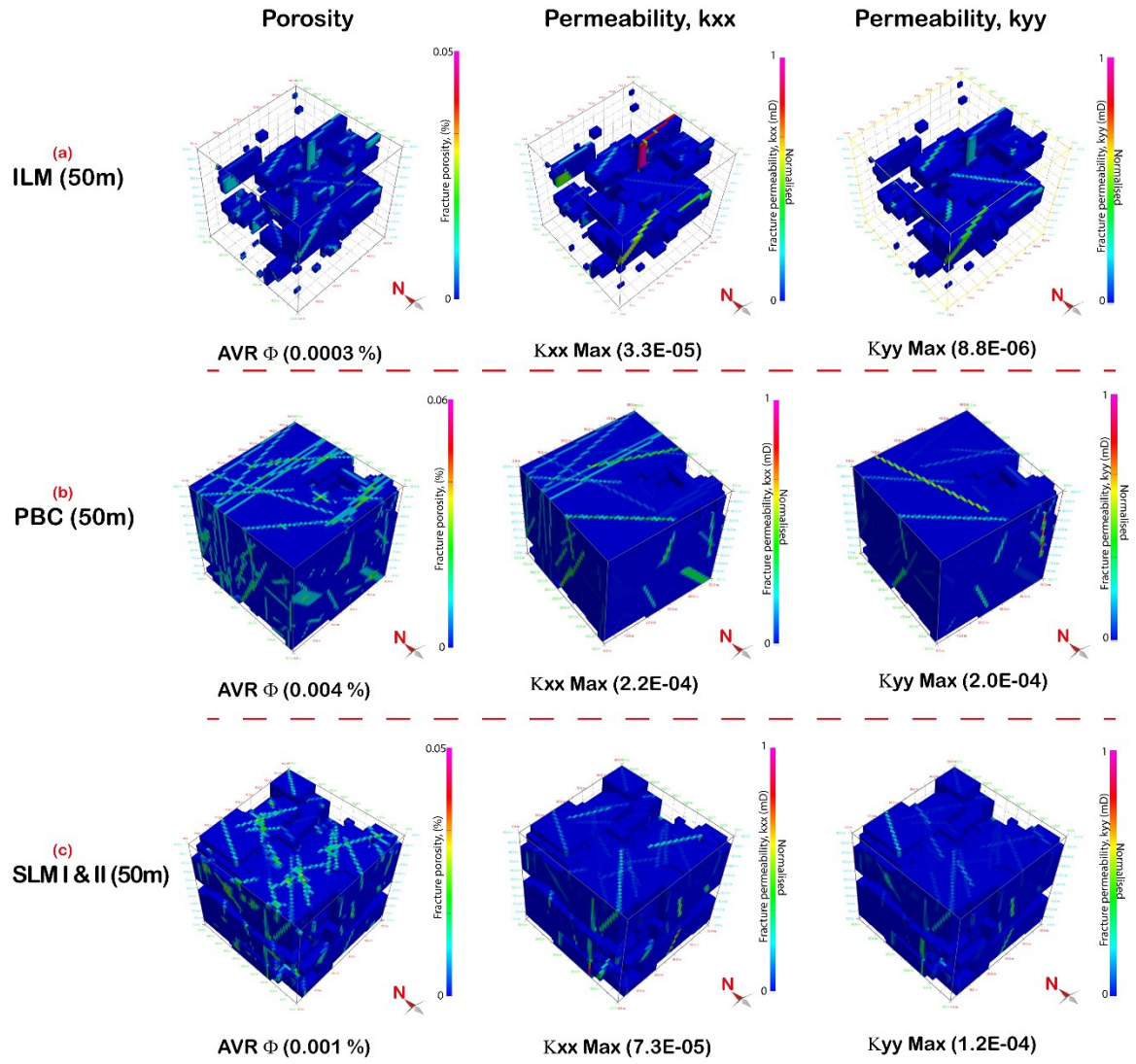


Figure 3.14 DFN results for the 50m outcrop scale configurations according to the sites investigated. Average porosity and maximum equivalent permeability (Kxx, Kyy) values are shown. (a) ILM (b) PBC (c) SLM I & II

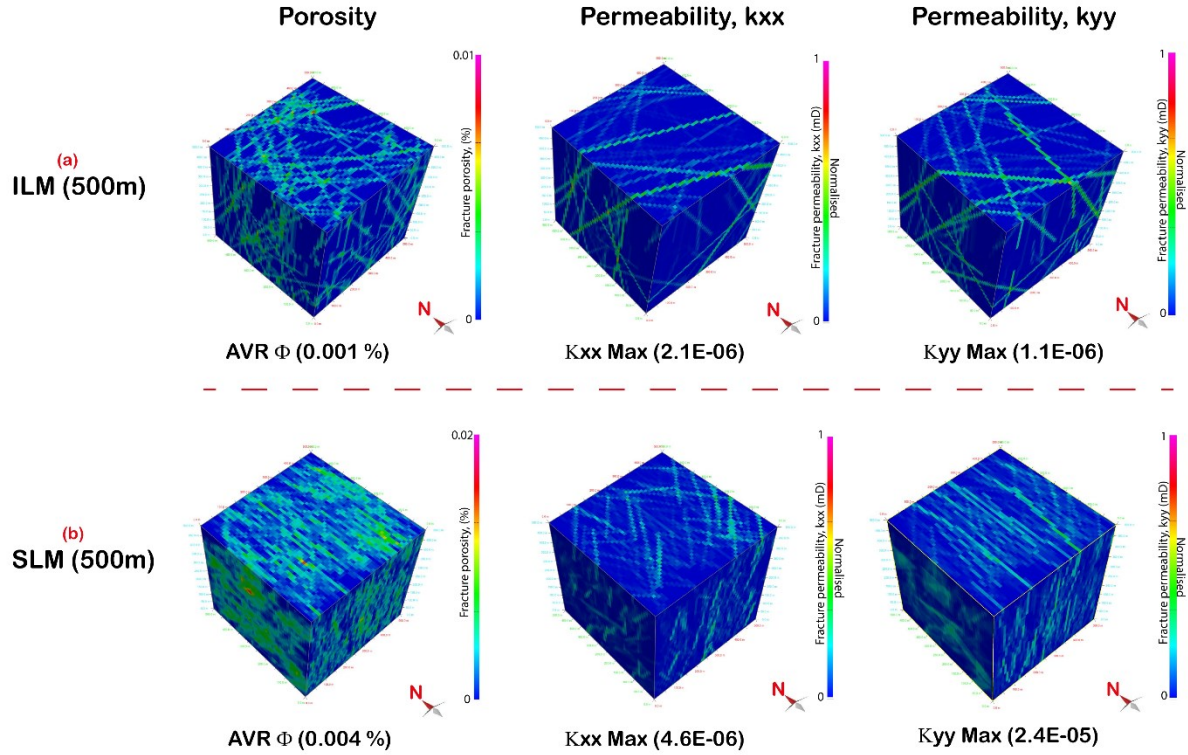


Figure 3.15 DFN results for the 500m reservoir scale configurations according to the sites investigated. Average porosity and maximum equivalent permeability (K_{xx} , K_{yy}) values are shown. (a) ILM (b) SLM

L. Jurassic Scarrone la Macchia (SLM I and SLM II sites)

The SLM I 5 m-side bed-package scale DFN model includes 108 fractures, with an average DFN P_{32} of 23.4 m^{-1} , a maximum porosity of 1.14 %, and an average porosity of 0.23 % (Figure 3.13c; Table 3.3; Appendix 3.1 & Appendix 3.2). With a fracture aperture proportional to fracture length, the computed average permeability is $2.21 \times 10^{-3} \text{ mD}$, and the maximum K_{xx} and K_{yy} permeability values respectively are 1.61×10^{-3} and $1.39 \times 10^{-3} \text{ mD}$ (Appendices 3.3a & 3.3b). Considering a fracture aperture proportional to root of fracture length, the average permeability is $4.90 \times 10^{-4} \text{ mD}$, and the maximum K_{xx} and K_{yy} permeability values are 3.40×10^{-4} and $3.22 \times 10^{-4} \text{ mD}$, respectively (Appendices 3.4a & 3.4b).

The SLM II 5 m-side bed-package scale DFN model includes 4612 fractures, with an average DFN P_{32} of 36.3 m^{-1} , a maximum porosity of 1.73 %, and an average porosity of 0.36 % (Figure 3.13d; Appendix. 3.1 & Appendix 3.2). Applying a fracture aperture proportional to fracture length, the average permeability is $3.80 \times 10^{-3} \text{ mD}$, and the maximum K_{xx} and K_{yy} permeability values respectively are 3.16×10^{-3} and $8.96 \times 10^{-4} \text{ mD}$ (Appendices 3.3a & 3.3b). Considering a fracture aperture proportional to root of fracture length, the average permeability is $7.58 \times$

10^{-4} mD, and the maximum K_{xx} and K_{yy} permeability values are 6.34×10^{-4} and 1.42×10^{-4} mD, respectively (Appendices 3.4a & 3.4b).

The SLM 50 m-side outcrop scale DFN model includes 807 faults, with an average DFN P_{32} of 0.14 m^{-1} , a maximum porosity of 0.05 %, a cumulative maximum porosity of 1.49 %, an average porosity of 0.001 % and cumulative average porosity of 0.3 % (Figure 3.14c; Table 3.3; Appendix 3.1 & Appendix 3.2). Considering a fracture aperture proportional to fracture length, the average permeability is 1.36×10^{-4} mD, cumulative average permeability is 3.02×10^{-2} mD, and the cumulative maximum K_{xx} and K_{yy} permeability values respectively are 2.39×10^{-2} and 1.15×10^{-2} mD (Appendices 3.3a & 3.3b). With a fracture aperture proportional to root of fracture length, the computed average permeability is 2.2×10^{-5} mD, cumulative average permeability is 6.26×10^{-3} mD, and the cumulative maximum K_{xx} and K_{yy} permeability values are 4.89×10^{-3} and 2.34×10^{-3} mD, respectively (Appendices 3.4a & 3.4b).

The large SLM 500 m-side DFN model includes 12104 faults, with an average DFN P_{32} of 0.39 m^{-1} , a maximum porosity of 0.02 %, a cumulative maximum porosity of 1.51 %, an average porosity of 0.003 % and a cumulative average porosity of 0.3 % (Figure 3.15b; Table 3.3; Appendix 3.1 & Appendix 3.2). Taking into account fracture aperture proportional to fracture length, the average permeability is 2.59×10^{-5} mD, cumulative average permeability is 3.02×10^{-1} mD, and the cumulative maximum K_{xx} and K_{yy} permeability values respectively are 2.39×10^{-1} mD and 1.15×10^{-1} mD (Appendices 3.3a & 3.3b). Considering a fracture aperture proportional to root of fracture length, the average permeability is 5.31×10^{-6} mD, cumulative average permeability is 6.26×10^{-2} mD, and the cumulative maximum K_{xx} and K_{yy} permeability values are 4.89×10^{-2} and 2.34×10^{-4} mD, respectively (Appendices 3.4a & 3.4b).

Table 3

Table reporting DFN results for multi-scale models

	Study Area	ILM		PBC		Large ILM		SLM I	SLM II	SLM I & II	Large SLM
	Volumes	5m	50m	5m	50m	500m	500m	5m	5m	50m	500m
	No of fractures/faults	1936	148	5069	585	793	793	108	4612	807	12104
	Average DFN P32 (m ⁻¹)	55.3	0.03	44.9	44.9	0.11	0.11	23.4	36.3	0.14	0.39
	Average porosity (%)	1.000	0.0003	0.450	0.004	0.001	0.001	0.230	0.360	0.001	0.004
	Max porosity (%)	2.000	0.052	1.930	0.057	0.009	0.009	1.140	1.730	0.050	0.019
Aperture α L	Average Permeability, k (mD)	2.12E-04	3.43E-05	2.30E-03	3.07E-04	2.32E-06	2.21E-03	3.80E-03	1.36E-04	2.59E-05	2.59E-05
	Max Permeability , Kxx (mD)	1.85E-04	3.33E-05	1.64E-03	2.16E-04	2.09E-06	1.61E-03	3.16E-03	7.28E-05	4.58E-06	4.58E-06
	Max Permeability , Kyy (mD)	1.38E-04	8.84E-06	1.18E-03	2.04E-04	1.07E-06	1.39E-03	8.96E-04	1.22E-04	2.40E-05	2.40E-05
	2D horizontal permeability tensor	1.34	3.77	1.38	1.06	1.96	1.16	3.53	1.67	5.23	5.23
Aperture α VL	Average Permeability, k (mD)	6.31E-05	2.79E-06	5.76E-04	3.72E-05	4.80E-07	4.90E-04	7.58E-04	2.20E-05	5.21E-06	5.21E-06
	Max Permeability , Kxx (mD)	4.78E-05	2.67E-06	3.99E-04	3.31E-05	4.02E-07	3.40E-04	6.34E-04	1.22E-05	1.20E-06	1.20E-06
	Max Permeability , Kyy (mD)	3.63E-05	1.31E-06	2.86E-04	2.65E-05	2.58E-07	3.22E-04	1.42E-04	1.95E-05	4.86E-06	4.86E-06
	2D horizontal permeability tensor	1.31	2.04	1.40	1.25	1.56	1.06	4.46	1.60	4.05	4.05

Table 3. 3 Table reporting DFN results for multiscale analyses.

3.5 Discussion

The outcomes of the field and digital structural analyses are first discussed in terms of geometry and persistency of the fractures and fault sets at the multiple scales of analysis. Then, the results of DFN modelling are key to evaluate the storage and migration fluid properties of the fractured shallow-water carbonates and summarized in a conceptual model describing the modalities of fluid flow under vadose and phreatic conditions.

3.5.1 Geometry of the Fracture and Fault Networks

Taking into account the limit imposed on scaling of open fractures by diagenesis (Nelson et al., 1997; Forstner and Laubach, 2012; Hooker et al., 2012), fracture and fault networks commonly exhibit variable dimensional and geometrical characteristics at multiple scales of observation (Marchegiani et al., 2006; Hooker et al., 2009; Mercuri et al., 2023). The variability of their dimension is assessed by considering the fracture length (or height) distribution of individual sets and then computing the scaling laws across several scales (Gillespie et al., 1993; Cowie et al., 1993; Mandelbrot et al., 1993; Andrews et al., 2019; Bonnet et al., 2001; Bossennec et al., 2021; Forstner et al., 2022). In this work, the dimension of single sets of SB and NSB fractures, and of small and medium faults is tackled in order to derive the input data for DFN modelling (cf. section. 4.3). Hereafter, we focus on the variation of fracture and fault geometry with the scales of observation, which have already been documented in a variety of lithotypes such as fractured crystalline basement rocks (Ceccato et al., 2022), sandstones (Villarreal and Rojas 2020), and shallow-water carbonates (Martinelli et al., 2021; Mercuri et al., 2022).

In the studied area of the Viggiano Mt., Abdallah et al. (2023) recently conducted a multiscale structural study also documented a scale-dependent geometry of both fractures (height: 6 cm – 3 m; Figure 3.16; Table 3.1) and small faults (heights: 2.5 m – 50 m; Figure 3.16; Table 3.2). Expanding the existing dataset with the results obtained for the up to 500 m-high digital planes documented after 3D photogrammetry analysis, and also including the rose diagrams of the morpho-lineaments at ILM, we confirm that a scale-dependent geometry spanning over several orders of magnitude characterizes the shallow-water carbonates. We infer that this discrepancy in fracture and fault geometry documented at various scales was caused by compartmentalization of small and medium faults within single rock volumes bounded by the larger-scale WNW-ESE faults (Carminati et al., 2014; Medici et al., 2019), and also clusters of small-scale WNW-ESE to NW-SE striking faults which have been documented throughout the Mesozoic platform carbonates exposed along the axial zone of the southern Apennines of Italy (Corradetti et al., 2018; Giuffrida et al., 2020; La Bruna et al., 2020, Smeraglia et al., 2023).

Furthermore, these faults form the main fault set documented at the reservoir scale at the Il Monte site, ILM (Figure 3.16), strike sub-parallel to the main fault zones cropping out in the area, as also reported in the geological map of Palladino et al. (2023), and in the WNW-ESE shear morpho-lineaments which, together with the NW-SE lineaments, form the most abundant set exposed in the area. Differently, at the SLM site, as already reported by Abdallah et al. (2023), the strong bias of data due sub-vertical cliffs does not allow any precise assessment of the fault geometry, and hence any meaningful data discussion.

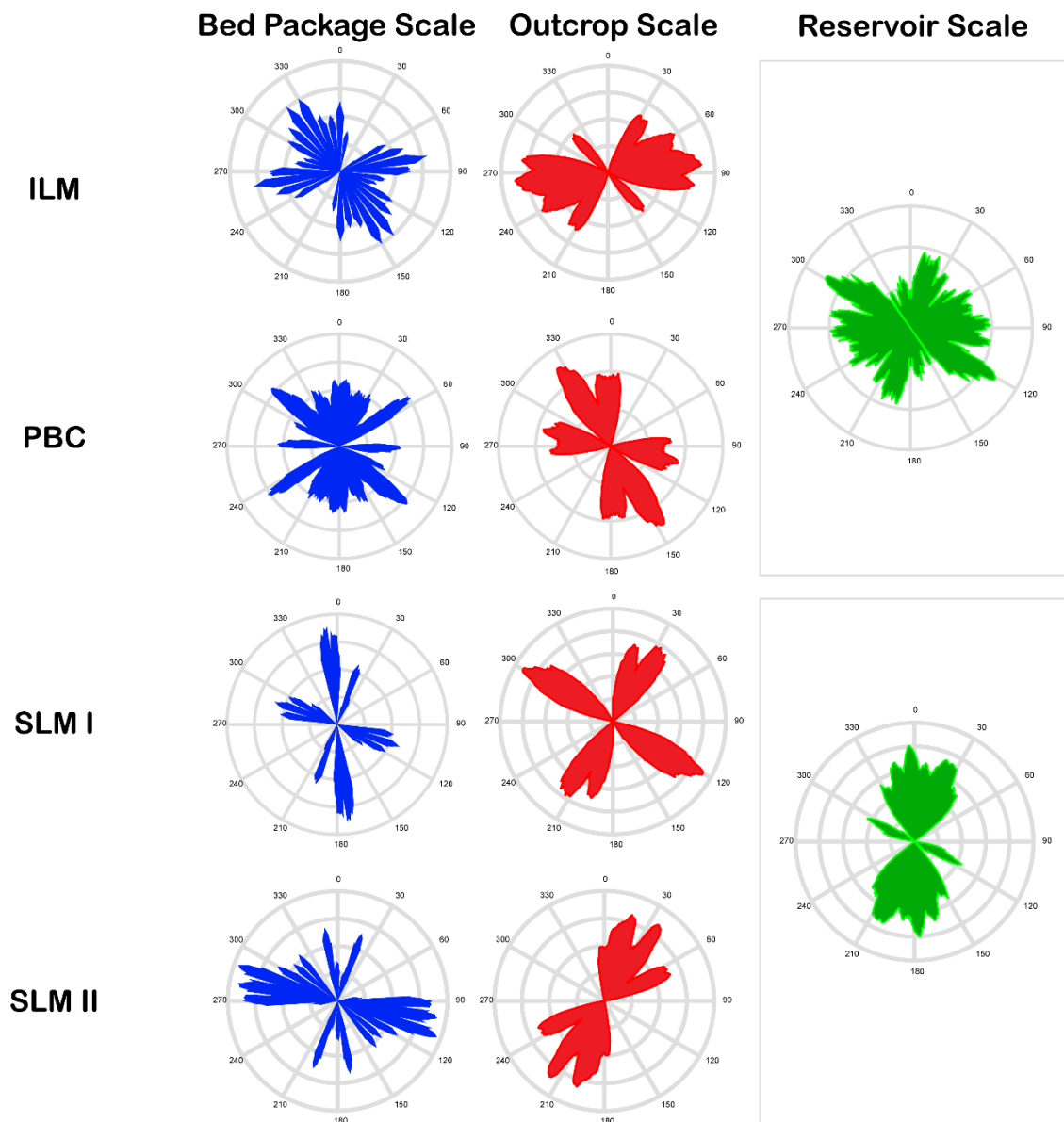


Figure 3.16 Moving Average rose diagrams (equal area, aperture of 9° , weighing factor of 9; Munro et al., 2012), according to the sites investigated and scales of observation.

3.5.2 Storage Capacity and Fluid-flow Properties

The results of DFN modelling (Figure 3.13 to 3.15) are consistent with values of average porosity comprised between 0.23 % and 1.00 % (bed-package scale), 0.30 % and 1.00 % (outcrop scale), and 0.30 % and 0.73 % (reservoir scale). As also proposed for other shallow-water carbonates of southern Italy (Panza et al. 2016, 2019; Giuffrida et al. 2019, 2020), we infer that these values are mainly affected by both SB and NSB fractures. These structural elements greatly contribute to the computed amounts of storage capacity, as suggested by the results of DFN modelling of the 5 m-side geocellular volumes, which are the highest among those obtained for this study (Table 3.3, Appendix 3.1 & Appendix 3.2).

Considering that the employed aperture values do not allow for a realistic assessment of bulk permeability, we focus on the horizontal permeability anisotropy (Appendix 3) calculated on the basis of the computed K_{xx} and K_{yy} values (Figures 3.13 to 3.15). At the smaller scale, the aspect ratio of the permeability ellipses ranges from 1.16 (ILM) to 1.38 (SLM I), and therefore shows a slight horizontal permeability anisotropy. Such a quite isotropic condition resembles the structural configuration obtained in plan-view for the studied sites (cf. Figures. 3.7c & 3.7d). Differently, the aspect ratio of 3.53 (SLM II; Figure 3.8d) is indicative of a strong directional flow (Lewis, 1988; Farrell & Taylor, 2014; Jourde et al., 2001). The latter results are interpreted as due to the high volumetric fracture density value ($P_{30} = 33.8 \text{ m}^{-3}$) computed for the WNW-ESE fracture set (Table 3.2), which also exhibits the highest D-fractal dimension, 1.55 ($R^2 = 0.91$) among all studied fracture sets (Bonnet et al., 2001). So, although the premise of this work, being that the fractures were collected away from major faults, we conclude that the WNW-ESE fractures at SLM are still associated with fault-related deformation. The strong horizontal permeability anisotropy is therefore imputable to the effects of strain localization, which favour fault-parallel horizontal permeability (Sibson, 2000).

At larger scales, most of the DFN models also show slight anisotropic horizontal permeability for the ILM site, with a value of 1.36 computed for the horizontal permeability ellipse after DFN modelling (Appendix 3.3c). Differently, at the SLM site the computed aspect ratio for the horizontal permeability ellipse is 2.07 (Appendix 3.3c). We interpret the latter result as due to the previously mentioned orientation bias (cf. section. 5.1) of the digital structural analyses conducted on the vertical cliff (Thomas, 2021; Abdallah et al. 2023). Nevertheless, irrespective of the scale of observation, and neglecting this orientation bias, the results of larger-scales DFN modelling suggest that the fractured volumes are characterized by a marked uniformity in the

modelled horizontal permeability. Such hydraulic configuration is similar to that computed for the Cretaceous shallow-water carbonates of Monte Alpi crosscut by background fractures (Giuffrida et al., 2019, 2020; La Bruna et al., 2020). The near isotropic horizontal permeability could be due to the ca. 4 -5 km Quaternary exhumation the carbonates (Manniello et al., 2022), which may have caused the enlargement of the pre-existing fractures and also determined the formation of new fracture sets (Nelson, 1997; English 2012).

3.5.3 Conceptual Model

In order to apply our knowledge of the horizontal permeability, ellipses computed after multiple DFN modelling, we summarize the aforementioned interpretation in a conceptual model of the trajectories of subsurface water circulation under both vadose and phreatic conditions. This model hence proposes scenarios of fluid flow through the fractured and faulted shallow-water carbonates at different scales of observation (Figure 3.17).

The conceptual model invokes meteoric fluid infiltration with vertical components of flow within the unsaturated zone, and then water circulation through the saturated zones characterized by horizontal flow. Within the latter zone, an almost sub-rounded shape of the aspect ratio is consistent with a quite isotropic horizontal permeability envisioned at all scales with the exception of the bed-package scale SLM II outcrop (cf. Section 5.2). However, the tendencies of computed horizontal fluid-flow changes directionally from site to site according to the scale of observation. This is because of the aforementioned scale-dependant fracture and fault geometry, and also because of the stratigraphic architecture and related depositional environments of the studied carbonate units.

Moving from largest to the smallest, at the Il Monte site we document a WNW-ESE geometrically controlled fluid flow at the reservoir scale (500m-side), then a change in the fluid flow towards the E-W direction at the outcrop scale (50m-side). Such behaviour, due to the small and medium E-W faults characterized by high P_{32} values (cf. Table 3.2), is reverted at the 5m bed package scale, which is consistent with the aforementioned scale-dependant geometry of the fracture and fault networks. At Scarrone la Macchia site, we also document WNW-ESE horizontal flow direction at the reservoir scale (500m-side), which changes at smaller 50m outcrop scale to a NE-SW, due to the presence of sub-parallel faults (cf. Table 3.2). At the bed-package scale (5m-side), SLM I show isotropic conditions, while SLM II very pronounced NW-SE horizontal permeability.

Finally, we emphasize that small and medium faults crosscutting bed packages interfaces and pre-existing thrust faults likely form local conduits at the linkage zones for fault-parallel fluid flow. In fact, the extensional fractures clustering within the releasing jogs are characterized by

high P_{20} and P_{21} values (cf. Figure 3.8) and can impact the components of horizontal fluid flow. A similar conclusion was proposed by Panara et al. (2023) after digital structural analyses of Upper Jurassic shallow-water carbonates of Saudi Arabia, which resulted in fracture linkage zones forming clusters of high P_{21} values that might impact the fluid paths at depth (green and gold inset, Figure 3.17).

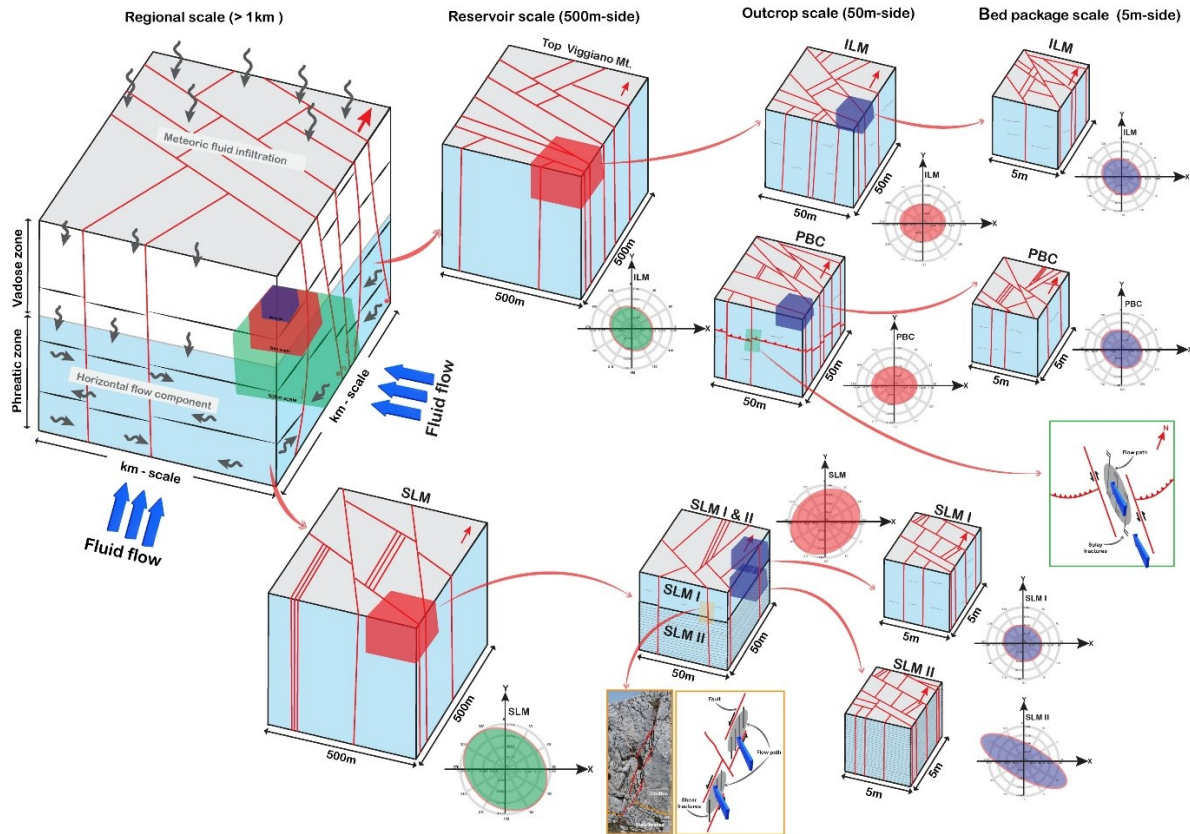


Figure 3.17 A conceptual model of the Viggiano mt. showing modalities of meteoric fluid infiltration in the vadose zone and horizontal fluid flow in the phreatic zone. The diagram shows the directional change in horizontal permeability ellipses with the scale of investigation. Gold inset shows sheared fractures localized within small – medium fault zones, the linkage of these fractures can act as effective conduit for fault-parallel fluid flow. Green inset shows a disruption of mechanical interface by high-angle faults with associated localized strain which could act also as an effective pathway for fluid movements.

3.6 Conclusions

The present contribution investigated the variation of computed values of fracture equivalent permeability throughout the Lower Jurassic (SLM) to Cretaceous shallow-water carbonate (ILM) succession exposed along the flanks of the Viggiano Mt. southern Italy. The laterally and vertically continuous carbonate exposures allowed detailed assessment of the nature, geometry, and multiscale distribution of high-angle fracture and fault sets.

We performed multiscale DFN modelling of geocellular volumes resembling the single carbonate bed-packages (5m-side volumes), outcrops (50m-side volumes) and reservoir (500m-side volumes). The single volumes were either considered as individual geocellular units, without any internal subdivision representing amalgamated carbonate beds, or made up of multiple sub-volumes representative of single beds or entire sedimentary units. The geocellular volumes were populated with fractures whose density/intensity, dimensional properties, and multiscale height/length distribution were after integrated results from field structural analyses, for the 5m-side geocellular volumes and 3D photogrammetric modelling, for the 50m and 500m-side geocellular volumes.

Preliminary structural results points to a geometry scale dependency of over 3-order magnitude for the fracture and fault networks crosscutting the carbonates. However, we acknowledge that 2D-like exposure of the SLM cliffs could bias results relating to the Lower Jurassic carbonates. After DFN modelling of the geocellular volumes, our results show the maximum value of fracture porosity ($\Phi_{\max}$), vary from 2 % to 0.02 % for the 5 to 500 m-side geocellular volumes, respectively. Hence, these data show the profound control exerted by pervasive smaller scale structural elements (strata bound and non-strata bound fractures) on the storage properties of the shallow-water carbonates.

In terms of computed equivalent permeability, we mainly focused on the results obtained for the horizontal components of the tensor because the employed algorithm does not allow to precisely model the baffle/barrier effects provided by bed-parallel bed and bed-package interfaces. Computed values showed near-isotropic horizontal permeability ellipses for most of the surveyed outcrops. That is, irrespective of the scale of observation, the fracture and fault networks form in plan-view quite isotropic network, although the principal axes for the permeability ellipses vary from site-to-site according to the attitude of the main structural discontinuities. The near isotropic permeability results obtained in our study are similar to previous scenarios computed for fractured carbonate rocks exposed along the axial zone of the Southern Apennines fold and thrust belt. The near isotropic permeability results could be as a result of the severe exhumation the studied carbonates experienced from depths of $\sim 4 - 5$ km during Quaternary uplift and downfaulting of the belt.

Finally, all results related to horizontal permeability anisotropies were summarized in a conceptual model illustrating the modalities of meteoric fluid infiltration under vadose conditions, and the subsequent horizontal flow under phreatic conditions at various scales of observation. Our results show that mesoscale heterogeneities in fractured carbonates should not be overlooked during the reserve estimation processes associated to groundwater

management, geothermal energy production, and for those targets for carbon capture and sequestration.

CHAPTER 4 - STRESS-INDUCED PERMEABILITY ANISOTROPY AND FLUID FLOW DYNAMICS IN A MESOZOIC FRACTURED CARBONATE AQUIFER OF SOUTHERN ITALY

4.1 Introduction

Understanding the impact of stress on fluid flow and permeability anisotropy in fractured rocks is essential across a wide range of geological and engineering disciplines, including groundwater management, hydrocarbon extraction, nuclear waste disposal, hydraulic fracturing, induced seismicity, carbon capture and storage and geothermal energy development (National Research Council, 1996; Neuman, 2005; Moreno and Neretnieks, 1993; Bodvarsson et al., 1999; Selroos et al., 2002; Pruess, 2006; Yasuhara et al., 2006; Razi-perchikolaee et al., 2014; Follin et al., 2014; Hyman, Jiménez-Martínez, et al., 2016; Jenkins et al., 2017). One region where these effects are particularly relevant is the Mesozoic fractured carbonate aquifers of Southern Italy, a complex geological system where fluid flow is heavily influenced by fracture to fault - induced permeability (Stabile et al., 2021; Beaubien et al., 2023; Spagnolo et al., 2024).

Stress fields, which can originate from regional tectonic forces or more localized geological processes, exert a significant influence on the fracture networks within these aquifers (Zoback et al., 1992; Lei & Gao, 2018). Depending on the orientation and magnitude of the principal stresses, fractures may either open or close, directly affecting permeability (Bai et al., 1994, 1999; Chen et al., 1998; Bisdom et al., 2016). Fractures subjected to high normal stress tend to compress, reducing permeability, while those experiencing higher shear stress are prone to fragmentation and cataclasis, which enhances fluid flow (Barton et al., 1995, Zhang and Sanderson, 1996, 1997; Olson and Barton, 2001). While these behaviours are well-documented for individual fractures (e.g., Bandis et al., 1983; Yoshinaka & Yamabe, 1986; Koyama and Jing, 2008; Yang et al., 2023), their influence on flow and transport properties within three-dimensional fracture networks remains less explored. In fact, previous research has demonstrated that the permeability of fractured rocks can undergo substantial changes under varying stress conditions, leading to flow channelling (Oda, 1986; Bai & Elsworth, 1994; Zhang & Sanderson, 1996; Chen & Bai, 1998; Min et al., 2004; Koyama et al., 2006; Baghbanan & Jing, 2008; Li et al., 2019; Sweeney and Hyman, 2020; Hyman et al., 2020;

Igbokwe et al., 2024). For this reason, despite significant progress in understanding single-fracture behaviour under stress, the broader implications for 3D complex, interconnected fracture networks remain a crucial area for further investigation.

In addition to permeability, solute transport, critical for modelling contaminant flow in groundwater systems, has also been shown to be affected by stress-induced changes in fracture flow dynamics (Moreno et al., 1988; Jeong & Song, 2005; Koyama et al., 2008; Zhao et al., 2011, 2013; Sweeney and Hyman, 2020). Experimental and numerical studies have modelled these coupled stress-flow-transport processes, with more recent studies employing three-dimensional models to provide more realistic results (Sweeney & Hyman, 2020; Song et al., 2024). These studies consistently highlight the role of stress-induced closure and channelization in controlling flow patterns within fracture networks, further emphasizing the need to incorporate stress effects into transport models. However, to the best of our knowledge, results based on real field data pertaining to 3D-fracture network in carbonates do not exist. Sweeney et al. (2020) carried out an idealistic experiment, which was not based on real field data, Song et al. (2024) worked with a theoretical approach on fine-scale fractures in carbonates, and recently Igbokwe et al. (2024) focussed on the dolomites of northern Italy for a 2D stress–aperture-permeability computation.

The objective of the present study is to investigate the effects of stress on permeability anisotropy in fractured carbonate aquifers through numerical simulations. Since it is known that fracture aperture measurements from outcrop studies do not directly represent hydraulic fracture properties at depth, this study specifically focuses on comparing these findings with previous results obtained for open fractures where no stresses were applied (as discussed in Chapter 3).

By contrasting the behaviour of stressed and unstressed fracture networks, we provide new insights into the role of local stresses in governing fluid flow in complex aquifer systems. Our primary goal is to examine how the structure of the flow field within the network changes with various in-situ stress conditions rather than on the flow field within a given fracture. The study applies to the existing field data collected in Chapter 3 by building realistic 5m-side DFN models with the *dfnWork*® code, which is capable of hydro-mechanical coupling to study the changes in effective permeability, as a response to closure/and or dilations of fracture aperture as a function of applied stress.

The achieved results are discussed in light of the conclusions from chapter 3, to confirm if elongated permeability anisotropy ratios are assessed at shallow crustal depths or similar results from the previous chapter, where near isotropic horizontal permeability persists. Hence, isolating the effects of exhumation on pre-existing fractures, and assuming all fractures sets exist at depth and no new set was formed during ca. 4 -5 km Quaternary exhumation of the Viggiano mt. carbonates (Nelson, 1997; English 2012; Manniello et al., 2022).

4.2 Methods

4.2.1 Discrete Fracture Network Modelling

We generate new sets of Discrete Fracture Network (DFN) models with high computational meshes, using dfnWorks® high-performance computational suite code (Hyman et al., 2015) developed by the Computational Earth Science Group (EES-16), Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM, USA, which allows to model flow and transport in three-dimensional fractured media at scales ranging from millimetres to kilometers. Additionally, the software package allows us to impose in-situ stresses, σ_v (σ_1), $\sigma_{H_{max}}$ (σ_2), and $\sigma_{h_{min}}$ (σ_3), and mimic depth-equivalent stresses in order to compute more realistic effective permeability results at subsurface conditions.

This protocol of work contrasts to the analyses reported in Chapter 3, where discrete fracture networks with open fractures were modelled with imposed mechanical, and hydraulic aperture. The high resolution meshes generated allow for non-reactive solute transport simulation through the stochastically generated DFNs and the effective permeability across these networks at various depths are monitored through the variation in breakthrough time of these particles. In comparison to MOVE® software package used in chapter 3, dfnWorks® offers more flexibility to control parameters used for the generation of the DFNs as well as upscaling to the effective continuum, although not implemented in this work. Also, while MOVE® computes maximum and bulk permeability achieved within cells confined in geocellular volumes, dfnWorks computes effective permeability values, allowing the researcher to make comparison with data acquired during production logging and well testing (pressure transient tests).

4.2.2 dfnWorks®

The dfnWorks software package consists of three main parts. The dfnGen, dfnFlow, dfnTrans (Figure 4.1a) The input for dfnWorks is a fractured site characterization that provides

distributions of fracture attitude, radius (length), fracture intensity (P32), aperture, etc. As input, we use existing data collected in Chapter 3, Table 3.1. Additional data input is listed in the subsequent section.

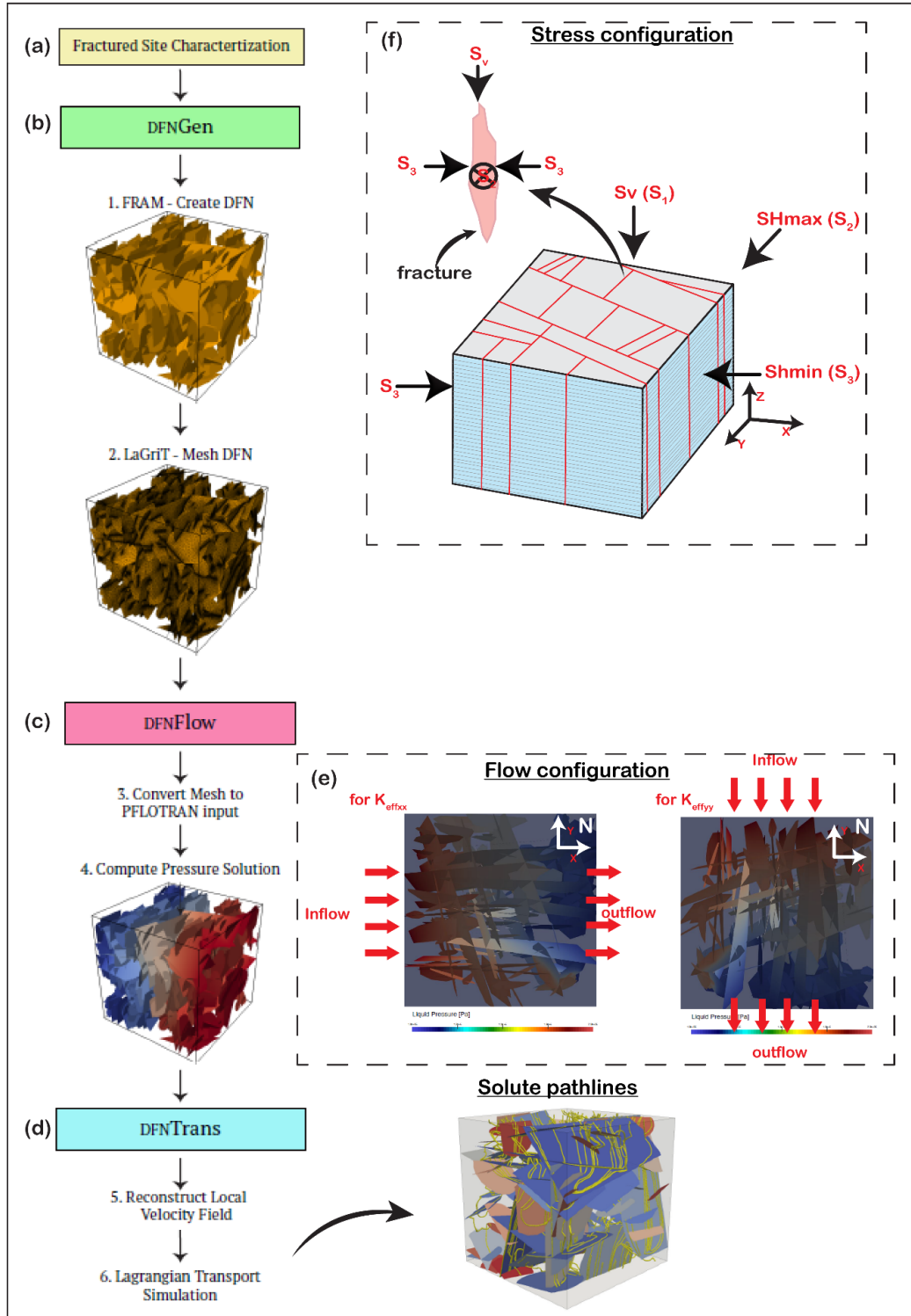


Figure 4.1 Methodology: a) field data collection and statistical analysis b) dfnGen - stochastic fracture generation, high resolution meshing c) dfnFlow – pflotran flow solution d) dfnTrans – solute transport e) flow configuration for effective permeability, effKxx and effKyy. (modified after Hyman et al., 2015)

The dfnGen uses a FRAM algorithm to create discrete fracture network where data gathered from fracture networks characterisation are stochastically replicated using the feature rejection algorithm for meshing (Hyman et al., 2014). The FRAM algorithm sets a minimum length scale, h and then restricts the generation of the network to only create features of that size and larger. This allows efficient usage of computational resources in an approach that is fully automated, and parallelized. dfnGen allows to generate an unstructured high-quality conforming Delaunay triangulation of each DFN with user minimal to no user intervention.

The second part of the dfnWorks software package is the LaGriT (Figure 4.1b). The LaGriT is a meshing toolbox that is used to create high quality conforming Delaunay triangulation mesh (Gartner and Kamenski, 2019) of the network (Hyman et al., 2014). The third part of the code is the dfnFlow (Figure 4.1c). Using pflotran code (<https://www.PFLOTTRAN.org/>), a state-of-the-art, massively parallel subsurface flow and reactive transport code, the dfnFlow converts fracture network meshes to pflotran input, where control volume information is formatted (Hammond et al., 2012, 2014; Lichtner et al., 2015). It also computes steady-state pressure solution in DFN. Then the dfnTrans (Figure 4.1d), which allows the reconstruction of local velocity field i.e., Darcy fluxes obtained using dfnFlow, used for particle tracking on the DFN and then Lagrangian transport simulation which is used to determine path lines through the network and simulate transport.

Various python scripts are used to couple the different parts of this code together in order to function. The software package is built for use originally using Ubuntu distribution of the Linux operating system. However, the easiest way to operate this code using the windows operating is by using a docker container. The code and other documentations are accessible at https://dfnworks.lanl.gov/index_docs.html. The modified code used in this study is attached (code 1), and the supporting codes (code 2, code 3). The software package functions on a normal PC, although high performance computing is recommended for the generation of DFN models with multiple fracture sets.

As input for the python script, named driver.py (Code 1), python libraries are imported then the domain size is set (equivalent to geocellular volume of chapter 3). In our study, we set the domain size as 5m x 5m x 5m for all the sites investigated. The minimum length, h is set at 0.01 for all the models. In order to keep the mesh size reasonable, it is recommended that h must be smaller than 1/10th the minimum fracture size, h must be larger than 1/1000th than minimum fracture size and h must be non-zero. On regions and layers, the set up used in chapter

3 are also replicated. Fracture aperture value of 0.1mm was adopted for this research work, contrasting with the hydraulic aperture value used in chapter 3. This is to arrive at realistic effective permeability values in the range expected for fractured carbonates at our computed depth. For more information on the generation of fractures and modification of meshes, we refer to the dfnWorks' manual found on the website above.

The number of fractures generated can be limited by a, “stop condition” command written in the code. This, together with setting a seed value, is especially important for recreating the same number of fractures network across different software packages or the same fracture network, within the same software package, as in our own case. It also offers an advantage to avoid overestimation of fracture intensity, ensuring the generation of more realistic models. Other parameters that can be set are shape of fracture, which could be an elliptical with pre-defined vertices (or points), or rectangular. In our case we used elliptical fractures (Griffith, 1921; Pollard and Segall, 1987) and used set default, 8. The distribution type of the fracture network can set as Log-Normal, Truncated Power-law, Exponential, or Constant. Minimum and maximum values of radius (used in place of length) must be provided for the first 3 along with the distribution parameters. For this study we used Truncated Power-law, similar to values set at Chapter 3, we then set the exponent of the Power-law for every fracture set, Alpha (or D-value). Fracture orientation (or attitude) distribution can be set to follow fisher distribution (Fisher, 1994) as in Chapter 3. However, it should be noted that von Mises-Fisher distribution becomes unstable for values greater than 100. The fracture intensity, P32 value are defined for each family (or set), or npoly, when the user chooses to use deterministic approach and set exact number of fractures in a domain. The fracture orientation parameter can be set as *Strike/Dip*, *Trend/Plunge* or *Normal Vector (x,y,z)* coordinates in the case of deterministic approach to fracture network generation.

Aperture parameter can be set by Log Normal distribution with parameters *meanAperture* and *stdAperture*, Aperture from Transmissivity defined using *apertureFromTransmissivity*, Constant Aperture *defined using constantAperture*, or Aperture perfectly correlated to fracture length using *lengthCorrelatedAperture*. In the first part of the work, unstressed fracture network models, we consider a fracture network model where hydraulic apertures are positively correlated to their radii via the equation:

$$b = F \cdot r^k \quad (1)$$

Where b is the aperture; r is the radius of the ellipse and,

F and k are user defined parameters that determine the relationship between fracture size and aperture. In the case of aperture proportional to length, we apply $k = 2$, and F varies according to set hydraulic aperture values. This assumption implies larger fractures have wider apertures and form less resistance to flow (Bogdanov et al., 2007; Wellman et al., 2009; Joyce et al., 2014; Aldrich, et al., 2016; Frampton and Hyman, 2019)

4.2.3 Fluid Flow Simulation

dfnWorks ® works with the assumption that the aperture is uniform within a single fracture and hence to solve for flow, we assume flow between parallel plate of Hagen-Poiseuille and the stokes equations, of those governing isothermal, incompressible, laminar flow, Newtonian fluid at the steady state can be integrated to determine the volumetric flow rate Q per unit fracture width normal to the direction of flow to obtain

$$Q = \frac{-b^3}{12\mu} \frac{dp}{dy} \quad (2)$$

Where Q is the volumetric flow rate per unit width normal to the flow, b is the fracture aperture, and μ is the dynamic viscosity of the fluid. Negative sign indicates the direction of flow in relation to pressure gradient.

The governing equation for flow within the fractures is derived from the Boussinesq approximation and Reynolds equation (Zimmerman & Bodvarsson, 1996; Sweeney and Hyman, 2020)

$$\nabla \cdot Q = 0 \quad (3)$$

and given mass conservation:

$$\nabla \cdot (b_3 \nabla P) = 0 \quad (4)$$

These equations describe the steady-state pressure distribution and flow field in the fracture network, and the elliptic partial differential equation (Reynolds equation) is solved to obtain the pressure field.

Dirichlet boundary conditions are set such that a pressure difference of 1 MPa is prescribed across the domain and aligned with the x or y axis, depending on the type of the analysis to be performed. For the Effective permeability in the X direction (K_{effxx}), that is East to West, in our case, we impose a pressure difference of 2 MPa at the inflow (East) and 1Mpa at the outflow (West) to create a drawdown and allow fluid to flow (Figure 4. 1e). This allows for a uniform driving force without feedback from mechanical stress (that is, no feedback between fluid pressure and the mechanical stress field) (Figure 4. 1e). The python code is edited correctly to reflect this (Code 1, line 134). Differently, the code is reedited to impose flow in the Y direction (K_{effyy}) from North to South, and similar conditions are applied to compute effective permeability in that direction.

In this study, the afore-mentioned configuration is repeated for every 500m, from a depth of 500m to 5000m, for case of an aquifer and same, for the case of hydrocarbon reservoir. The slight difference between the two cases (aquifer, reservoir) are the in-situ stresses applied, pore pressure and properties of fluid, such as fluid viscosity, density, etc. Aquifer assumes density of water at 20°C as 1000kg/cm³, while for reservoir, the density of hydrocarbon found in the Val d'agri 850 - 875 kg/cm³ (30 – 35 API gravity), we used the higher value. These values are used to compute the pore pressure of at varying depth. Dynamic viscosity of water at 20 degree (μ_{H2O}) is taken at 8.9E-4 Pa.s for effective permeability computations and computed with the equation:

$$K_{eff} = \frac{q^* \mu}{\nabla P} \quad (5)$$

where,

K_{eff} is effective permeability, q darcy flux over entire fracture face (m³/m²/s), μ is dynamic viscosity and Δp is pressure gradient (Pa).

Some assumptions in the modelling are that the surrounding rock matrix is non-porous, meaning fluid flow is confined strictly to the fractures, hence matrix flow is neglected. Also, the effect of gravity is unaccounted for, except during later our pore pressure computations to determine S_3 stress. Hence flow is driven purely by the applied pressure gradient. Hence, while this study isn't an ideal situation, it offers a simplistic way to elucidate the importance of considering the effectives stresses on three-dimensional fracture networks and their effects on flow and transport (hence, compare results with that of chapter 3).

Using PFLOTTRAN and a two-point flux finite volume scheme, the pressure and volumetric flow rate distributions are calculated numerically integrating eqn (5), allowing for high-resolution analysis. Based on pressure and flux distributions, the Eulerian velocity field $u(x)$ within the Discrete Fracture Network (DFN) is reconstructed. The method follows approaches by Makedonska et al. (2015) and Painter et al. (2012), which detail how to handle flow in complex fracture networks. Lastly, isolated fractures are removed during effective permeability computation, as they do not contribute hydraulically to the network.

4.2.4 Stress-Aperture Correlation

The dfnWorks attempts to model the effect of stress on effective permeability and fluid flow patterns in 3D-fractured network. The software allows us to perform this computation by adopting the method proposed Baghbanan and Jing (2008) where aperture is correlated to fracture trace length. This model was built after the works of Barton – Bandis model, that describes the effects of surface roughness on fracture deformation and strength under various anisotropic stress conditions.

Typically, the modification made by Baghaban and Jing (2008) ignores the fracture surface roughness and assumes equal hydraulic aperture across the entire fracture plane, however our field data, Chapter 3, Table 3.1, already accounts for average JRC (Joint Roughness Coefficient) within the hydraulic aperture computation.

This model provides a simplistic approach towards coupling stress field with aperture compression/dilation as a direction function of normal stress and shear displacement. Pre-set geo-mechanical data from the model used in the python script are shown in Table 4.3. Additional data are for elastic modulus, $Kr = \eta G/l$, where η is a geometric constant assumed to be 0.92), and l is the half-length of the fracture in meters. Dilation/compression relationship with and stress field is analytically computed by means of projection of the stress tensor (σ_{ij}) onto the orientation of the fracture (n) to compute the normal stress σ_n .

The model requires an initial hydraulic aperture (b_o), which is provided in Table 4.3 and a critical normal stress (σ_{nc}), which accounts for the behaviour of different apertures,

$$\sigma_{nc} (MPa) = 0.487b_o(\mu m) + 2.51, \quad (6)$$

The stiffness of each fracture below and above the critical shear stress is denoted K_1 and K_2 , respectively. Before slip, the stiffness is defined by both the fracture stiffness and the elastic shear resistance of the surrounding rock, $K_1 = K_f + K_r$. After slip, the stiffness is defined solely

by the shear modulus of the surrounding rock, $K_2 = Kr$. The magnitude of the normal stress on the fracture plane is calculated by

$$\sigma_n = \sigma_{ij} n_i n_j \quad (7)$$

where σ_{ij} is the prescribed stress tensor and n_i are the components of the unit normal vector of the fracture. The normal displacement (U_n) is given by the relationship

$$U_n = \frac{9 \sigma_n b_o}{\sigma_{nc} + 10 \sigma_n} \quad (8)$$

The model assumes an elastic perfectly plastic model in the shear direction, with a Mohr-Coulomb failure criterion with constant shear stiffness and no cohesion. No dilation due to shear displacement will occur if the shear stress acting on a fracture is below the critical shear stress given by,

$$\tau_c = \sigma_n \tan \phi \quad (9)$$

However, if shear failure is reached, then the shear displacement (U_s) is related to shear dilation (U_d) by the constant dilation angle (ψ_d) by the equation,

$$U_d = U_s \tan \psi_d \quad (10)$$

And the magnitude of the shear stress is calculated by the equation,

$$\tau_n = \sqrt{(T^{(n)})^2 - \sigma_n^2} \quad (11)$$

While,

$$T^{(n)} = \sigma_{ij} n_i n_j \quad (12)$$

Given both the normal and shear displacement, the computed fracture is given by the equation,

$$b = b_o - U_n + U_d \quad (13)$$

The dfnWorks code takes in geo-mechanical parameters as inputs (Table 4.3) and in-situ stresses, S_1 , S_2 and S_3 . (S_v , S_{Hmax} and S_{hmin} , respectively). For our study area, we assume extensional regime, hence, $S_v > S_{Hmax} > S_{hmin}$. We used the afore mentioned geomechanical input parameter from Baghbanan and Jing (2008) and Zhao et al., (2013). Though their analysis was on granitic rocks, their parameters provide a basis to obtain the first result for our work. The stresses are oriented as in Figure 4f, where S_v is in the z-direction, S_{Hmax} in the y direction and S_{hmin} in the x direction (code 1, line 133 -117).

S_v (S_1) values are computed by the formular, $P = \rho_{\text{rock}} \cdot g \cdot h$, where the density, ρ of carbonates is taken as an average of 2700 kg/m³ based on real measurement from the Viggiano carbonates at confining pressure of 600 psi (Manniello et al., under review), g is the acceleration due to gravity (approximately 9.81 m/s²), and h is the depth (respective depth from 500m up to 5000m). While pore pressure (P_p) is computed using the same formular, but density of rock is substituted for that of oil, $P_p = \rho_{\text{oil}} \cdot g \cdot h$. or water, $P_p = \rho_{\text{H}_2\text{O}} \cdot g \cdot h$, for an aquifer computation.

S_3 values are computed by using the formular proposed by Jaeger and Cook (2007), initial reservoir pore pressure for the Val d' Agri field, $P_p = 3.66\text{E}+07$ Pa and coefficient of friction as 0.6 (Eni data, Stabile et al., 2021).

$$S_3 = \frac{S_1 - P_p - \mu(S_1 - P_p)}{1 + \mu} \quad (14)$$

The values of S_2 are computed from the theoretical model of Lisle model (Lisle et al., 2006),

$$\text{We use stress ratio, } R = \frac{S_2 - S_3}{S_1 - S_3}, \quad (15)$$

where $R = 0.39$, a universal average (Lisle et al., 2006), since R at the Val d' Agri is unknown.

Computed stresses are shown in Figures 4.2, 4.3.

The limitation of this approach however is that it provides only one-way coupling. Meaning that the interaction between fluid pressure and mechanical stress field is unaccounted for. Though, the developers consider that many of the pressure gradients within the subsurface fracture networks is often typically small enough that their impact on hydraulic apertures is minor (Nordqvist et al., 2008). Also, it is worth mentioning that the model doesn't account for stress shadowing nor growth of fractures due to shearing. While this might limit the outcome of the work, this approach allows us to begin to better understand the interplay between stress field and aperture closure/dilation and by implication permeability anisotropy within 3D fracture networks. The computed stresses are shown in Figure 4.2, Figure 4.3, Table 4.1 and 4.2.

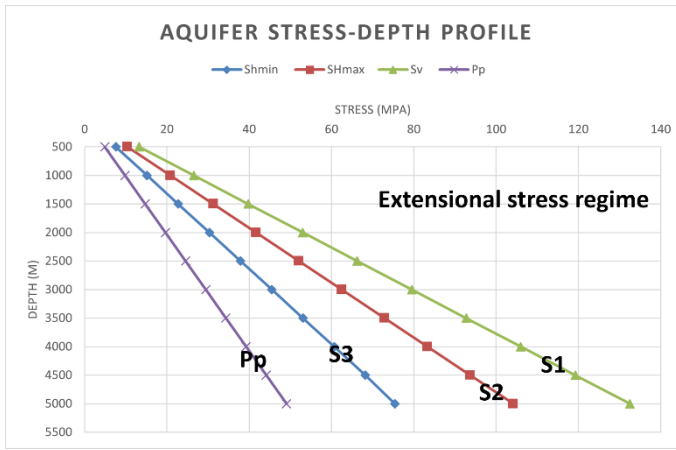


Figure 4.2 Aquifer stress-depth profile

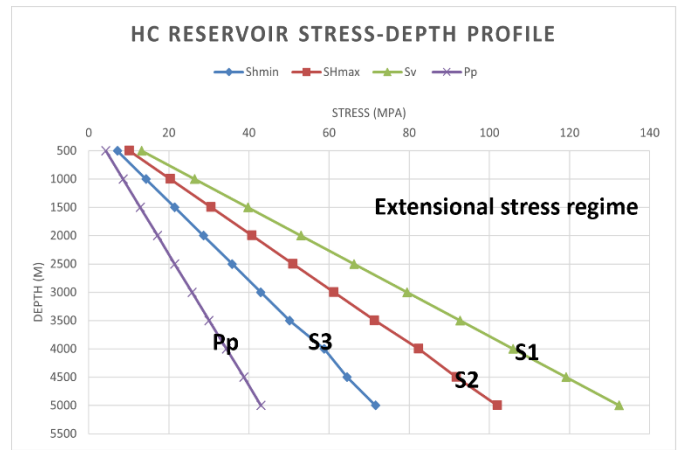


Figure 4.3 Reservoir stress-depth profile

Table 4.1 Aquifer stress data

Aquifer Stress Summary

Depth (m)	S_1 (MPa)	S_2 (MPa)	S_3 (MPa)	P_p (MPa)
500	13.24	10.02	6.80	4.905
1000	26.48	19.92	13.36	9.81
1500	39.72	29.90	19.88	14.715
2000	52.96	39.94	26.43	19.62
2500	66.20	49.94	32.94	24.525
3000	79.44	59.94	39.49	29.43
3500	92.68	69.98	46.04	34.335
4000	105.92	80.00	52.55	39.24
4500	119.16	90.02	59.10	44.145
5000	132.40	100.00	65.60	49.05

Table 4.2 Reservoir stress data

Hydrocarbon Reservoir Stress Summary

Depth (m)	S_1 (MPa)	S_2 (MPa)	S_3 (MPa)	P_p (MPa)
500	13.24	10.20	7.16	4.29
1000	26.48	20.40	14.32	8.58
1500	39.72	30.60	21.48	12.87
2000	52.96	40.80	28.63	17.16
2500	66.20	51.00	35.80	21.45
3000	79.44	61.20	42.95	25.74
3500	92.68	71.40	50.11	30.03
4000	105.92	82.40	58.80	36.60
4500	119.16	91.80	64.51	38.73
5000	132.40	102.00	71.60	42.90

4.2.5 Solute Transport Simulation

Non-reactive particles are transported within the velocity field to follow path lines, as in the case of Lagrangian approach to solute transport. These particles are introduced at specific planes (Figures 4.1e, 4.4c, 4.4d), usually oriented perpendicular to the average direction of flow to simulate inflow of fluid into a network of fractures. In other cases, particles may be randomly distributed, and an extraction well can be situated and the properties of all the solute particles recorded as they move towards the well. The distribution of particles along an inlet plane is established through flux weighting, meaning that the number of particles present at a given position correlates with the proportion of total inflow flux occurring at that point, hence they are usually flux weighted. This method ensures that the particle concentration reflects the actual flow dynamics, enhancing the realism of the simulation. (Kreft & Zuber, 1978; Hyman, Painter, et al., 2015; Kang et al., 2017, 2019; Sweeney et al., 2020). In this transport simulation, we followed this by setup, however, setting maximum of 1000 particles to flow through the network. In cases whereby the input nodes are larger than the particle, the system increases the

particles to complement the nodes. Once each particle crosses the control plane, its position, velocity, time, and distance travelled is written to an ascii file.

For more information on the solute transport simulation in dfnWorks, we refer the reader to Makedonska et al. (2015). For our simulation, we call in the function for the Python code (code 1, line 18,132) and edit the control file, */PTDFN_control.dat* to pre-set conditions. Within the file, we define inflow and outflow boundary, set particle numbers, set seed number for solute transport simulation and also properties for matrix, which is outside the scope of this work.

Table 4.3 Geomechanical input parameters for modelling (from Baghhanan and Jing, 2008)

Parameter	Description/Value
sigma_mat	
friction_angle	25.0 degrees
dilation_angle	5 degrees
critical_shear_displacement	0.003 m
shear_modulus	10e9 Pa
min_b	1e-10 m
shear_stiffness	400e9 Pa

4.3 Results

We report the results of DFN modelling of geocellular volumes resembling the bed-package-scale (5m-side) configurations designed for the studied SLM II, SLM I, PBC and ILM outcrops. Firstly, we show the stochastically generated fracture network, their spatial distribution, geometrical and dimensional properties (dfnGen). Then, we document the amounts of effectively permeability, and assessed horizontal anisotropy ratio, (K_{effxx}/K_{effyy} or k_{effyy}/K_{effxx}), computed after DFN modelling of the afore mentioned volumes (dfnFlow). The results are presented firstly for unstressed DFN models, i.e., models with open fractures and then for stressed DFN models (Table 4.4). In total, results of 160 simulations are presented. Graphical result for SLM I is shown as an example, (Figure 4.4), to provide the reader a visual of the network with 3 fracture sets, permeability, liquid pressure and solute particles path lines. Finally, we show result of reactive transport simulation by assessing the breakthrough time and tortuosity of the particles (dfnTrans).

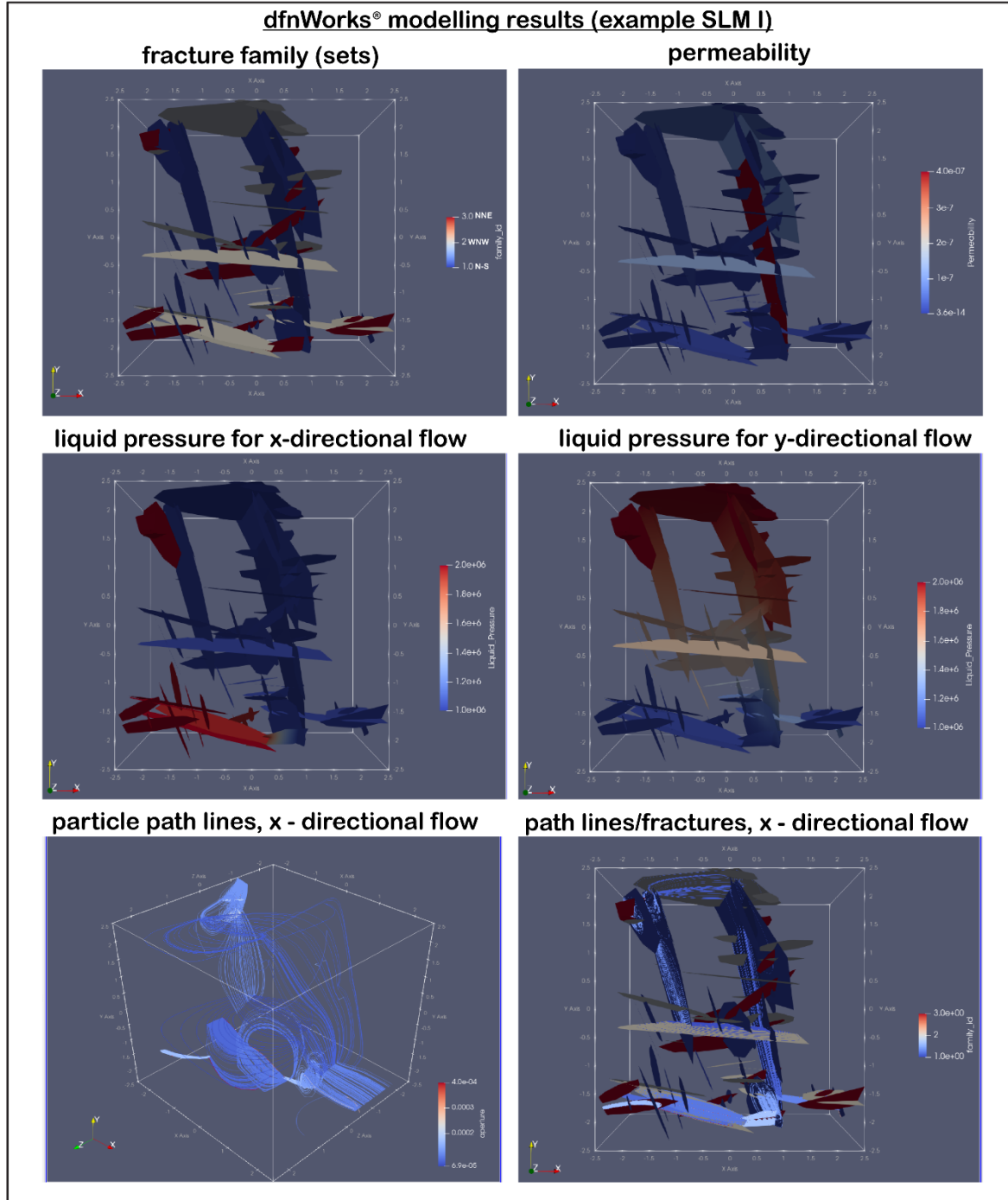


Figure 4.4 Visual output from dfnWorks for SLM I shown: a) fracture sets. b) permeability of individual fractures. c) liquid pressure, when flow is imposed from west to east for effkxx computation. d) liquid pressure, when flow is imposed from north to south for effkyy computation. d) and e) path lines shown for particles flowing east to west for the network of fractures; only 200 particles are shown here.

4.3.1 Discrete Fracture Network Modelling results

The DFN model with domain size 5m x 5m x 5m, generated the following output.

1. For SLM II, 300 fractures were generated within the domain, 253 truncated to fit the domain, total surface area of fractures, 868.29 m², total fracture density (P30), 2.4 m⁻²,

total fracture intensity, P32, 6.94 m^{-1} . The final number of fractures were 217, after 83 isolated fractures were removed from the network.

2. For SLM I, 300 fractures were generated within the domain, 116 truncated to fit the domain, total surface area of fractures, 388.4 m^2 , total fracture density (P30), 2.4 m^{-2} , total fracture intensity, P32, 3.10 m^{-1} . The final number of fractures were 82, after 218 isolated fractures were removed from the network.
3. For PBC, 300 fractures were generated within the domain, 123 truncated to fit the domain, total surface area of fractures, 390.19 m^2 , total fracture density (P30), 2.4 m^{-2} , total fracture intensity, P32, 3.12 m^{-1} . The final number of fractures were 58, after 242 isolated fractures were removed from the network.
4. For ILM, 600 fractures were generated within the domain, 218 truncated to fit the domain, total surface area of fractures, 697.81 m^2 , total fracture density (P30), 4.8 m^{-2} , total fracture intensity, P32, 5.58 m^{-1} . The final number of fractures was 259, after 341 isolated fractures were removed from the network.

4.3.2 Effective permeability results

The modelled effective permeability results due to depth-equivalent stresses on $5\text{m} \times 5\text{m} \times 5\text{m}$ DFN models for the SLM II, SLM I, PBC and ILM are presented for two different scenarios. Firstly, for aquifer computation (Figure 4.5; Table 4.5,) and then, for hydrocarbon reservoir (Table 4.6, Figure 4.6). We then compare these results with those computed as open fracture-no stress (Table 4.4).

Below, we focus on the results obtained at 500m the aquifer model with depth-equivalent stresses (Table 4.6, Figure 4.6) and compare them with unstressed-open fracture DFN models computed in dfnWork ®. (Table 4.4).

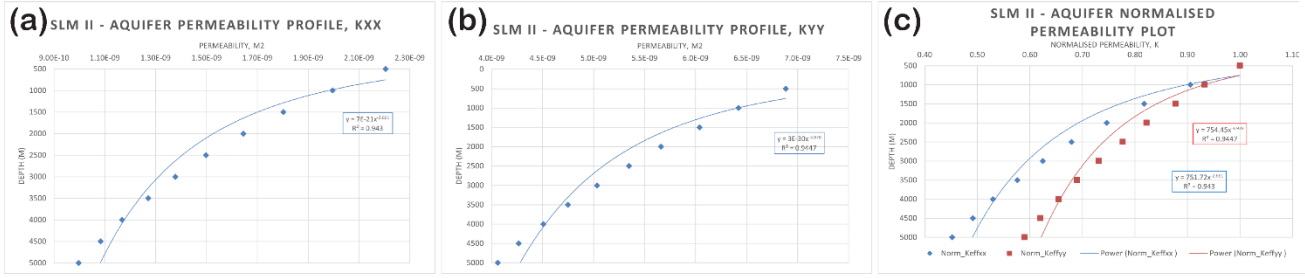
1. For SLM II, effective permeability results of $1.40\text{E}+06 \text{ mD}$, K_{xx} and $1.55\text{E}+07 \text{ mD}$, k_{yy} were achieved for the unstressed DFN with open fractures, and $2.23\text{E}+06 \text{ mD}$, k_{xx} and $6.98\text{E}+06 \text{ mD}$, for the stressed aperture DFN models. We observe a reverse in permeability anisotropy, with a permeability ratio from unstressed DFN with open fractures, 11.07, to a permeability ratio of 3.12 at a depth of 500m. Applied in-stresses at this depth were 13.24 MPa, 10 MPa, and 7.58 MPa, for S_v , S_{Hmax} and S_{Hmin} , respectively. Moving average diagram for the affected fracture sets, are shown in Figure 4. 5.

2. For SLM I, effective permeability results of $7.32\text{E}+04$ mD, K_{xx} and $5.90\text{E}+04$ mD, k_{yy} were achieved for the unstressed DFN with open fractures, and $4.22\text{E}-01$ mD, k_{xx} and $8.16\text{E}+04$ mD, for the stressed aperture DFN models. We see a marked increase in permeability anisotropy, with a permeability ratio of 1.24, to an outrageously large value in the order of $1.9\text{E}+06$, for the simulation at a depth of 500m, for the stressed aperture DFN models. Applied in-stresses at this depth were, 13.24 MPa, 10 MPa, and 7.58 MPa, for S_v , S_{Hmax} and S_{Hmin} , respectively. Moving average diagram for the affected fracture sets, are shown in Figure 4. 5b. The same applied in-stresses, as above, were applied. Moving average diagram for the affected fracture sets, are shown in Figure 4.5.
3. For PBC, effective permeability results of $2.26\text{E}+03$ mD, K_{xx} and $5.08\text{E}+03$ mD, k_{yy} were achieved for the unstressed DFN with open fractures, and $2.40\text{E}+02$ mD, k_{xx} and $1.34\text{E}+03$ mD, for the stressed aperture DFN models. We observe an increase in permeability anisotropy, with a permeability ratio from unstressed DFN, with open fractures, at 2.25, to a permeability ratio of 3.93 at a depth of 500m. The same applied in-stresses, as above were applied. Moving average diagram for the affected fracture sets, are shown in Figure 4.5.
4. For ILM, effective permeability results of $6.49\text{E}+04$ mD, K_{xx} and $1.85\text{E}+04$ mD, k_{yy} were achieved for the unstressed DFN with open fractures, and $5.90\text{E}+03$ mD, k_{xx} and $4.29\text{E}+02$ mD, for the stressed aperture DFN models. We observe an increase in permeability anisotropy, with a permeability ratio from unstressed DFN, with open fractures, at 3.51 (Table 4.4), to a permeability ratio of 13.74 (Table 4.5) at a depth of 500m. The same applied in-stresses, as above were applied. Moving average diagram for the affected fracture sets, are shown in Figure 4. 5.

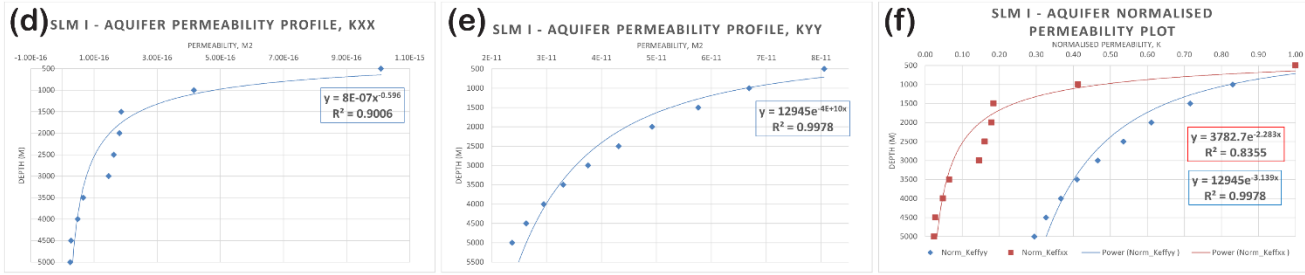
Table 4.4 Effective permeability output from unstressed, dfnWorks

Unstressed DFN models (Open fractures)				
Study Area	ILM	PBC	SLM I	SLM II
Volumes	5m	5m	5m	5m
Max Permeability (mD)	4.96E+08	4.05E+08	4.56E+08	8.11E+09
Effective perm K_{xx} (mD)	6.49E+04	2.26E+03	7.32E+04	1.40E+06
Effective perm K_{yy} (mD)	1.85E+04	5.08E+03	5.90E+04	1.55E+07
Effect Perm 2D horizontal permeability tensor	3.51	2.25	1.24	11.07

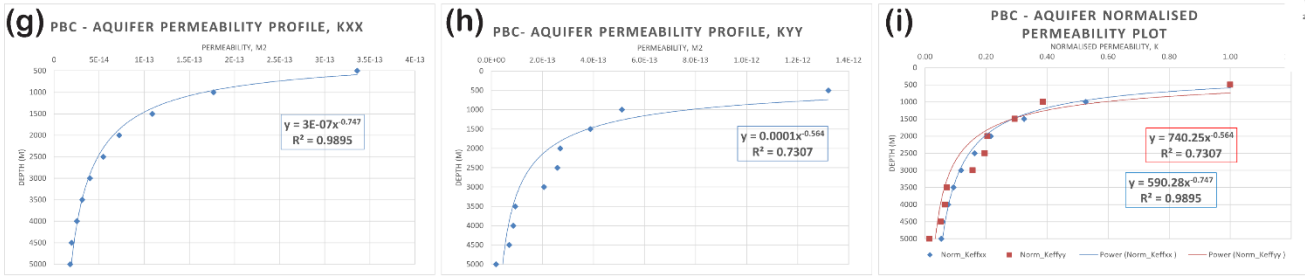
SLM II



SLM I



PBC



ILM

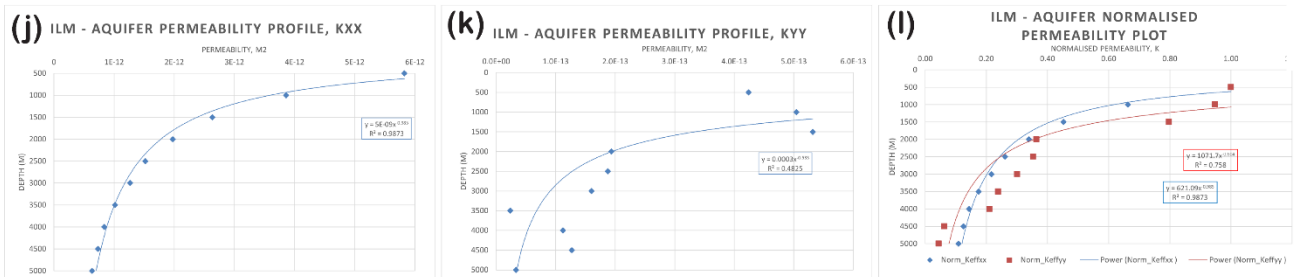
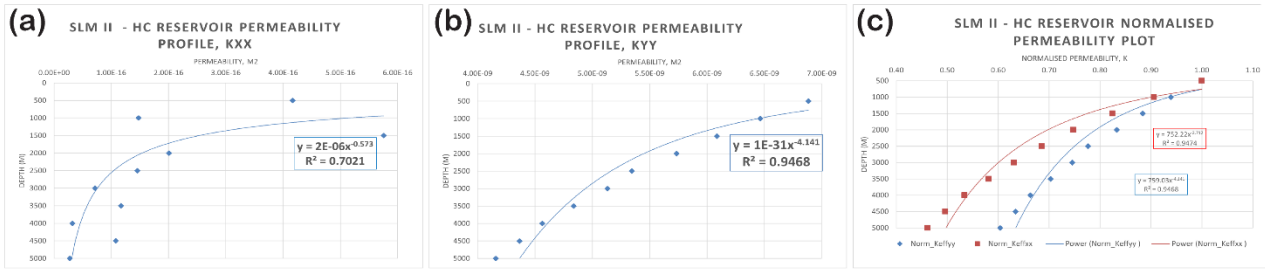
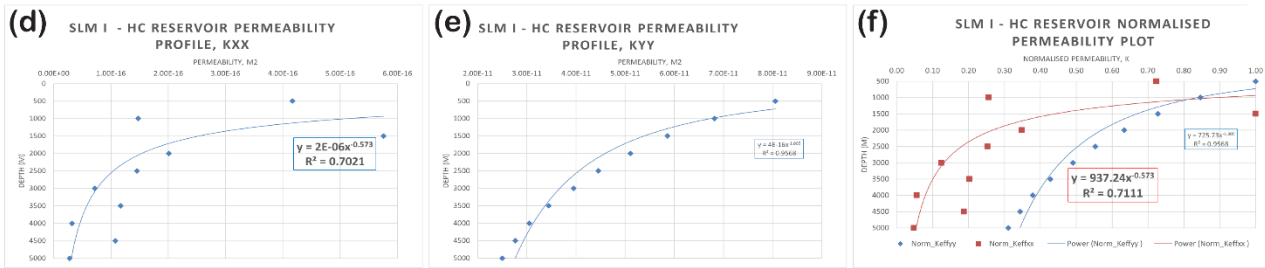


Figure 4.5 a) SLM II: Aquifer permeability profile, effkxx, b) Aquifer permeability profile, effkyy, c) Normalised aquifer permeability profile, effkxx, effkyy; SLM I: d) Aquifer permeability profile, effkxx, e) Aquifer permeability profile, effkyy, f) Normalised aquifer permeability profile, effkxx, effkyy; PBC: g) Aquifer permeability profile, effkxx, h) Aquifer permeability profile, effkyy, i) Normalised aquifer permeability profile, effkxx, effkyy; ILM: j) Aquifer permeability profile, effkxx, k) Aquifer permeability profile, effkyy, l) Normalised aquifer permeability profile, effkxx, effkyy;

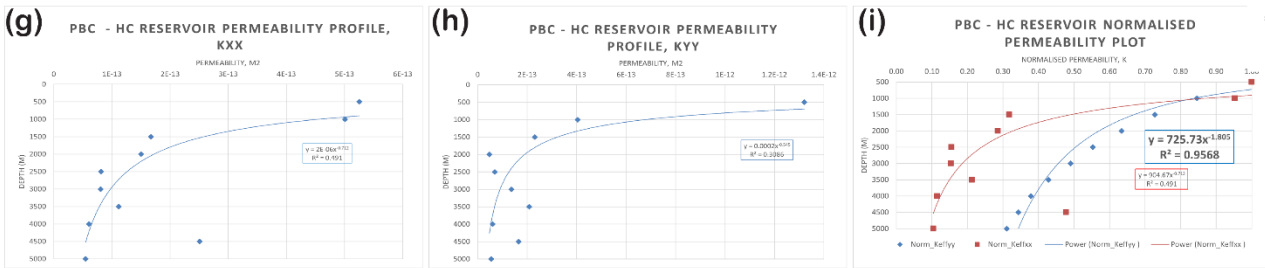
SLM II



SLM I



PBC



ILM

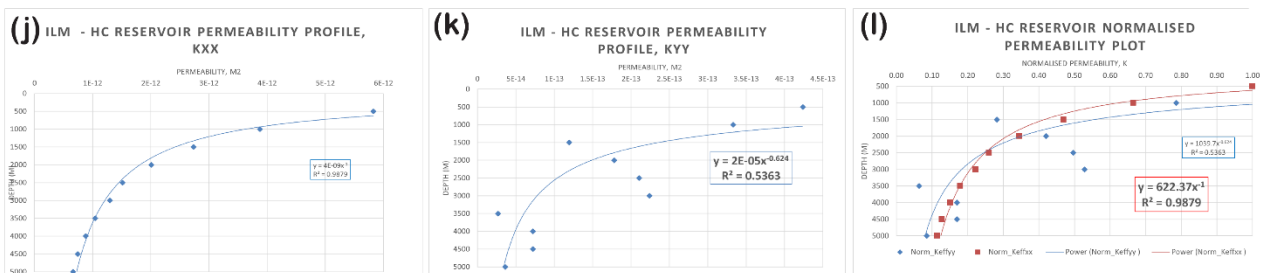


Figure 4.6 SLM II: Hydrocarbon reservoir permeability profile, effkxx, b) Reservoir permeability profile, effkyy, c) Normalized reservoir permeability profile, effkxx, effkyy; SLM I: d) Reservoir permeability profile, effkxx, e) Reservoir permeability profile, effkyy, f) Normalized reservoir permeability profile, effkxx, effkyy; PBC: g) Reservoir permeability profile, effkxx, h) Reservoir permeability profile, effkyy, i) Normalized reservoir permeability profile, effkxx, effkyy; ILM: j) Reservoir permeability profile, effkxx, k) Reservoir permeability profile, effkyy, l) Normalized reservoir permeability profile, effkxx, effkyy

Aquifer										
	Depth (m)	Pp (Mpa)	Sv	Shmax (Mpa)	Shmin (Mpa)	Keffxx (m ²)	Keffyy (m ²)	Keffxx mD	Keffyy mD	2D Perm ratio
SLM I	500	4.905	13.24	10.41	7.577	4.17E-16	8.06E-11	4.22E-01	8.16E+04	193421
	1000	9.81	26.5	20.83	15.16	1.47E-16	6.69E-11	1.48E-01	6.78E+04	456461
	1500	14.715	39.75	31.25	22.74	1.01E-15	5.76E-11	1.02E+00	5.84E+04	57129
	2000	19.62	53	41.66	30.32	5.96E-17	4.92E-11	6.04E-02	4.99E+04	825486
	2500	24.525	66.25	52.07	37.895	1.62E-16	4.31E-11	1.64E-01	4.37E+04	265784
	3000	29.43	79.5	62.49	45.48	1.86E-16	3.75E-11	1.89E-01	3.80E+04	201575
	3500	34.335	92.75	72.9	53.055	6.55E-17	3.30E-11	6.64E-02	3.35E+04	504115
	4000	39.24	106	83.32	60.64	4.85E-17	2.95E-11	4.92E-02	2.99E+04	607789
	4500	44.145	119.25	93.73	68.215	2.43E-17	2.63E-11	2.47E-02	2.66E+04	1079331
	5000	49.05	132.5	104.15	75.4	2.74E-17	2.37E-11	2.78E-02	2.41E+04	866368
SLM II	500	4.905	13.24	10.41	7.577	2.21E-09	6.88E-09	2.23E+06	6.98E+06	3.12
	1000	9.81	26.5	20.83	15.16	2.00E-09	6.42E-09	2.02E+06	6.51E+06	3.22
	1500	14.715	39.75	31.25	22.74	1.80E-09	6.04E-09	1.83E+06	6.12E+06	3.35
	2000	19.62	53	41.66	30.32	1.65E-09	5.66E-09	1.67E+06	5.74E+06	3.44
	2500	24.525	66.25	52.07	37.895	1.50E-09	5.35E-09	1.52E+06	5.42E+06	3.57
	3000	29.43	79.5	62.49	45.48	1.38E-09	5.03E-09	1.40E+06	5.10E+06	3.65
	3500	34.335	92.75	72.9	53.055	1.27E-09	4.75E-09	1.29E+06	4.81E+06	3.74
	4000	39.24	106	83.32	60.64	1.17E-09	4.51E-09	1.18E+06	4.57E+06	3.86
	4500	44.145	119.25	93.73	68.215	1.08E-09	4.27E-09	1.10E+06	4.32E+06	3.94
	5000	49.05	132.5	104.15	75.4	9.96E-10	4.06E-09	1.01E+06	4.12E+06	4.08
PBC	500	4.905	13.24	10.41	7.577	3.36E-13	1.32E-12	3.40E+02	1.34E+03	3.93
	1000	9.81	26.5	20.83	15.16	1.77E-13	5.12E-13	1.79E+02	5.18E+02	2.89
	1500	14.715	39.75	31.25	22.74	1.09E-13	2.58E-13	1.10E+02	2.62E+02	2.37
	2000	19.62	53	41.66	30.32	7.22E-14	1.88E-14	7.32E+01	1.90E+01	3.84
	2500	24.525	66.25	52.07	37.895	5.46E-14	2.06E-13	5.53E+01	2.09E+02	3.78
	3000	29.43	79.5	62.49	45.48	3.97E-14	9.40E-14	4.02E+01	9.53E+01	2.37
	3500	34.335	92.75	72.9	53.055	3.12E-14	2.70E-13	3.16E+01	2.74E+02	8.65
	4000	39.24	106	83.32	60.64	2.54E-14	3.88E-13	2.58E+01	3.93E+02	15.25
	4500	44.145	119.25	93.73	68.215	1.94E-14	8.63E-14	1.97E+01	8.74E+01	4.45
	5000	49.05	132.5	104.15	75.4	1.79E-14	6.95E-14	1.81E+01	7.05E+01	3.89
ILM	500	4.905	13.24	10.41	7.577	5.83E-12	4.24E-13	5.90E+03	4.30E+02	13.74
	1000	9.81	26.5	20.83	15.16	3.86E-12	5.04E-13	3.91E+03	5.11E+02	7.66
	1500	14.715	39.75	31.25	22.74	2.63E-12	5.32E-13	2.67E+03	5.39E+02	4.95
	2000	19.62	53	41.66	30.32	1.98E-12	1.94E-13	2.00E+03	1.96E+02	10.21
	2500	24.525	66.25	52.07	37.895	1.52E-12	1.88E-13	1.54E+03	1.90E+02	8.09
	3000	29.43	79.5	62.49	45.48	1.26E-12	1.60E-13	1.28E+03	1.62E+02	7.89
	3500	34.335	92.75	72.9	53.055	1.02E-12	2.38E-14	1.03E+03	2.41E+01	42.79
	4000	39.24	106	83.32	60.64	8.37E-13	1.12E-13	8.48E+02	1.14E+02	7.46
	4500	44.145	119.25	93.73	68.215	7.31E-13	1.27E-13	7.41E+02	1.29E+02	5.76
	5000	49.05	132.5	104.15	75.4	6.35E-13	3.34E-14	6.44E+02	3.39E+01	18.99

Table 4.5 Summary table: Aquifer stressed model permeability computation, dfnWorks

Hydrocarbon reservoir										
	Depth (m)	Pp (Mpa)	Sv (Mpa)	Shmax (Mpa)	Shmin (Mpa)	Keffx m ²	Keffy m ²	Keffxx mD	Keffyy mD	2D Perm ellipse
SLM I	500	4.29	13.24	10.2	7.16	4.17E-16	8.06E-11	4.22E-01	8.16E+04	193421
	1000	8.6	26.48	20.4	14.32	1.47E-16	6.82E-11	1.49E-01	6.91E+04	462240
	1500	12.87	39.72	30.6	21.48	5.76E-16	5.86E-11	5.83E-01	5.94E+04	101784
	2000	17.2	52.96	40.8	28.63	2.01E-16	5.11E-11	2.03E-01	5.17E+04	254213
	2500	21.45	66.2	51	35.8	1.46E-16	4.45E-11	1.47E-01	4.51E+04	306104
	3000	25.8	79.44	61.2	42.95	7.17E-17	3.95E-11	7.26E-02	4.00E+04	551538
	3500	30.03	92.68	71.4	50.11	1.17E-16	3.45E-11	1.19E-01	3.49E+04	294655
	4000	34.4	105.92	82.4	58.8	3.20E-17	3.05E-11	3.25E-02	3.09E+04	952056
	4500	38.73	119.16	91.8	64.51	1.08E-16	2.77E-11	1.09E-01	2.80E+04	256325
	5000	43	132.4	102	71.6	2.77E-17	2.50E-11	2.81E-02	2.54E+04	903193
SLM II	500	4.29	13.24	10.2	7.16	2.21E-09	6.88E-09	2.23E+06	6.98E+06	3.12
	1000	8.6	26.48	20.4	14.32	2.00E-09	6.46E-09	2.02E+06	6.55E+06	3.24
	1500	12.87	39.72	30.6	21.48	1.82E-09	6.09E-09	1.84E+06	6.17E+06	3.35
	2000	17.2	52.96	40.8	28.63	1.65E-09	5.73E-09	1.67E+06	5.81E+06	3.48
	2500	21.45	66.2	51	35.8	1.51E-09	5.35E-09	1.53E+06	5.42E+06	3.54
	3000	25.8	79.44	61.2	42.95	1.39E-09	5.13E-09	1.41E+06	5.20E+06	3.69
	3500	30.03	92.68	71.4	50.11	1.28E-09	4.84E-09	1.30E+06	4.90E+06	3.77
	4000	34.4	105.92	82.4	58.8	1.18E-09	4.56E-09	1.19E+06	4.62E+06	3.88
	4500	38.73	119.16	91.8	64.51	1.09E-09	4.37E-09	1.11E+06	4.42E+06	3.99
	5000	43	132.4	102	71.6	1.02E-09	4.16E-09	1.03E+06	4.21E+06	4.09
PBC	500	4.29	13.24	10.2	7.16	3.60E-13	1.32E-12	3.65E+02	1.34E+03	3.67
	1000	8.6	26.48	20.4	14.32	1.77E-13	5.12E-13	1.79E+02	5.18E+02	2.89
	1500	12.87	39.72	30.6	21.48	1.11E-13	2.62E-13	1.12E+02	2.65E+02	2.36
	2000	17.2	52.96	40.8	28.63	7.22E-14	1.94E-14	7.32E+01	1.97E+01	3.72
	2500	21.45	66.2	51	35.8	5.47E-14	2.06E-13	5.54E+01	2.09E+02	3.77
	3000	25.8	79.44	61.2	42.95	3.98E-14	9.50E-14	4.03E+01	9.63E+01	2.39
	3500	30.03	92.68	71.4	50.11	3.13E-14	2.79E-13	3.17E+01	2.83E+02	8.91
	4000	34.4	105.92	82.4	58.8	2.55E-14	3.93E-13	2.58E+01	3.98E+02	15.42
	4500	38.73	119.16	91.8	64.51	1.95E-14	8.73E-14	1.98E+01	8.85E+01	4.48
	5000	43	132.4	102	71.6	1.87E-14	6.95E-14	1.89E+01	7.05E+01	3.72
ILM	500	4.29	13.24	10.2	7.16	5.83E-12	4.24E-13	5.90E+03	4.30E+02	13.74
	1000	8.6	26.48	20.4	14.32	3.88E-12	3.33E-13	3.93E+03	3.37E+02	11.63
	1500	12.87	39.72	30.6	21.48	2.74E-12	1.19E-13	2.77E+03	1.21E+02	22.90
	2000	17.2	52.96	40.8	28.63	2.01E-12	1.78E-13	2.04E+03	1.80E+02	11.28
	2500	21.45	66.2	51	35.8	1.52E-12	2.11E-13	1.54E+03	2.13E+02	7.20
	3000	25.8	79.44	61.2	42.95	1.30E-12	2.24E-13	1.31E+03	2.27E+02	5.78
	3500	30.03	92.68	71.4	50.11	1.04E-12	2.69E-14	1.06E+03	2.73E+01	38.80
	4000	34.4	105.92	82.4	58.8	8.82E-13	7.22E-14	8.94E+02	7.31E+01	12.22
	4500	38.73	119.16	91.8	64.51	7.44E-13	7.22E-14	7.54E+02	7.31E+01	10.31
	5000	43	132.4	102	71.6	6.64E-13	3.61E-14	6.73E+02	3.66E+01	18.37

Table 4.6 Summary table: HC reservoir stressed model permeability computation, dfnWorks

4.3.3 Solute transport simulation results

Due to time constraints and the dfnWorks code undergoing continuous development to eliminate bugs, we are able to present the result of two non-reactive solute transport simulation. We focused on the well-layered, SLM II and the amalgamated beds oolitic-SLM I outcrop. Since the Viggiano Mt. Aquifer has a depth of approximately 500m, we focus on the results at that depth.

The results of the solute transport simulation for SLM II and SLM I are presented in form of a graph showing, firstly, the cumulative number of particles that outputted the system against their breakthrough time (Figure 4.7a, b), and then for the cumulative number of particles against the distance travelled by each particle (Figure 4.7c, d). These results are shown for both unstressed DFN models and stressed DFN models for each outcrop, in the x-direction and then in y-direction.

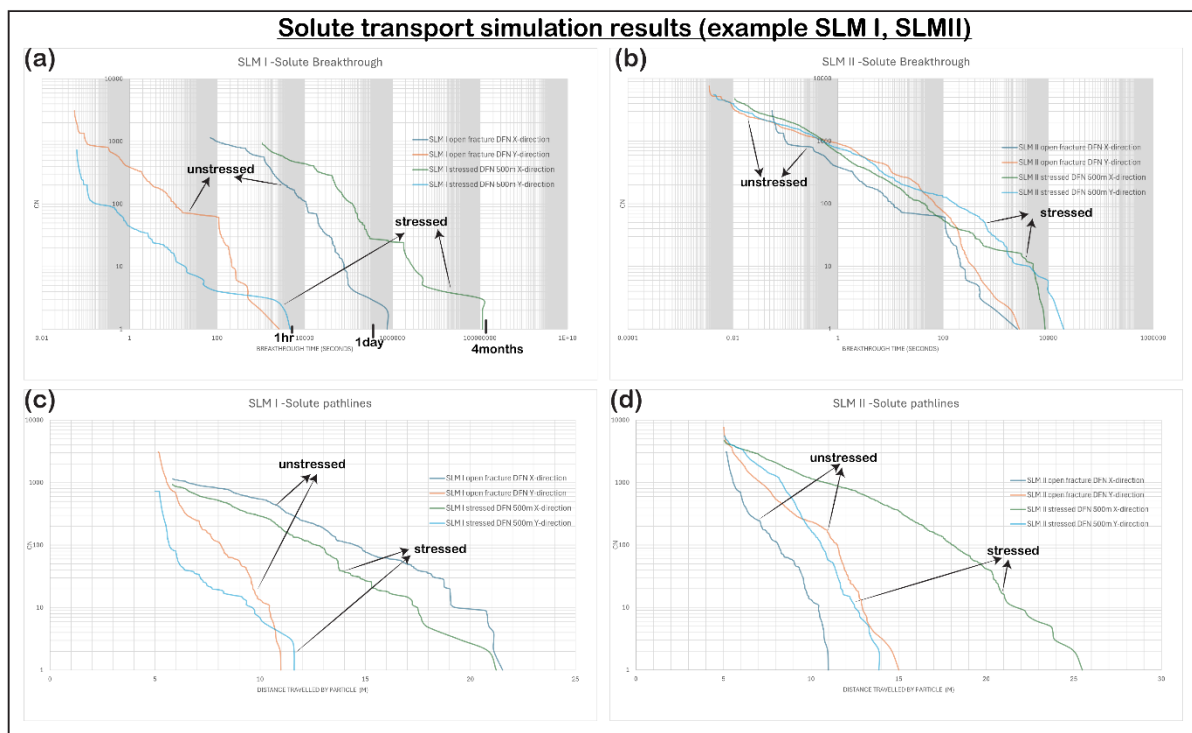


Figure 4.7 Output from solute transport simulation a) particles breakthrough: No of particles Vs. breakthrough time in seconds and c) solute pathlines: No of particles Vs. distance travelled by each particle, SLM I; b) particles breakthrough and d) solute pathlines, SLM II.

For SLM II, the stressed DFN case, characterized by increase a slight increase in k_{xx} , and reduction in k_{yy} permeability (chapter 4.3.2), as compared to the unstressed case is marked by an overall delay in the delivery of some particles exiting the system (Figure 4.7b). This result

is highlighted by more tortuosity, i.e., the particle taking longer paths to exit the system, Figure 4.7d).

For the SLM I, the stressed DFN case, characterised by increase a slight increase in k_{xx} , and reduction in k_{yy} permeability (chapter 4.3.2), as compared to the unstressed case is marked by an overall delay in the delivery of some particles exiting the system (Figure 4.7b). This result is highlighted by more tortuosity, i.e., the particle taking longer paths to exit the system, Figure 4.7d).

For SLM II, the results are quite opposite such that, the stressed DFN case is characterised by a major decrease in k_{xx} , and a slight increase in k_{yy} permeability (chapter 4.3.2), relative to the unstressed case, leading to high permeability anisotropy ratio. This result is marked by an overall discrepancy in the delivery of some particles, x-, and y directions, in the stressed DFN model. There, we see a delay in the delivery of particles in the x-direction due to the massive reduction in permeability (Figure 4.7a). The corresponding distance travelled by the particles are shown (Figure 4.7c).

4.4 Discussion

Near isotropic horizontal permeability ratios, similar to those computed in chapter 3 have been also documented from Discrete Fracture Network modelling of fractured carbonate rocks exposed along the axial zone of the Southern Apennines fold and thrust belt (Giuffrida et al., 2019; 2020). The results of which were obtained after modelling performed by the application of real aperture values collected during field investigations. The question remains, are these aperture values reflective of what is seen in the subsurface? Since they have a huge impact on assessed permeability anisotropy. This section discusses the results obtained from this research work, assessing the impact in-situ stresses has on with on the closure/dilation of fracture aperture and by implication, effective permeability on a 3D-network of fractures. To support the discussion, changes to flow fluid and flow dynamics from non-reactive transport simulation are also assessed.

4.4.1. Permeability anisotropy in open fracture DFN models and stressed DFN models

Is hydraulic fracture aperture totally lost at depth? What impact does it have on effective permeability? To what degree is the effective permeability lost or gained at the Viggiano mt. aquifer-depth of 500m? Is the isotropic permeability ratio maintained or lost with depth?

These are the motivating factors that fuelled our interest in this research work at the HAV Basin of southern Italy. Focusing on the contribution provided by meso-scale fractures to the hydraulic properties of the Viggiano Mt. aquifer, our results allow us to infer the behaviour fractured carbonates at depth.

Two scenarios are considered in this discussion. Firstly, assessed permeability anisotropy ratio from the modelled DFNs representative of SLM I, ILM and PBC, which tends to be elongated as a function of applied stresses (chapter 4.3.2, Tables 4.4, 4.5 and 4.6) and secondly, assessed permeability anisotropy ratio results from modelled DFN representative of SLM II, where the permeability anisotropy ratio reduces drastically as a function of stress.

According to the first scenario, flow is drastically reduced in pathways oriented normal to the principal stress axis, if not closed, relative to others, hence leading to enhanced anisotropy (Zhang and Sanderson, 1996, Min et al., 2004; Baghbanan and Jing, 2008; Latham et al., 2012; Zhao et al., 2013; Hyman, 2020). Hence, flow anisotropy is mainly attributed to the angle formed between flow direction (open fractures) and major compressive principal stress directions. This partial reduction/closure of selected paths can lead to delay in breakthrough of solute particles travelling through the network, as shown in Figure 4.7a, for the x-direction. In cases where fracture aperture is completely occluded, hence closure of pathways, solute particles are forced to re-route through separate paths, sometimes longer or in some cases short (Zhao et al., 2012; Sweeney et al., 2020; Hyman, 2020; Figure 4.7c). The question of which fracture path will conduct, and which pathway wouldn't depend on the orientation of the stress axis, the geometry of each individual fracture, and their connectivity (Baghbanan and Jing, 2008; Bisdom et al., 2016; Igbokwe et al., 2024).

SLM I, which is modelled with three main fracture sets N-S, NE-SW and WNW-ESE is considered (Figure 4.4; inset of Figure 4.5). The principal stress axis is vertical hence, all sub-vertical fractures will experience tensional effects. S₂, being relatively high will have a dilational effect on the N-S fracture, since it is oriented in the same direction. Differently, minimal horizontal confining effect will be provided by S₃ in an attempt to close aperture related to the N-S fracture. Hence, a marked increase in permeability in the y-direction, from an unstressed model with 5.90E+04 mD, to the stressed model with 8.16E+04 mD.

Another factor that affects the effective permeability of a fracture network is the trace length of fracture. Using the same SLM I DFN model, WNW-ESE set of fractures, oriented almost normal to S₂, experiences drastic reduction in effective permeability, K_{effx} from 7.32E+04

mD in an unstressed DFN, to $4.22\text{E-}01$ mD in a stressed DFN model due to the effect of normal loading (Koyama et al., 2008). This has been explained by the work of Baghbanan and Jing. (2008), who considered the case of distributed aperture as a function of fracture-trace-length to study the effect of stress on permeability and flow pattern and discovered that in a system with high stress ratio such as ours, overall permeability and flow patterns are controlled by the combination of highly conductive large-scale fractures and fractures with shear slipping and dilation. In certain cases, breakthrough of particles might be delayed due to low velocity zones within the network (Sweeney et al., 2020) as seen in Figure 4.4c, for the flow in x-direction, and its effect on the behaviour is SLM I unstressed DFN with flow in the x-direction (Figure 4.7a) and the long tailing behaviour in solute travel path (Figure 4.7c).

According to the second scenario, the fracture network exhibits a decrease in permeability anisotropy as a function of applied stresses at a depth of 500m, SLMII relative to the case of an unstressed DFN model (Figure 4.5, Figure 4.7). The SLMII, which are well-layered carbonates with SB fractures confined within mechanical interfaces and, NSB fractures that cut across are modelled with four main fracture sets, WNW-ESE, N-S, NNE-SSW, E-W. This system of fractures when subjected to 500m depth equivalent stresses exhibit reverse anisotropic behaviour. With marked increase in permeability value from $1.40\text{E}+06$ mD, K_{xx} to $2.23\text{E}+06$ mD, k_{xx} , and reduction in permeability, $1.55\text{E}+07$ mD, k_{yy} to $6.98\text{E}+06$ mD, the network of fractures behave in a non-linear manner, meaning while there was an increase dilation in aperture of fractures oriented in the x-direction, the y-direction was marked a 1-order reduction in permeability. This non-linear behaviour of permeability as a function of aperture closure or dilation is documented for highly connected system of fractures subjected to both normal and shear stresses (Vilarrasa et al., 2011; Huang et al., 2019; Liu et al., 2022).

4.4.2 Effective permeability-depth correlations

The effective permeability results from all the stressed-DFN models (Figures 4.5, 4.6) show two different trends. Firstly, a relatively significant loss in permeability up to depth $\sim 2000\text{m}$ and then slow decline (Figures 4.5d, 4.5g, 4.5h, 4.6a, 4.6d, 4.6h), and secondly, consistent decline in modelled effective permeability with depth for the entire plot (Figures 4.5a, 4.5b, 4.5e, 4.5g). Overall, permeability declines with respect to depth (Louis, 1974; Brace, 1980; Manning and Ingebritsen, 1999; Shmonov et al., 2003; Stober and Bucher, 2007; Ingebritsen and Manning, 2010; Stober, 2011; Song et al., 2024).

Our permeability-depth profiles show quite strong coherence with the power law model (Bredehoeft et al., 1983, 1992, 1994; Manning and Ingebritsen, 1999; Ingebritsen and Manning, 2002; Stober and Bucher, 2007; Ingebritsen and Manning, 2010) with regression ranging from $R^2 = 0.70$ – $R^2 = 0.99$ (Figures 4.5a, 4.5b, 4.5d, 4.5e, 4.5j), the exception being, the DFN models (Figures 4.5k, 4.6g, 4.6h, 4.6k) with irregularities. Here, we infer sudden increase in effective permeability at certain depths due to dilation of critically oriented fractures as a function of shear displacement and hence opening of new fluid pathways. These permeability models are of importance as they are adopted for crustal-scale numerical models for fluids flow especially in groundwater studies (Belitz and Bredehoeft, 1988; Bredehoeft et al., 1992, 1994; Cardenas and Jiang, 2010; Jiang et al., 2010a; Jiang et al., 2011; Wang et al., 2011; Zlotnik et al., 2011). In an ideal system, with perfectly coupled hydro-mechanical properties, a permeability-depth (or stress) plot can also be used to compute fracture normal stiffness (Jiang et al., 2008, 2009; Zimmerman et al., 2008; Li et al., 2021).

4.5 Conclusion

Aimed at investigating the effects of in-situ stresses on permeability anisotropy in fractured carbonate aquifers through numerical simulations. This study focused on the effects of fracture aperture closure/dilation as a function of normal/shear stresses and how it affects effective permeability computation at depth. The study adopts existing data input (Chapter 3) collected from Mesozoic shallow-water carbonates flanking eastern side of High Agri Valley Basin, southern Italy. The units comprise of,

- i) Scarrone la Macchia I, (SLM I), Toarcian oolitic carbonates characterized by bed amalgamation originally formed in a ramp setting rimmed by oolitic sand shoals.
- ii) Scarrone La Macchia II, (SLM II), well-layered, Sinemurian–Pleinsbachian carbonate succession of wackestone-packstones to grainstones arranged in discrete bed packages originally deposited in a low-energy, open lagoon environment.
- iii) Piana del Buon Cuore (PBC), Lower Cretaceous - Upper Jurassic limestones whose clasts consist of oolites, oncolites and intraclasts deposited in a high-energy platform margin environment.
- iv) The Il Monte (ILM), massive, amalgamated, Cretaceous carbonate rudstones and grainstones originally deposited along the paleo-slope of the carbonate platform.

With a focus on computing effective permeability values, k_{effxx} , k_{effyy} , and assessing the permeability anisotropy ratios of the fractured rocks at the bed-package scale, 5m-side Discrete

Fracture Network (DFN) models are built representative of the four units for both stressed and unstressed fracture networks. For the latter, by modifying the hydraulic aperture values in response to depth-equivalent stresses. The models are built using the high computational code, dfnWorks ® of Los Alamos National laboratory, NM, USA.

Focusing on the results achieved at Viggiano mt.-aquifer-depth of 500m, coupled with equivalent stresses of ~13MPa, 10 MPa, and 7.58 MPa, σ_v , σ_{Hmax} , σ_{Hmin} , respectively, and comparing with the scenario of unstressed-open fracture-DFN models, effective permeability results from SLM I, PBC, ILM exhibit an increase in permeability anisotropy ratio as a function of the stresses, hence, supporting flow channelling within the network. Lagrangian solute transport simulation supports the afore-mentioned results by marked changes in primary flow path, increase in path tortuosity, as a function of stress, and delay in breakthrough time.

Differently, SLM II undergoes the opposite effect, where the permeability anisotropy ratio reduces drastically at a depth of 500m and stabilizes after that. We infer this behaviour as due to non-linear behaviour of effective permeability as a function of aperture closure or dilation, as seen sometimes in a highly connected system of fractures that are subjected to both normal and shear stresses, characterized by combined closure due to normal stresses and opening of previously closed flow-paths due to shear-dilation effect.

This research highlights the complex behaviour of permeability anisotropy in fractured carbonate rocks in response to depth-equivalent stresses, and the importance of building realistic hydro-geomechanically-DFN models to estimate fluid-flow and storage properties of fractured rocks at depth. It finds application not only in the study of groundwater contamination and remediation, but also to the hydrocarbon extraction, nuclear waste disposal, hydraulic fracturing, induced seismicity, CCS and geothermal energy development.

CHAPTER 5 – CONCLUSION

Aimed at gaining insights into the non-negligible contribution of mesoscale faults and fractures to fracture porosity and equivalent permeability within carbonates aquifers, the main goals of the doctoral research carried out in the last three years of activity were the following:

- (1) assess the influence exerted by the high-angle basin bounding faults on carbonate lithofacies, geometry and distribution of fractures across different scales, from outcrop to reservoir scale (Chapter 2).

(2) assess the control exerted by mesoscale structural elements on the storage and transport properties of fractured carbonates; and to investigate the variation in computed values of fracture equivalent permeability and flow anisotropy throughout the carbonate succession (chapter 3 and Appendix A).

(3) Assess the interaction between in-situ stress, effective permeability, and solute transport in complex and highly connected system of fractures (Chapter 4).

This work focused on the multiscale structural analyses of Mesozoic shallow-water carbonates flanking eastern side of High Agri Valley Basin, lying along the axial zone of the southern Apennines fold and thrust belt of southern Italy. The units comprise the following stratigraphic units:

- Scarrone la Macchia I, (SLM I), Toarcian oolitic carbonates characterized by bed amalgamation originally formed in a ramp setting rimmed by oolitic sand shoals.
- Scarrone La Macchia II, (SLM II), well-layered, Sinemurian–Pleinsbachian carbonate succession of wackestone-packstones to grainstones arranged in discrete bed packages, that were originally deposited in a low-energy, open lagoon environment.
- Piana del Buon Cuore (PBC), Lower Cretaceous - Upper Jurassic limestones whose clasts consist of oolites, oncolites and intraclasts deposited in a high-energy platform margin environment.
- The Il Monte (ILM), massive, amalgamated, Cretaceous carbonate rudstones and grainstones originally deposited along the paleo-slope of the carbonate platform.

Taking advantage of the exposures, we conducted integrated field and digital structural analyses to fully assess the nature, geometry, and multiscale distribution of high-angle fractures and faults dissecting the shallow-water carbonates. The results of this work were discussed to decipher the possible control exerted by carbonate lithologies and scales of observation on the afore-mentioned structural elements. The results of the work led to the following conclusions.

In terms of fracture geometry, via field investigation we identified a diffuse network of high-angle fractures majorly comprised of WNW-ESE, N-S, NNE-SSW, and E-W striking sets whose multiscale spacing distributions were negative exponential. Two minor sets striking NW-SE and NE-SW were also documented. At specific outcrops, we also computed power law spacing distributions, with D-values ranging from 0.42 (N-S set at SLM II) and 0.49 (NNE-

SSW set at SLM I) to 0.58 (WNW-ESE set at ILM), and 0.65 (NE-SW set at PBC). The latter data were interpreted as due to fault-related deformation, in which the D-values were consistent with poorly to fairly developed fault zones.

When we considered data collected both in the field ($6\text{ cm} < \text{fracture heights} < 3\text{ m}$) and from digital models ($2.5\text{ m} < \text{fault heights} < 45\text{ m}$), all studied carbonate units showed a geometry-scale dependency. We documented a higher degree of anisotropy at larger scales and interpreted this occurrence as due to strain localization and bias due to source image resolution during digital acquisition along vertical digital outcrop walls. We concluded that the larger-scale digital analysis is more efficient to portray the occurrence of fracture corridors and localized deformation.

Considering any possible control exerted by carbonate lithologies on the fracture properties, the results of field analyses showed a great variation of 1D (P10) and 2D fracture intensity (P21), as well as of 2D fracture density (P20). We noted that the values did not vary with the bed thickness; they were interpreted as due to presence of fracture clusters ($C_v > 1$). Fault growth by shearing along pre-existing fractures, linkage across bed and bed packages interfaces, and formation of new fractures at releasing jogs were invoked as specific deformation mechanisms.

Comparing and contrasting the results achieved after field and digital structural analyses, we computed a P21 scaling factor close to 20. Differently, inconsistent results were gotten for P20 variations. Such a discrepancy was interpreted as due to the deformation mechanism described above and the associated truncation effects (missing fault-related fractures localized at releasing jogs).

The results of the first part of this research work highlighted the importance of traditional field structural analysis to precisely document the amount of fracture density both away and within the carbonate fault damage zones, with important implications for the characterization of the amount of fluid storage within fractured rock volumes. We arrived at the conclusion that the fracture properties change according to the original depositional setting of the shallow-water carbonates, and also to the scales of observation.

Focusing on the contribution of meso-scale fractures and faults, we investigated the variation of computed values of fracture equivalent permeability throughout the carbonate succession. The laterally and vertically continuous carbonate exposures allowed detailed assessment of the nature, geometry, and multiscale distribution of high-angle fracture and fault sets. We then

performed multiscale DFN modelling of geocellular volumes resembling the single carbonate bed-packages (5m-side volumes), outcrops (50m-side volumes) and reservoir (500m-side volumes). The models were built using Move ® geological software package of Petroleum Expert Limited. The single volumes were either considered as individual geocellular units, without any internal subdivision representing amalgamated carbonate beds, or made up of multiple sub-volumes representative of single beds or entire sedimentary units. The geocellular volumes were populated with fractures whose density/intensity, dimensional properties, and multiscale height/length distribution were after integrated results from field structural analyses, for the 5m-side geocellular volumes and 3D photogrammetric modelling, for the 50m and 500m-side geocellular volumes.

Preliminary structural results points to a geometry scale dependency of over 3-order magnitude for the fracture and fault networks crosscutting the carbonates. However, we acknowledge that 2D-like exposure of the SLM cliffs could bias results relating to the Lower Jurassic carbonates. After DFN modelling of the geocellular volumes, our results show the maximum value of fracture porosity (Φ_{max}), vary from 2 % to 0.02 % for the 5 to 500 m-side geocellular volumes, respectively. Hence, these data show the profound control exerted by pervasive smaller scale structural elements (strata bound and non-strata bound fractures) on the storage properties of the shallow-water carbonates.

In terms of computed equivalent permeability, we mainly focused on the results obtained for the horizontal components of the tensor because the employed algorithm does not allow precisely model the baffle/barrier effects provided by bed interfaces. Computed values showed near-isotropic horizontal permeability ellipses for most of the surveyed outcrops. That is, irrespective of the scale of observation, the fracture and fault networks form in plan-view quite isotropic network, although the principal axes for the permeability ellipses vary from site-to-site according to the attitude of the main structural discontinuities. The near isotropic permeability results obtained in our study are similar to previous scenarios computed for fractured carbonate rocks exposed along the axial zone of the Southern Apennines fold and thrust belt. The near isotropic permeability results could be as a result of the severe exhumation the studied carbonates experienced from depths of ~ 4 - 5km during Quaternary uplift and downfaulting of the belt.

All results related to horizontal permeability anisotropies were summarized in a conceptual model illustrating the modalities of meteoric fluid infiltration under vadose conditions, and the subsequent horizontal flow under phreatic conditions at various scales of observation. Our results show that mesoscale heterogeneities in fractured carbonates should not be overlooked

during the reserve estimation processes associated to groundwater management, geothermal energy production, and for those targets for carbon capture and sequestration.

Finally, aimed at investigating the effects of in-situ stresses on permeability anisotropy in fractured carbonate aquifers through numerical simulations. This study focused on the effects of fracture aperture closure/dilation as a function of normal/shear stresses and how it affects effective permeability computation at depth. The study adopts existing data input (Chapter 3) collected from the studied outcrops. With a focus on computing effective permeability values, k_{effxx} , k_{effyy} , and assessing the permeability anisotropy ratios of the fractured rocks at the bed-package scale, 5m-side Discrete Fracture Network (DFN) models are built representative of the four units for both stressed and unstressed fracture networks. For the latter, by modifying the hydraulic aperture values in response to depth-equivalent stresses. The models are built using the high computational code, *dfnWorks*® of Los Alamos National laboratory, NM, USA. Focusing on the results achieved at Viggiano mt.-aquifer-depth of 500m, coupled with equivalent stresses of ~13MPa, 10 MPa, and 7.58 MPa, σ_v , σ_{Hmax} , σ_{Hmin} , respectively, and comparing with the scenario of unstressed-open fracture-DFN models, effective permeability results from SLM I, PBC, ILM exhibit an increase in permeability anisotropy ratio as a function of the stresses, hence, supporting flow channelling within the network. Lagrangian solute transport simulation supports the afore-mentioned results by marked changes in primary flow path, increase in path tortuosity, as a function of stress, and delay in breakthrough time. Differently, SLM II undergoes the opposite effect, where the permeability ratio seems to reduce drastically at a depth of 500m and stabilizes after that. We infer this behaviour as due to non-linear behaviour of effective permeability as a function of aperture closure or dilation, as seen sometimes in highly connected system of fractures that are subjected to both normal and shear stresses, characterized by combined closure due to normal stresses and opening of previously closed flow-paths due to shear-dilation effect.

This research highlights the complex behaviour of permeability anisotropy in fractured carbonate rocks in response to depth-equivalent stresses, and the importance of building realistic hydro-geomechanically-DFN models to estimate fluid-flow and storage properties of fractured rocks at depth. It finds application not only in the study of groundwater contamination and remediation, but also to the hydrocarbon extraction, nuclear waste disposal, hydraulic fracturing, induced seismicity, CCS and geothermal energy development. Though maximum effort and care was dedicated to achieving this PhD research work and the accompanying dissertation within the stipulated three-year period of the programme, the PhD student

acknowledges some improvements, and possibly new research topics could emerge to better assess the contributions of these mesoscale structural elements to overall reservoir computation, such as:

- Incorporating results of fluid transmissivity across single structural elements, i.e., large faults with known dimensional properties in DFN model computations. Also, better characterizing fault intersections, etc.
- A better understanding and collection of mechanical aperture values in the HAV basin area. This could be achieved by adopting methods proposed by Vermilye and Scholz, (1994), and Hooker et al. (2013, 2014) on average vein thickness as aperture value used in modelling. This of course will be performed after the geochemical analyses have been conducted on the vein to determine that the infilling postdates the formation of open fractures. Analyses like Beryllium-10 can be carried out on rock samples from this region to determine the extent of weathering, and if the assessed mechanical aperture values can be relied upon. The Raparo area, southwest, HAV basin (Appendix A) is a potential site for vein data collection due to the abundance of veins.
- A better two-way geomechanically coupled DFN model that accounts for pore pressure feedback to in-situ stresses will produce more reliable effective permeability results. This can be achieved by using high computational industry standard software packages. Also, accurate field specific geo-mechanical data should be incorporated to achieve more efficient results.
- Though out of the scope of this PhD work, accounting for karstic features present in the subsurface could better improve the computed hydraulic property of the Viggiano mt. aquifer.
- Accounting for the hydraulic properties of bed parallel interfaces could lead to better characterization of effective permeability in the z-direction, $k_{eff_{zz}}$.
- Since the parallel plate model isn't an ideal method for flow-flow computation, experimental permeability analysis within single fracture planes could be achieved, incorporating the effects of fracture asperities and minerals within the fracture plane and their positive/negative implication to computed permeability.

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Appendix 3. 1 Table reporting: (a) multiscale maximum fracture porosity results (%) (b) cumulative multiscale maximum fracture porosity results (%). I.e., result from each model combined with that of the previous model.

Appendix 1

Max fracture Porosity (%)			
Volumes	5m	50m	500m
ILM	2.00	0.05	0.01
PBC	1.93	0.06	
SLM I	1.14	0.05	0.02
SLM II	1.73		

Cumulative Max fracture Porosity (%)			
Volumes	5m	50m	500m
ILM	2.00	2.05	2.03
PBC	1.93	1.99	
SLM I	1.14	1.49	1.51
SLM II	1.73		

Appendix 3. 2 Table reporting: (a) multiscale average fracture porosity results (%) (b) cumulative multiscale average fracture porosity results (%).

Appendix 2

Average fracture Porosity (%)			
Volumes	5m	50m	500m
ILM	1.00	0.0003	0.0011
PBC	0.45	0.4500	
SLM I	0.23	0.2950	0.0039
SLM II	0.36		

Cumulative average fracture Porosity (%)			
Volumes	5m	50m	500m
ILM	1.00	1.0003	0.7280
PBC	0.45	0.4535	
SLM I	0.23	0.2964	0.3003
SLM II	0.36		

Appendix 3. 3 Table reporting: multiscale fracture permeability values, (a) k_{xx} , (b) k_{yy} (c) 2D horizontal permeability ratio. Computation for Aperture proportional to Length.

Appendix 3

Cumulative Max fracture permeability, k_{xx} (mD) (Aperture $\propto L$)			
Volumes	5m	50m	500m
ILM	1.85E-04	1.88E-03	9.24E-02
PBC	1.64E-03	1.66E-02	
SLM I	1.61E-03	2.39E-02	2.39E-01
SLM II	3.16E-03		

Cumulative Max fracture permeability, k_{yy} (mD) (Aperture $\propto L$)			
Volumes	5m	50m	500m
ILM	1.38E-04	1.39E-03	6.72E-02
PBC	1.18E-03	1.20E-02	
SLM I	1.39E-03	1.15E-02	1.15E-01
SLM II	8.96E-04		

2D Horizontal Permeability tensor (Aperture $\propto L$)			
Volumes	5m	50m	500m
ILM	1.34	1.36	1.38
PBC	1.38	1.38	
SLM I	1.16	2.07	2.07
SLM II	3.53		

Appendix 3. 4 Table reporting: multiscale fracture permeability values, (a) k_{xx} , (b) k_{yy} (c) 2D horizontal permeability ratio. Computation for Aperture proportional the square root of Length.

Appendix 4

Cumulative Max fracture permeability, k_{xx} (mD) (Aperture $\propto \sqrt{L}$)			
Volumes	5m	50m	500m
ILM	4.78E-05	4.80E-04	2.25E-02
PBC	3.99E-04	4.03E-03	
SLM I	3.40E-04	4.89E-03	4.89E-02
SLM II	6.34E-04		

Cumulative Max fracture permeability, k_{yy} (mD) (Aperture $\propto \sqrt{L}$)			
Volumes	5m	50m	500m
ILM	3.63E-05	3.65E-04	1.63E-02
PBC	2.86E-04	2.89E-03	
SLM I	3.22E-04	2.34E-03	2.34E-02
SLM II	1.42E-04		

2D Horizontal Permeability tensor (Aperture $\propto \sqrt{L}$)			
Volumes	5m	50m	500m
ILM	1.31	1.32	1.39
PBC	1.40	1.40	
SLM I	1.06	2.09	2.09
SLM II	4.46		

Appendix A - STRUCTURAL ANALYSES AND DFN MODELLING OF FAULTED AND FRACTURED PLATFORM CARBONATES, RAPARO MT. SOUTHERN, ITALY

A.1 Introduction to the Raparo Mt. Area

The Raparo Mt. is of hydrological importance for the population living along the southern portion of the Basilicata Region. As previous field studies have shown, in the Raparo Mt. are only the Sant'Angelo Spring is characterized by a significant flow rate to account for the active recharge rate of the aquifer. This spring is not even lying in the areas with the most topological depression, and hence poses question on the hydrogeological setting of the area. This further strengthens previous assertions that the entire Raparo Mt. is an equivalent porous medium recharged by meteoric fluids that permeate through sinkholes, faults, and fractures with the surface and underground flow line directed towards this spring.

This study aims to conduct a preliminary study of the Mt. Raparo area, carrying out several structural field surveys with an integrated 3D digital outcrop data acquisition at specific well-exposed outcrops and hand sample collections. Microstructural analyses will enable us to decipher the exert age of the outcrops. In addition to this, data collection through the field and digital outcrop analysis will enable us to compute the estimate of the fluid storage and migration properties of these carbonate outcrops through Discrete Fracture Network (DFN) modeling. The results can be further developed to simulate geofluid movement through fractures and faults within the aquifer.

The study area

Four tectonic units are outcropping within our study area. They are Gorgoglione formation, Sicilide complex, Liguride complex, Apenninic platform units, and the Lagonegro units, I and II. The focus of the study was the Apenninic platform carbonates of this area. Specifically, three sites were selected to carry out our analyses based on the representativeness of the different ages these carbonates were deposited, which according to the Lentini et al. (1991) geological map was from the Eocene – Cretaceous. The sites were the Eocene – Upper Cretaceous Top Raparo Mt., the Cretaceous carbonates of the Raparello Mt., and the Lower Cretaceous carbonates of Castel Saraceno.

Geographically, the entire study area is situated in the High Agri Valley (HAV) area of southern Italy, situated between 40°15' N – 40°10' N and 15°54' E – 16°6' E. The Top Raparo Mt. has an altitude of 1763m ASL, the Raparello Mt. is 1288m ASL and the Castelsaraceno about 950m. The hydrologically linked area comprises municipalities of Castelsaraceno, Grumento Nova, Lauria, Moliterno, Montemurro, San Chirico Raparo, San Martino D'Agri, Sarconi, and Spinoso (Figure A.1). Geomorphologically, the area (Figure A.2) is characterized by its own complexities, as it has a mountainous landscape that is characterized by significant topographical variations due to multiple phases of tectonic processes and due to the presence of paleo-surfaces and karst-related dissolved exposures that are preserved at high altitudes of the limestone reliefs. The phenomena of denudation and dissection triggered by orogenic uplifts have led to the exhumation of contact planes between lithologies. Lithologies more resistant to erosive processes, such as carbonate rocks, give rough and rugged morphologies, in contrast to the tabular reliefs typical of sandy-conglomeratic successions with the gentle, low slope, where the clay component predominates (Schiattarella et al., 2011; Bonardi et al., 2016).

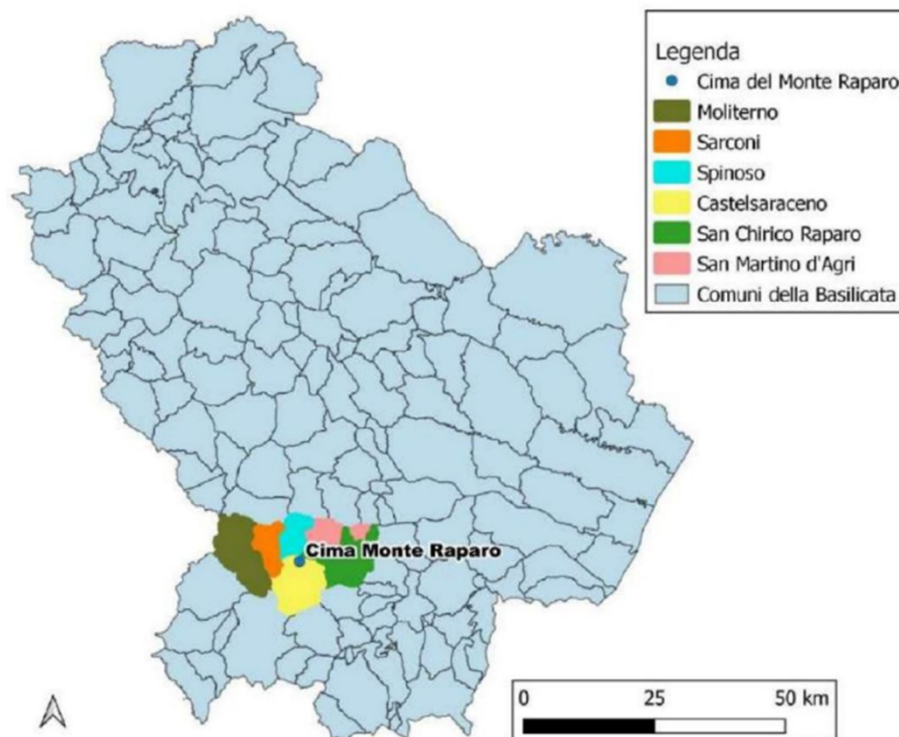


Figure A.1. Location of Monte Raparo relative to the municipalities of Basilicata



Figure A.2. Geomorphological view of Mt. Raparo area. View from E. (GoogleEarth). Star 1 for Top. Raparo Mt., Star 2 for Raparello Mt., and Star 3 for Castelsaraceno

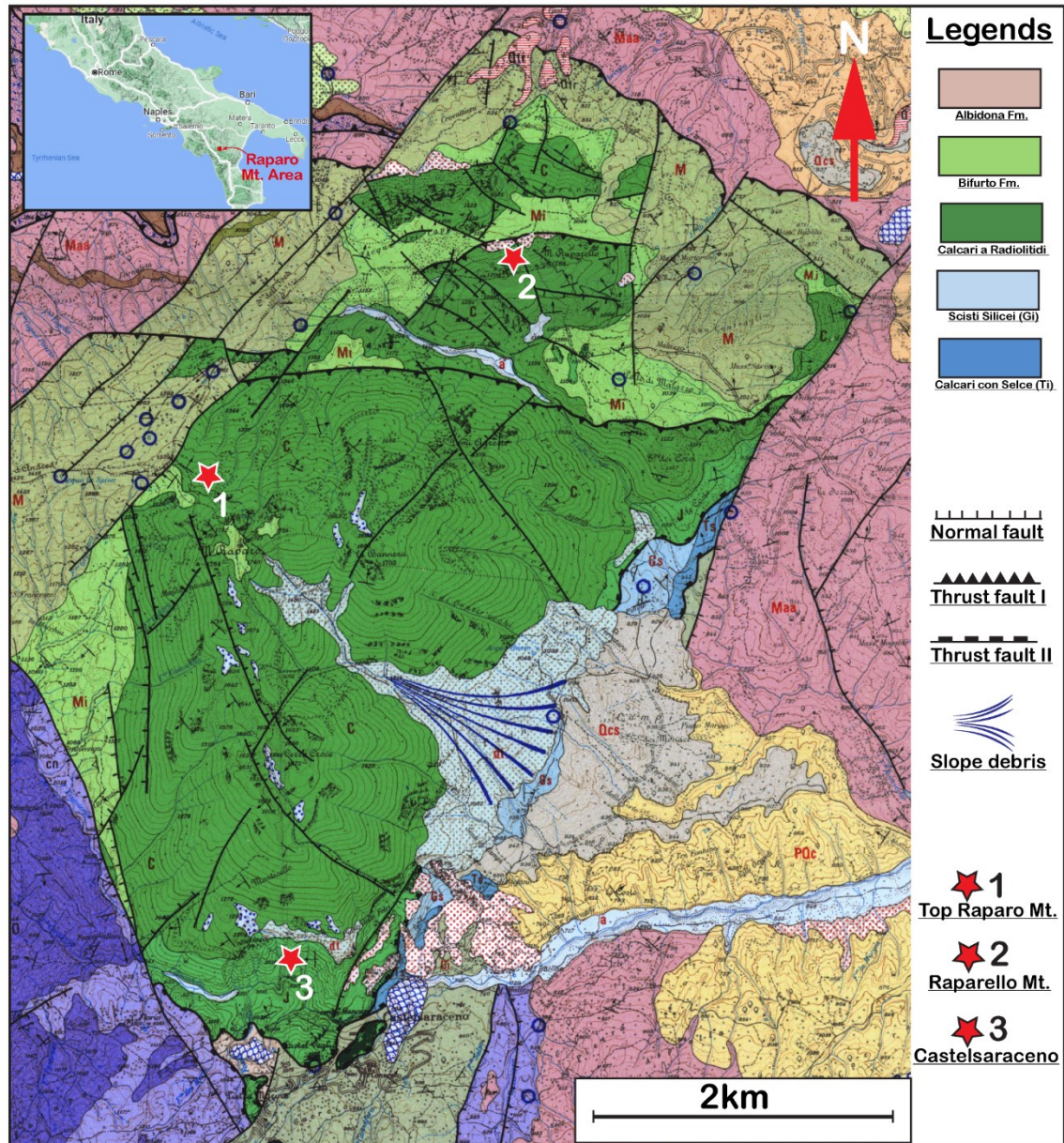


Figure A.3. Geological map of southern Italy. Study sites are indicated with stars. 1 for Top. Raparo Mt., 2 for Raparello Mt., and 3 for Castelsaraceno (modified after Lentini et al., 1991)

A.2 Methods

Thin section analyses

During the field survey, hand samples were collected for petrographic characterization and microstructural analysis. Usually, this process is conducted by cutting the hand samples into smaller sizes, and thereafter shaping and grinding until the surfaces are smoothened. They are then glued onto glass slides with transparent glues that are highly adhered to the slides. They are then subjected to pressure to remove air bubbles. The samples are then cut further with diamond discs until they reach a thickness of about 30 μ .

A.3 Carbonates of Top Raparo Mt.

Lithostratigraphic logs

In this study site, carbonates form gentle anticlines cut by high-angle faults that result in bed rotation under the vertical axis. Hence, the bedding attitudes varied by structural position. The single carbonate beds varied in thickness from 20cm-thick beds up-to-1.3m thick, although bed amalgamation was observed at some of the outcrops. These beds were mainly comprised of micritic carbonates with some packstone beds (Figure A.4). The carbonates analysed were divided into sections A to E as shown in Figure A.4a, where the lithostratigraphic logs are shown according to the afore-mentioned sections.

At block A, majorly, the average bedding was about N355/15, but certain parts of this outcrop had areas where beddings were oriented at about N325/16. Bedding at block B were oriented N270/23. At block C, average attitude for the bedding was N56/17 throughout the block. At block D, the average bedding was N354/28 then changed to an average of N10/25 at other parts. At block E, the average bedding was N358/19, and at other parts of this block, we recorded an average of about N10/22.

(a)

Carbonates of Top Raparo Mt.



(b)

Litho-stratigraphic logs

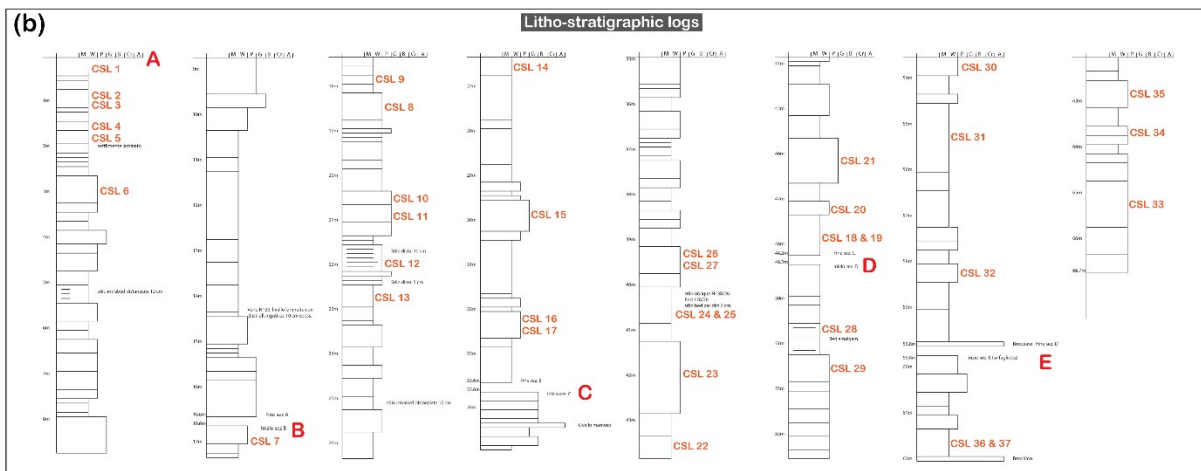


Figure A.4. Lithostratigraphic logs of the Top Raparo Mt. carbonates. Single carbonate beds on which circular scanline analyses were carried out are indicated, CSL 1, CSL 2, etc.

Morpho-lineament Interpretation

The top-view of the 3D virtual outcrop model of these carbonates was used to conduct a morpho-lineament analysis. Here we were able to trace out the main high-angled faults that cut and rotate these carbonate beds. 40 planes were extracted and associated rose diagram reported (Figure A.5 and inset).

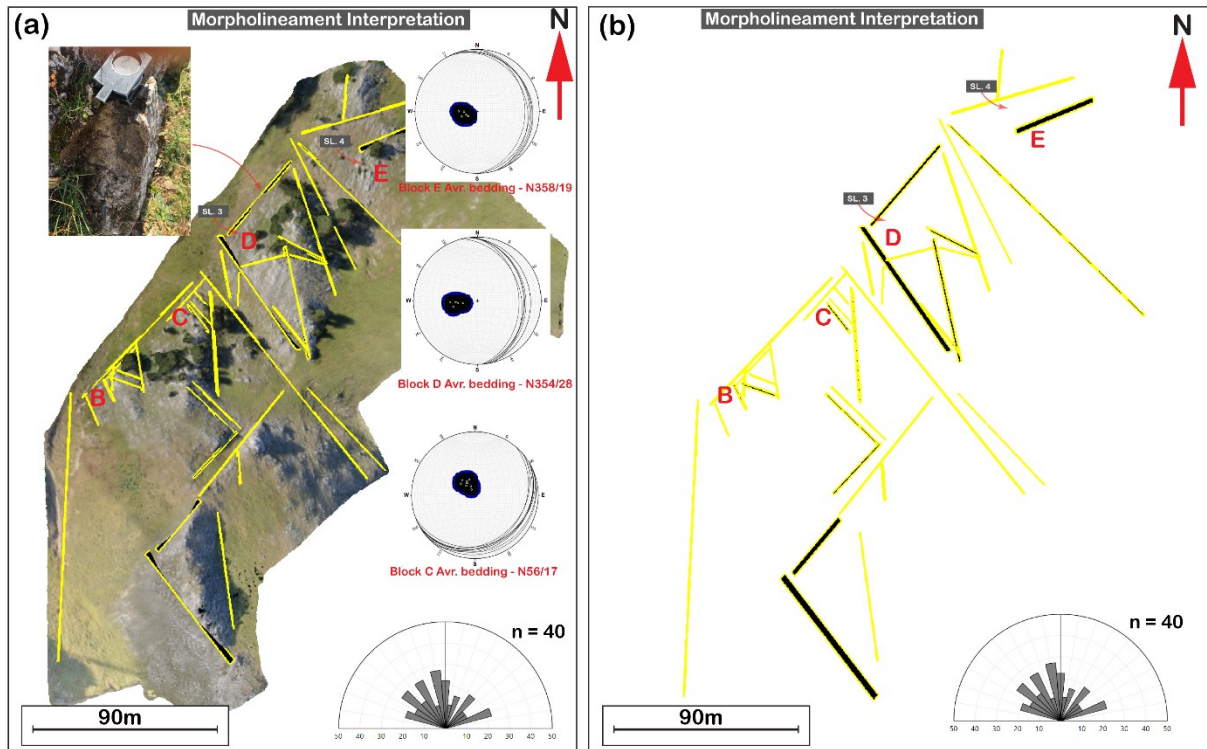


Figure A.5. Morpho-lineament interpretation for carbonates of the Top Raparo Mt. The carbonate sections associated to lithostratigraphic logs are shown in red from B to E. Around block D and E, we observed brecciated mineralised rock (~1m-thick), i.e., along the N30-N40 bounding fault.

Thin sections for carbonates of Top Raparo Mt.

The microfacies analyses show the occurrence of wackestone to packstone with abundant benthic foraminifera and algae that are indicative of a shallow water environment (Figure A.6, R1, R3, R4, R5, R7, R8). The association of benthic foraminifera among which *Rotaloidea* (*Rotorbinella* sp.), miliolids with calcareous algae such *Thaumatoporella parvovesiculifera* are comparable to same association of Middle-Upper Cretaceous for Apennine and Apulian platforms (Brandano and Loche, 2014; Consorti et al., 2017; Fabbi et al., 2020). The sample R6 show an arenite with abundant quartz (Figure A.6 R6).

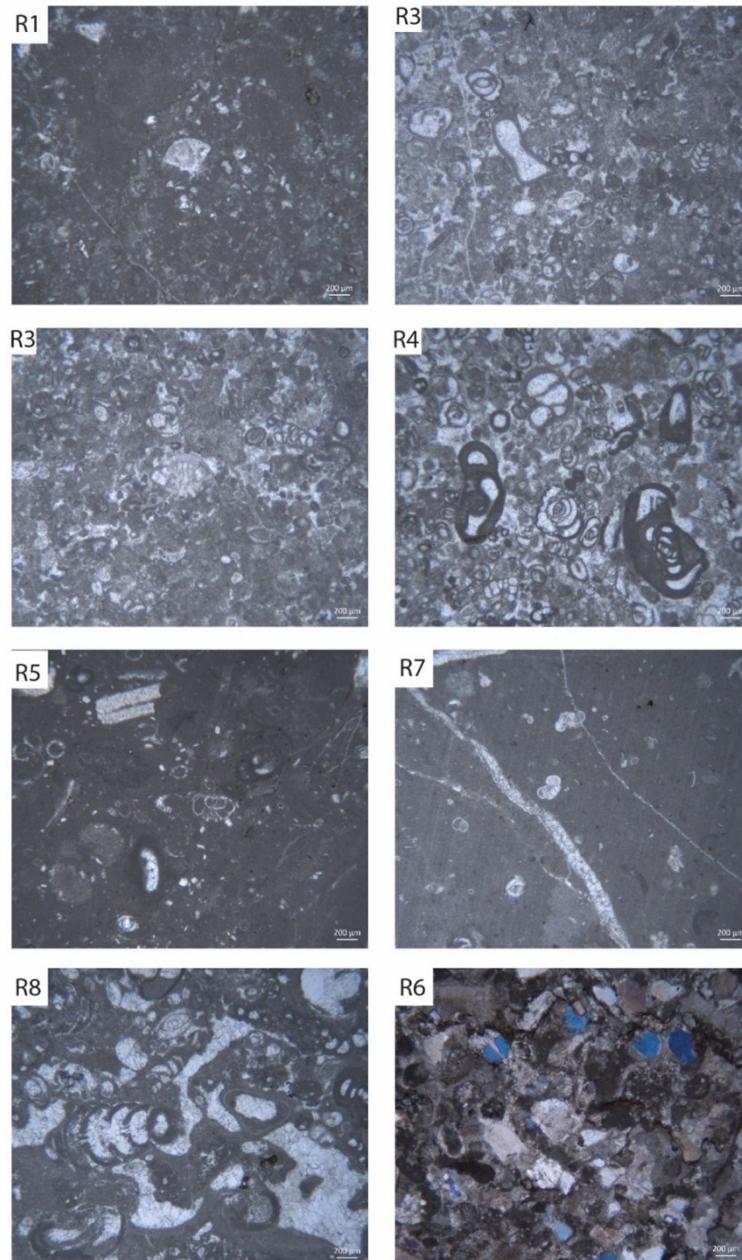


Figure A.6. Microfacies plate of the Top Raparo Mt. carbonates

Linear Scanlines

4 linear scanline analyses were conducted that allowed to assess the attributes relating to 214 fractures from this location (Figure A.7a). Their associated equal-area lower hemisphere projection for fracture attitude data is shown on their respective stereo plots (Figure A.7b). The

multiscale fracture height distribution properties for these carbonates are shown, and they all best-fit power-law distribution with D-fractal values ranging from 1.52 to 1.78 (Figure A.7c).

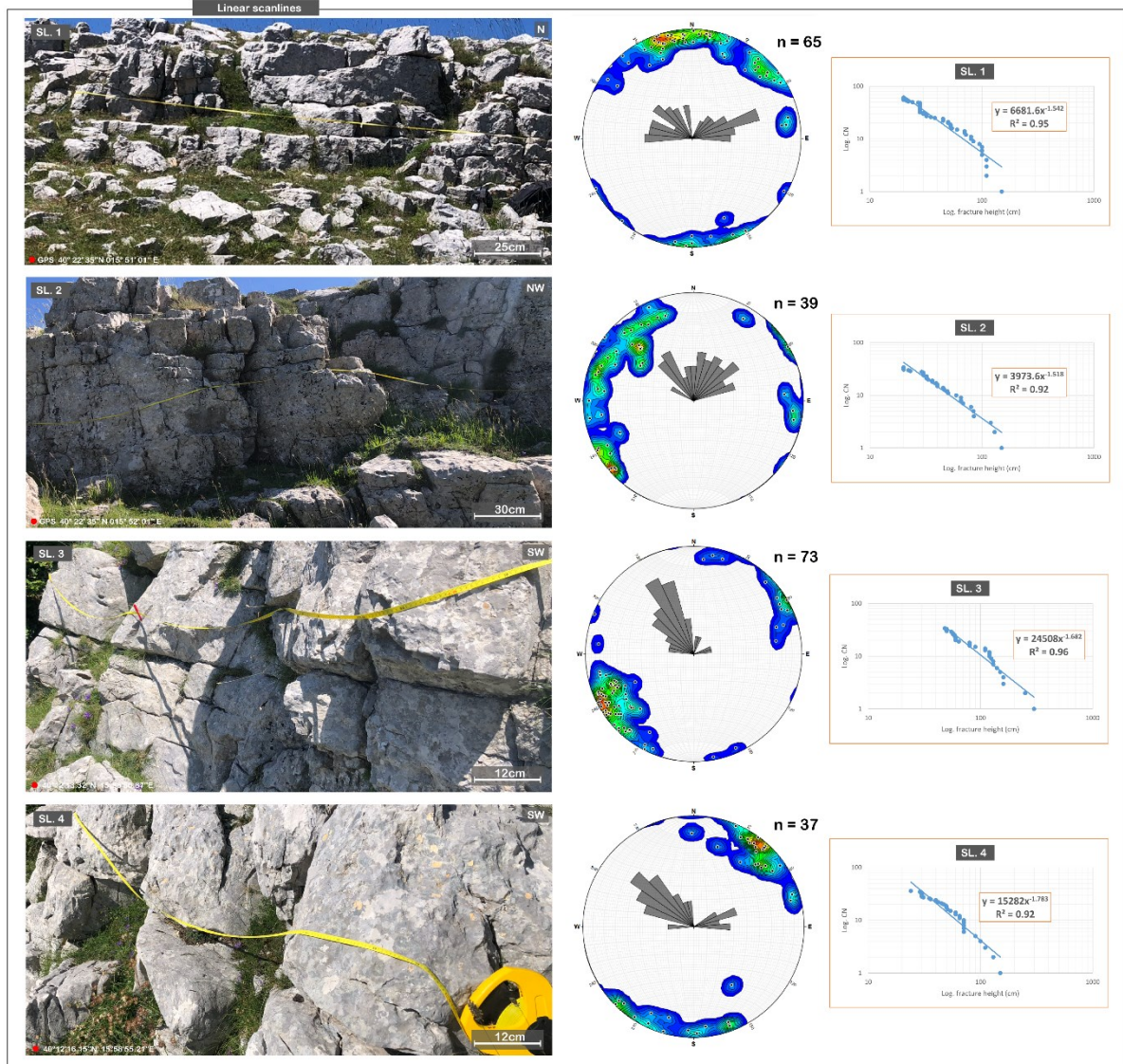


Figure A.7. Linear scanlines are shown with corresponding stereo plots. Multiscale fracture height properties are assessed by the plot of Log. cumulative number against Log. of fracture height. Power-law distribution equations are shown in orange boxes.

Circular scanlines

37 circular scanline analyses were carried out on single carbonate beds according to their lithologies (Figure A.4b). Two graphs are plotted for these data (Figure A.8) The first is a histogram graph that shows the frequency variation of P20 and P21 according to single

carbonate bed lithologies. The second graph is a box plot showing the minimum, maximum, median values, etc of the P20 and P21 according to the studied lithologies.

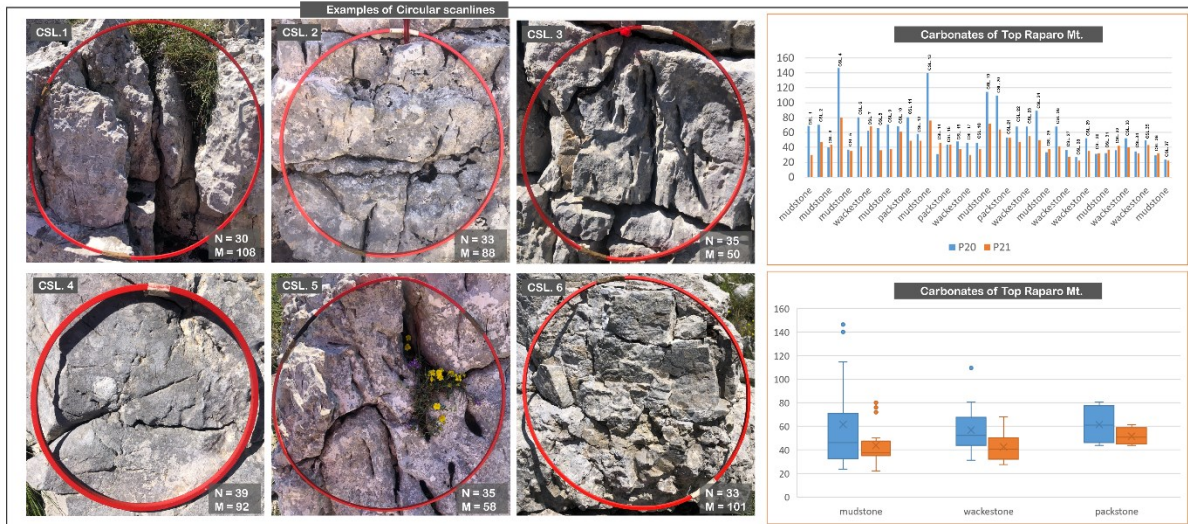


Figure A.8 (a) Examples are shown of the circular scanline analyses carried out on fractured outcrops. Fracture intersection, N and fracture termination, M values for each scanline are indicated. (b) Histogram showing frequency variation of P20 and P21 according to single carbonate bed lithologies. (c) Box plot showing the minimum, maximum, median values, etc of the P20 and P21 according to the studied lithologies.

Other observations from the Top Raparo Mt. carbonates

1. At the eastern portion of the Top Raparo Mt., we observed clinoform-like carbonate structures (Figure A.9). These structures were characterised by unconformity, as seen by the significant variation amongst the bedding attitudes.
2. This study area was characterized by a lot of beautifully exposed veins. We observed sheared veins (Figure A.10a), veins striking N30/sub-vertical and N120/sub-vertical with mutual cross-cutting relationships (Figure A.10b), and other veins with thickness up to 4mm that were trending N-S, localised mainly along within the vicinity of the inferred N-S trending fault bounding block A and B (Figure A.10c, Figure A.5). Others are, thick sub-parallel veins trending N240 - 60 with N30 thin veins abutting against them – left lateral, veins-oriented N-S with N30 abutting against them - right lateral, cluster veins oriented N30, N-S veins, N120 veins, N60 veins, Pervasive N-S and N60 veins,
3. N30 fractures within parallel N140 fault of block C.

4. Fractures N290/35 and N300/40 at block D
5. Terrigenous Bifurto formation outcrops between blocks A & B.
6. Pronounced weathering of these carbonates made it impossible to observe kinematic markers, however brecciated rocks were exposed along the inferred faults as traced on the lineament map, N30 – N40 fault (Figure A.5a inset) and along the N-S trending fault (Fig. 10d)
7. Hand samples were collected along N120/subvertical fault zone of block D with small patches of tar. Sent for analysis out of the scope of this study.

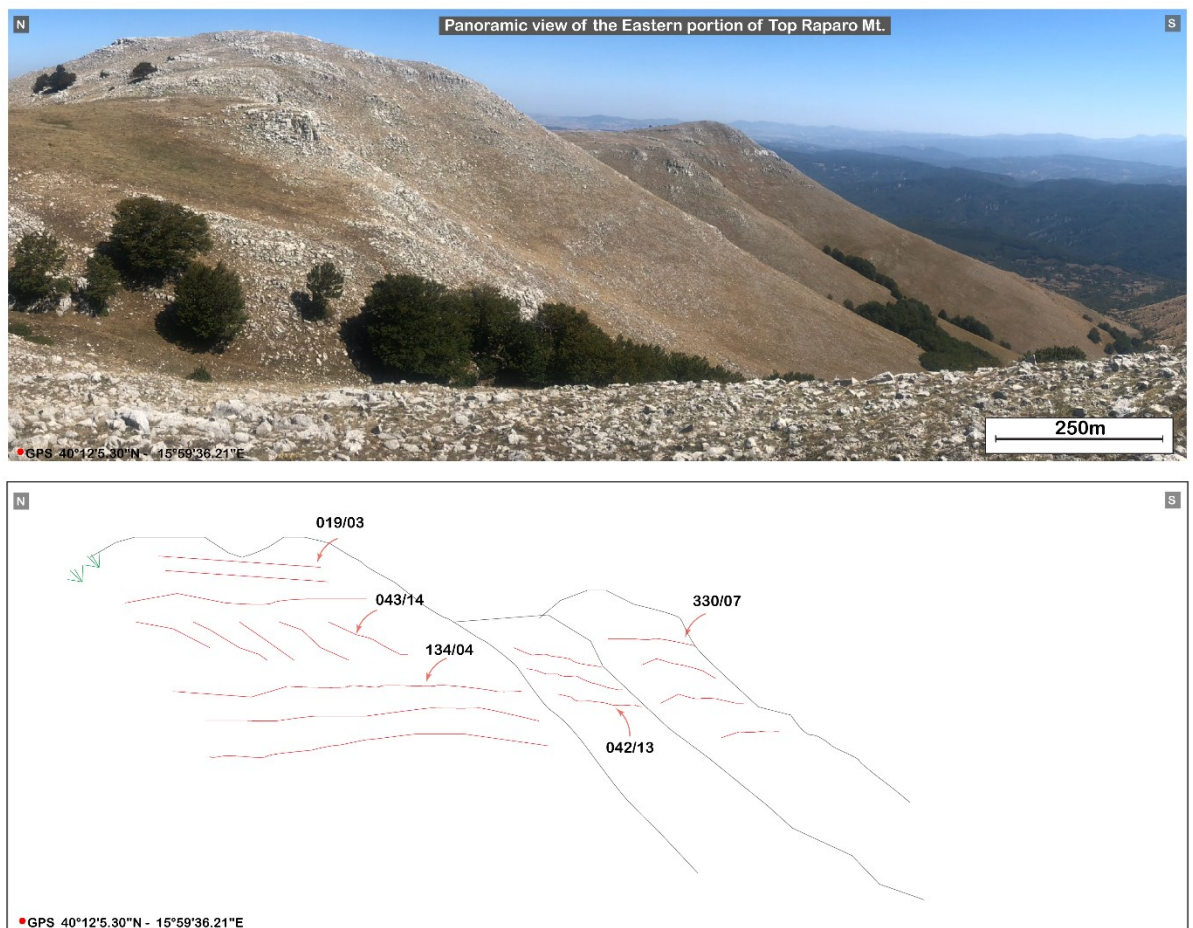


Figure A.9 Clinoform-like structure at the eastern portion of Top Raparo Mt. carbonates.



Figure A.10 (a) Sheared veins collected at the vicinity of the N-S inferred fault bounding block A and block B. (b) Mutual crosscutting relationships between veins oriented N110 - N120 and those oriented N30 - N40. These veins are abundant throughout the study outcrops. (c) 4mm-thick veins as observed within the N-S inferred fault zone. (d) Brecciated rocks collected along the N-S inferred fault zone.

A.4 Carbonates of Raparello. Mt.

Morpho-lineament Interpretation

191 lineaments were extracted from the aerial-view of the 3D virtual outcrop models and the orientation of the planes reported on the rose diagram (Figure. A.11a & A.11b).

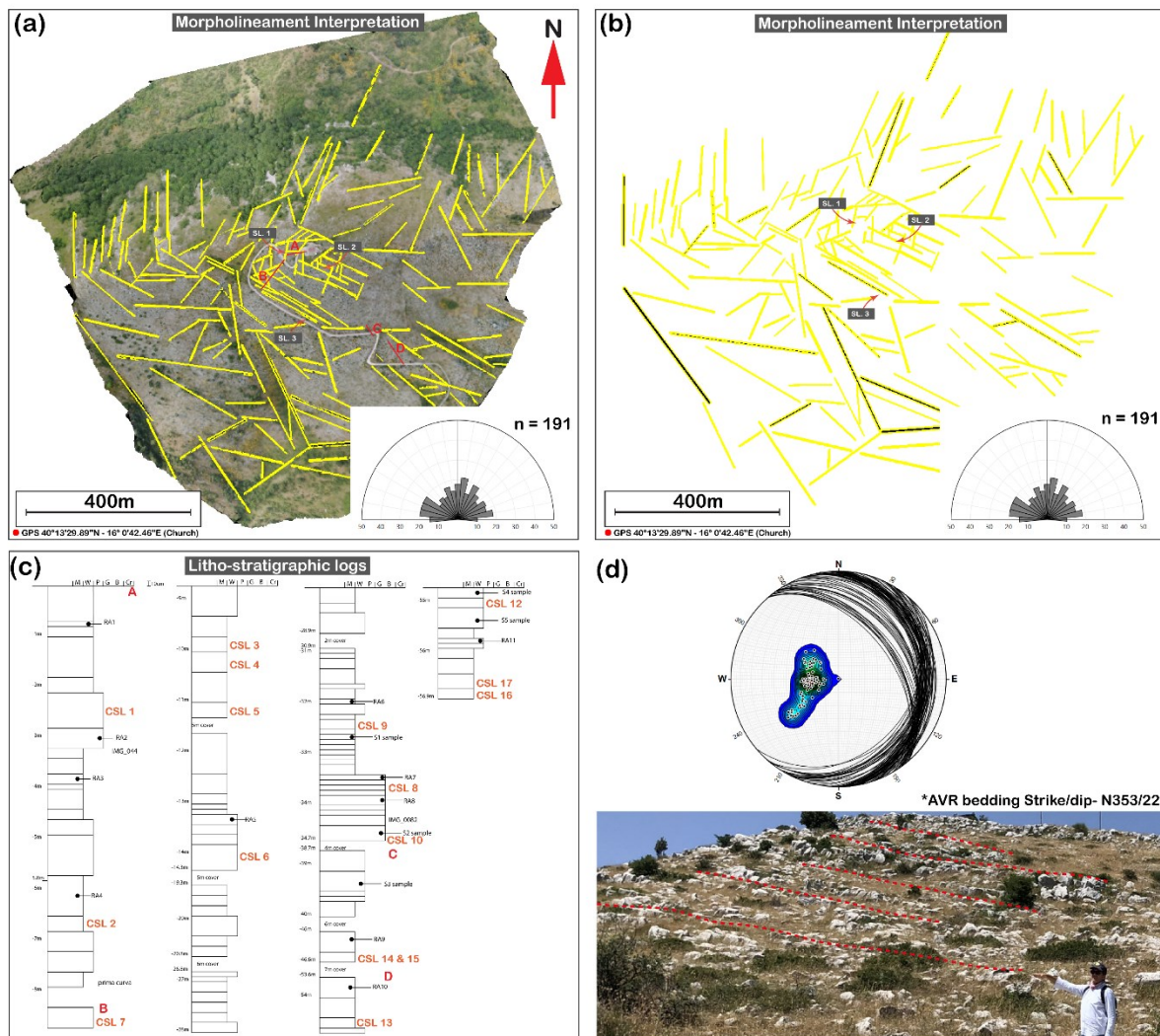


Figure A.11. (a) 191 large scale morpho-lineament interpretation. Locations for lithostratigraphic logging are indicated, A, B, etc. Locations where linear scanlines were carried out are indicated, SL 1, SL 2, etc. Locations of inferred left-lateral strike slip faults are indicated, RP1, RP2, etc. Inset reports the orientations of the extracted traces on an equal area rose diagram (b) Extracted traces are shown and locations where linear scanlines were performed W.R.T to the inferred faults. (c) Lithostratigraphic logs are reported. Beds where hand samples were collected are indicated, RA 1, RA 2, etc. (d) An equal area lower hemisphere projection is shown for 100 measurements of carbonate beds, an average orientation of N353/22 (strike/dip) was recorded. The NE – E dip direction of the beddings is shown by hand.

Lithostratigraphic logs

Litho-stratigraphic logging was carried out on these outcrops as indicated, section A – D (Figures. A.11a to A.11c). The single beds varied in thickness from 25cm up to 70cm large carbonate beds made up of mudstone-wackestone to packstone and few grainstone beds (Figure. A.11c). Unlike the carbonates of the top Raparo Mt., these carbonates are not folded.

Instead, they collectively dip towards the NE to E (Fig. 11d). Bedding measurements were confirmed by means of bed - parallel stylolites. Field survey conducted confirmed that these carbonates were heavily eroded and karstified, hence no kinematic markers were visible.

We observed local variations in bed attitudes across inferred planes, as reported in the morpho-lineament interpretation (Figures A.11a & A.11b, Figure. A.12), which are indicative of beds that have undergone rotation under vertical axis. Hence, these carbonates are inferred to have been affected by pronounced strike-slip related faulting. Bed rotations (Figure A.12), brecciated rocks (Figure A.13), sheared veins in en-echelon arrangements (Figure A.14) and extensional fractures at the dilational quadrant of these inferred faults RP1, RP2 and RP3 supported the assertion that the aforementioned faults are WNW-ESE trending left-lateral strike-slip faults.

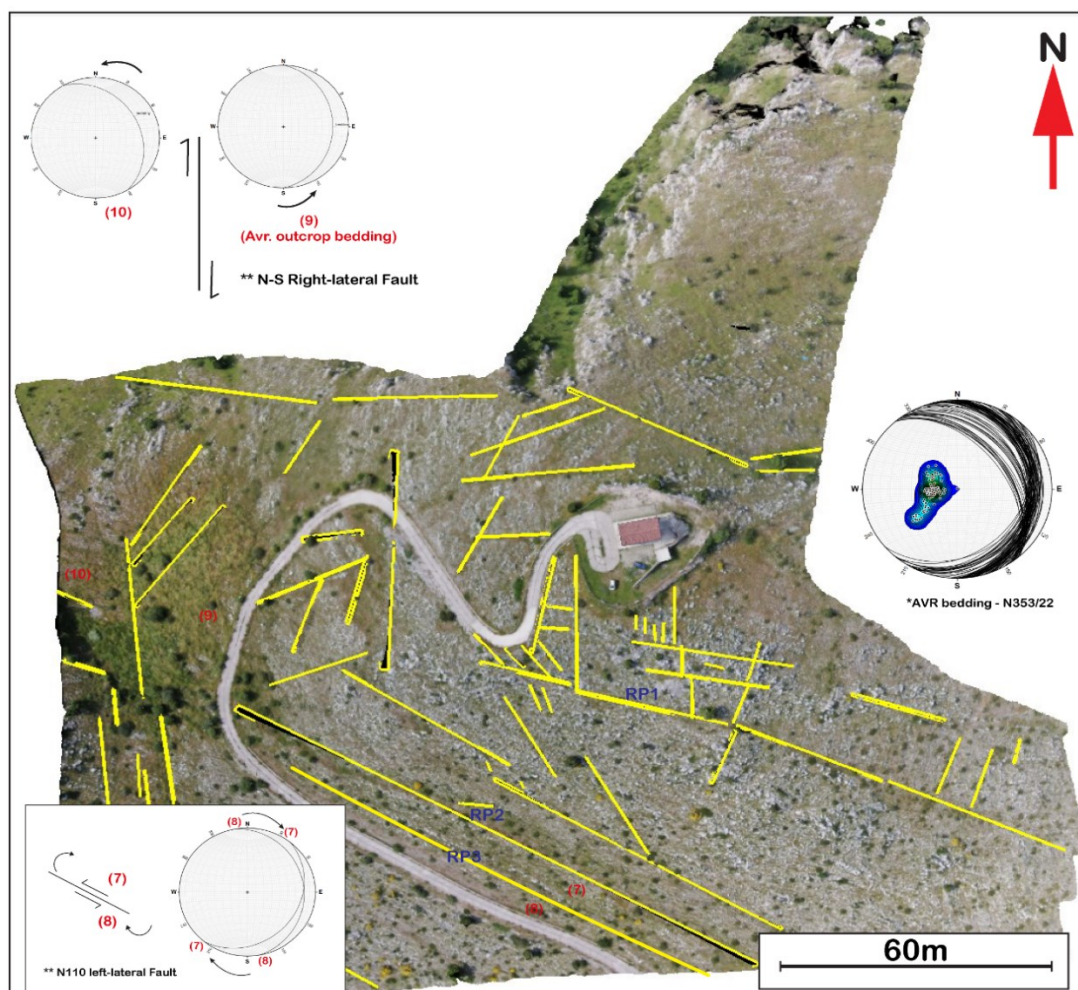


Figure A.12 Morpho-lineament extraction and interpretation for a relatively small portion of the Raparello Mt. Here, stereo plot shows average bedding attitude. Bed rotations across inferred fault

planes based of several bed measurements. Location of RP1, RP2, RP3 inferred N110-N120 left-lateral strike-slip faults are shown.

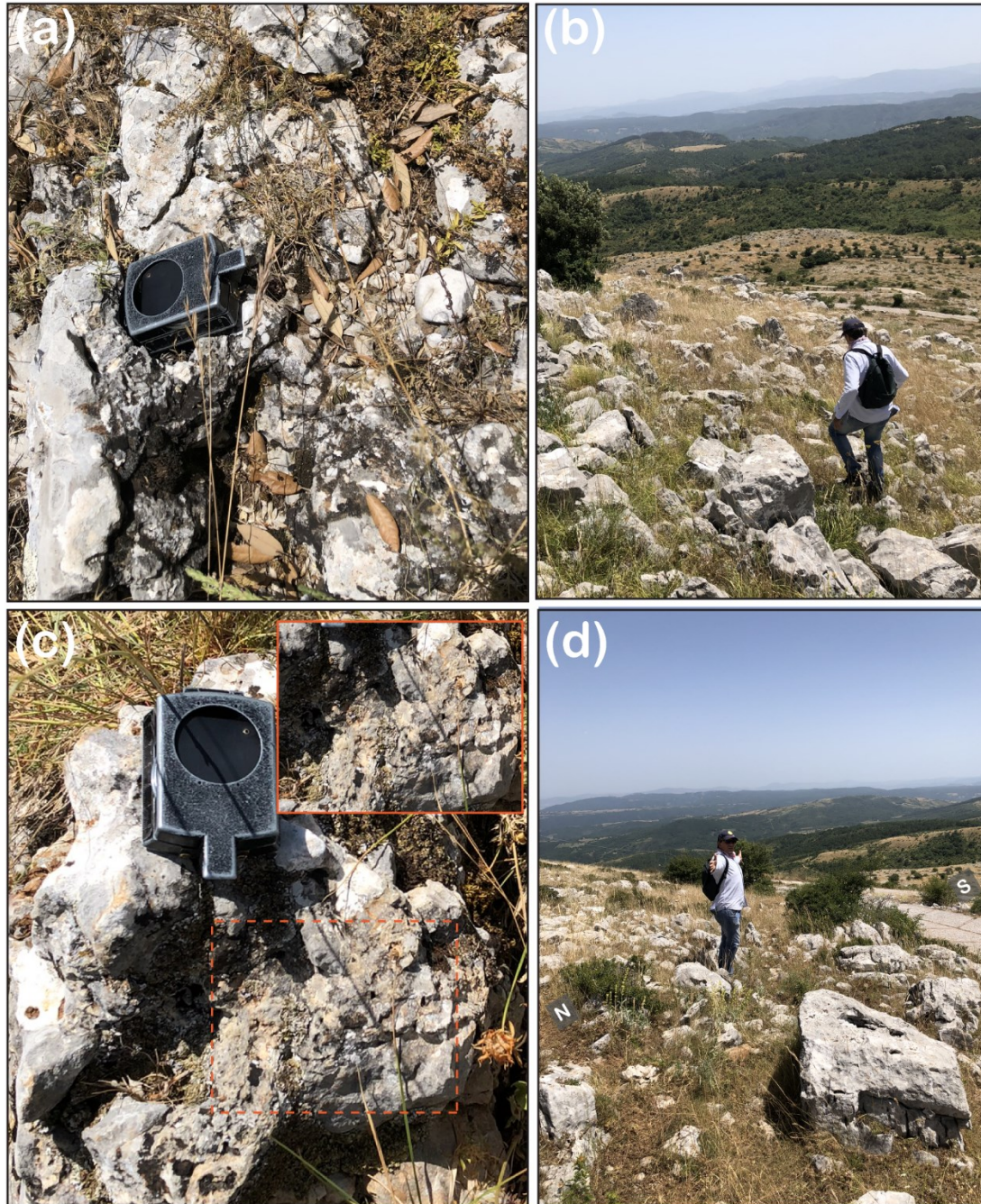


Figure A.13 Uncemented fault breccia observed along a N110-120E morphological scarp (a) and (b) along RP1 (b) and (c) along RP2

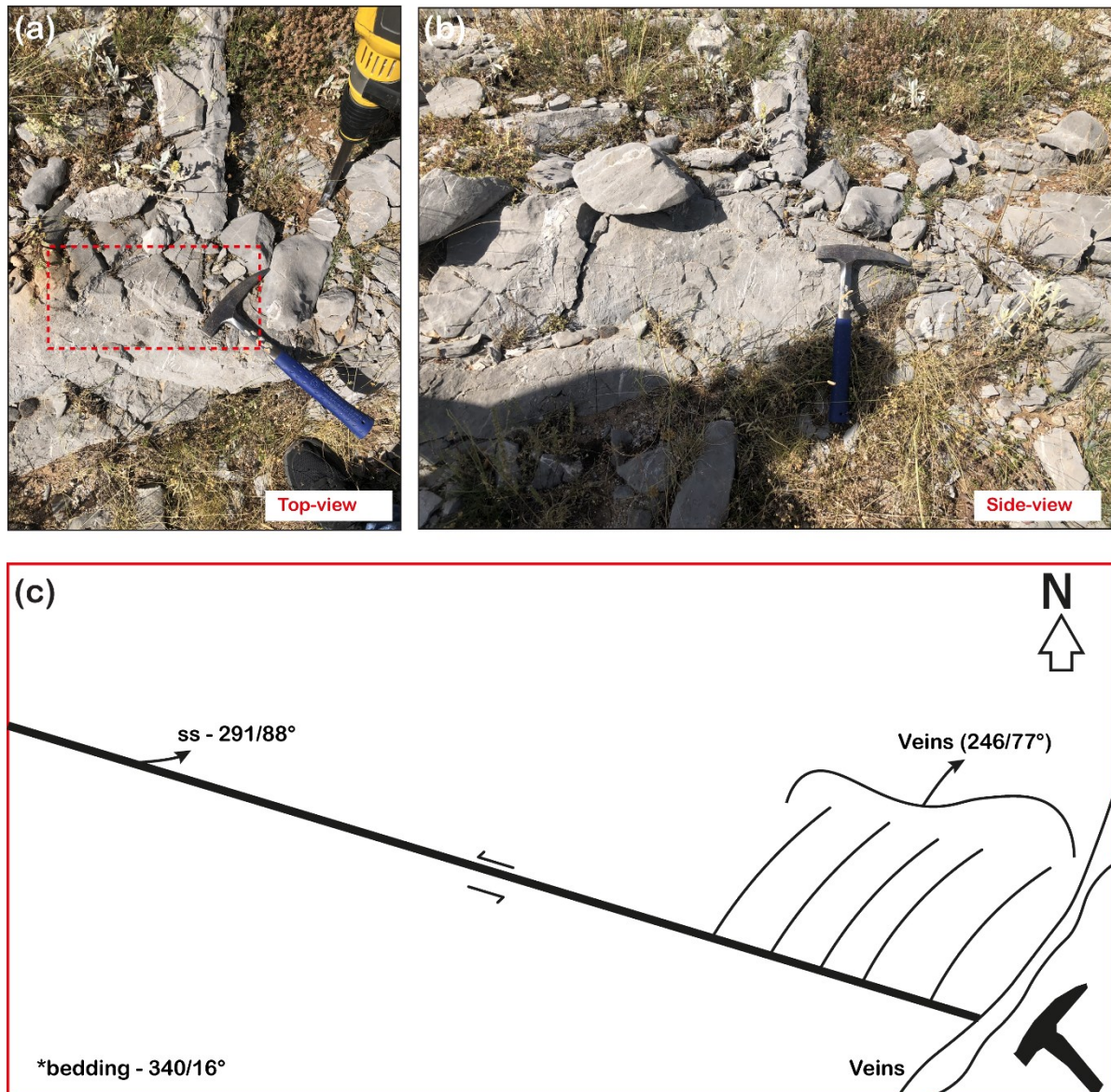


Figure A.14 (a) and (b) En-echelon sheared veins observed along the WNW-ESE left-lateral inferred fault, RP3. (b) Slip surface direction is N291/88, and the sheared veins are oriented N246/77. Bedding here was N340/16

Thin sections of the Raparello Mt. carbonates

In the Raparello section, on the base of the macroscopic texture, outcrops two main lithofacies cyclically arranged (Figure A.15a). The first lithofacies is characterized by muddy texture in which is common the occurrence of rudists biostrome (Radiolitidae) (Figure A.15b). The second lithofacies is characterized by planar texture belonging to a stromatolitic structure. The microfacies analyses made on samples labelled RA, include wackestone-packstone characterized by the association of benthic foraminifera and calcareous algae (*Actinoporella*

sp.) (Figure A.15c, d, e, f). The age of the section can be referred to Lower (?) Cretaceous. More analyses are being conducted to be certain.

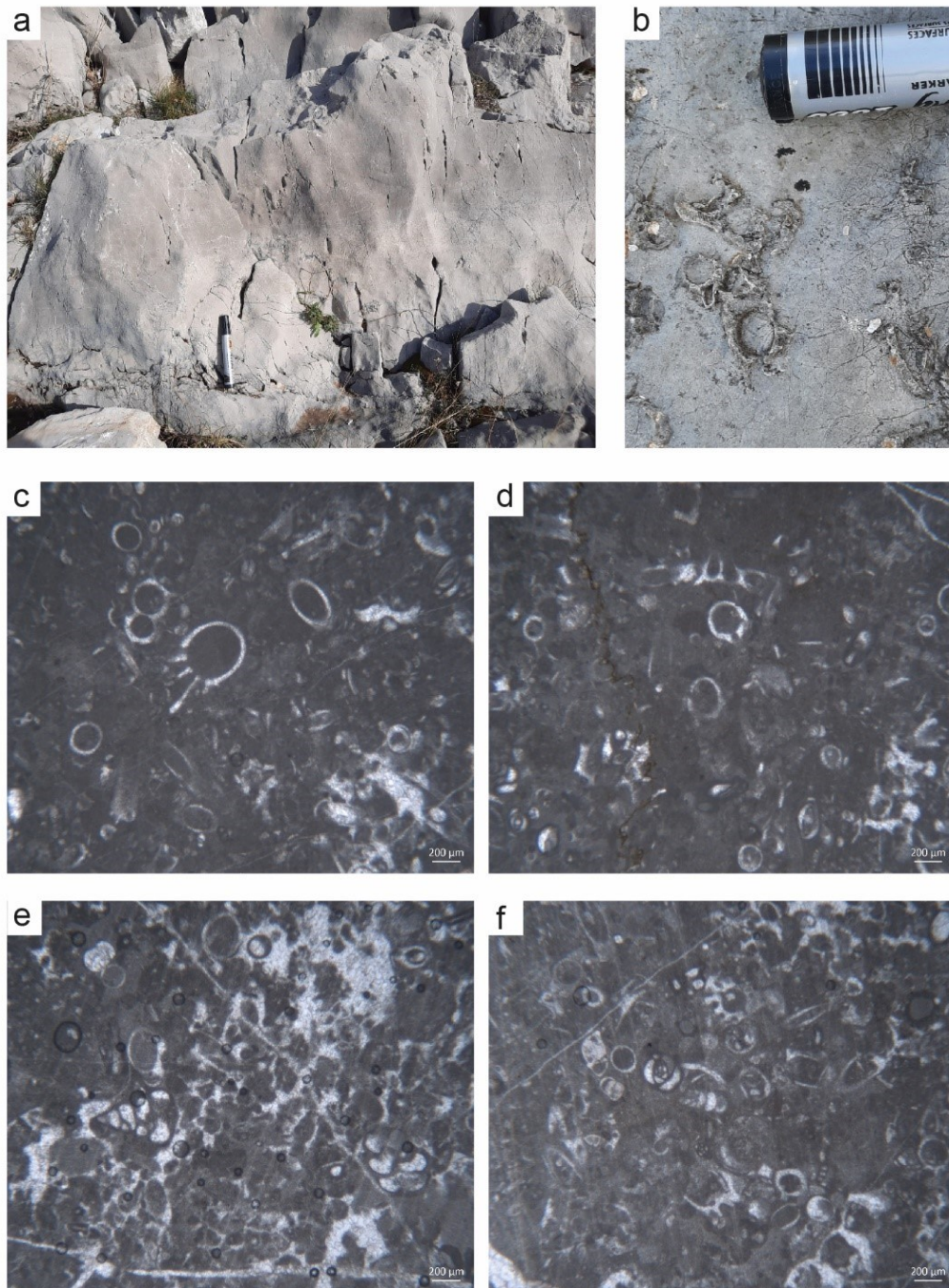


Figure A.15 (a) and (b) lithofacies observed in the Raparello section. (c) and (d) Microfacies association of the Raparello section.

Linear Scanlines

4 Linear scanline analyses allowed the attributes for 191 fractures to be assessed (Figure A.16a). Locations where scanlines were carried out are shown in Figure A.11a. Equal-area lower hemisphere projection fracture data are shown on the stereo plots (Figure A.16b). The multiscale fracture height distribution properties of these carbonates are shown (Figure A.16c). Here, fracture height data are best-fit both by negative exponential distributions at SL 1, SL 2 and bi-fractal power-law distribution at SL 3.

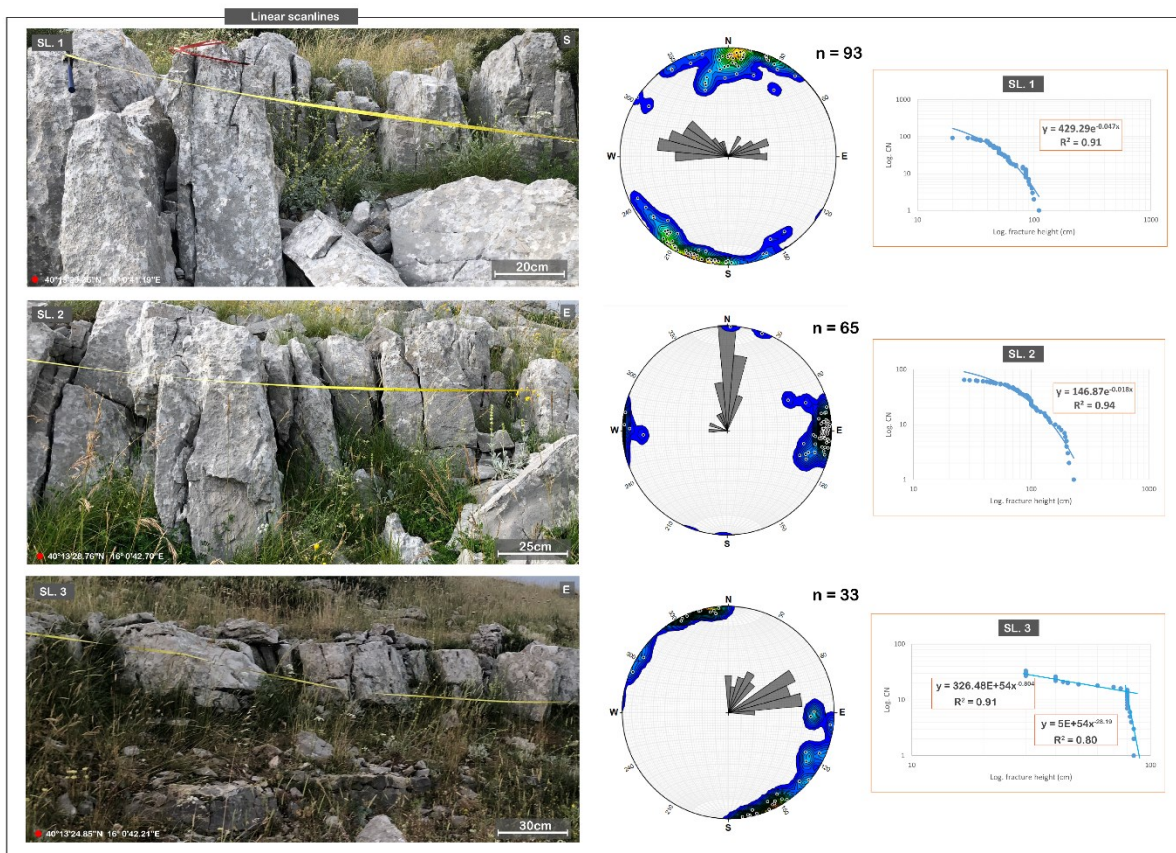


Figure A.16. (a) Linear scanlines measurements (b) Equal-area lower hemisphere stereo plots projection of fracture data for orientations from linear scanline measurements. (c) Multiscale fracture height distribution properties of these carbonates.

Circular scanlines

17 circular scanline measurements were carried out at the Raparello Mt. carbonates (Figure A.17). Examples of some of the scanlines are shown. P20 and P21 results are projected on histogram and box plot according to the different lithologies analysed (Figures A.17b & c).

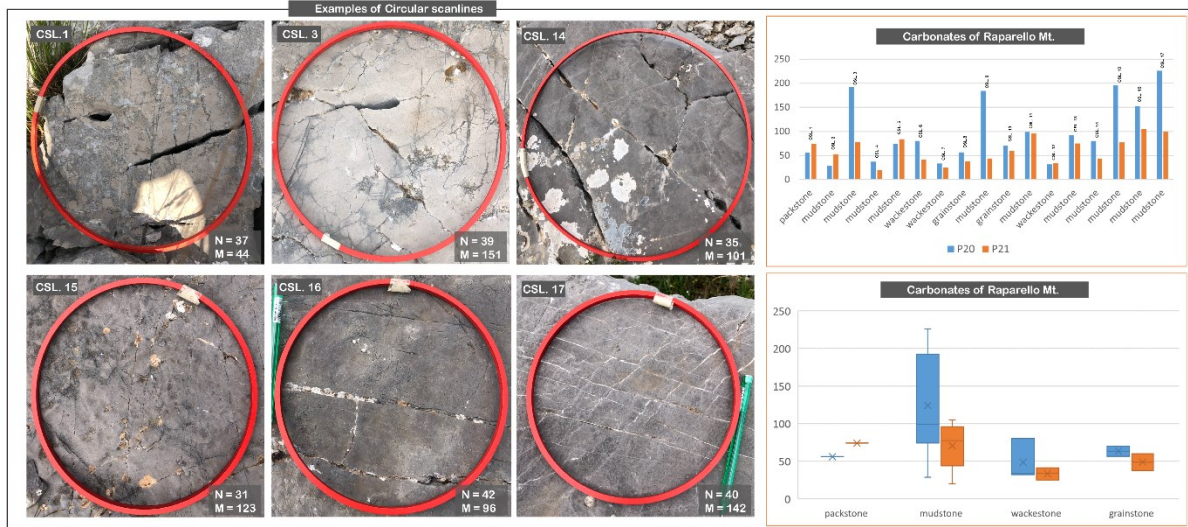


Figure A.17 (a) Examples of some of the circular scanlines from Raparello Mt. are shown. (b) and (c) P20 and P21 results are projected on histogram and box plot according to the different lithologies analysed

Other observations

1. N100 left-lateral fault that displaces wackestone-mudstone beds by a throw of 60cm (Figure A.14b) The strike of the fault is indicated by stretched arms. Mudstones are dark-coloured and bitumen rich (smells of hydrocarbon). Samples were collected for further analysis outside the scope of this study. This fault is located within the vicinity of RP3. Linear scanline 3 was carried out on the wackestone beds.

A. 5 Carbonates of Castelsaraceno

Morpho-lineament Interpretation

160 lineaments were extracted from the aerial-view of the 3D virtual outcrop models and the orientation of the traces are reported on the equal area rose diagram (Figure A.18a & b).

Lithostratigraphic logs

Litho-stratigraphic logging was carried out on certain portion of these outcrops as indicated, section A – C (Figure A.18a to c). The single beds varied in thickness from 40cm up to 65cm carbonate beds, made up of mudstone-wackestone and packstone-grainstone medium sized

beds. These beds are sometimes interlayered by few centimetres-thick clay rich-argillaceous stratas as shown in the logs (Figure A.18c). The studied portion of the Castelsaraceno shallow-water carbonates is characterized by gentle folded beds that seem to have been affected by syn-sedimentary faulting events that led to the decoupling of these carbonates into decollements with some onlapping on others (orange coloured in Figure A.18a, Figures. A.19a to e). Discrete fracture modelling of these carbonates will later be performed according to the fracture and fault data assessed on these decollement blocks.

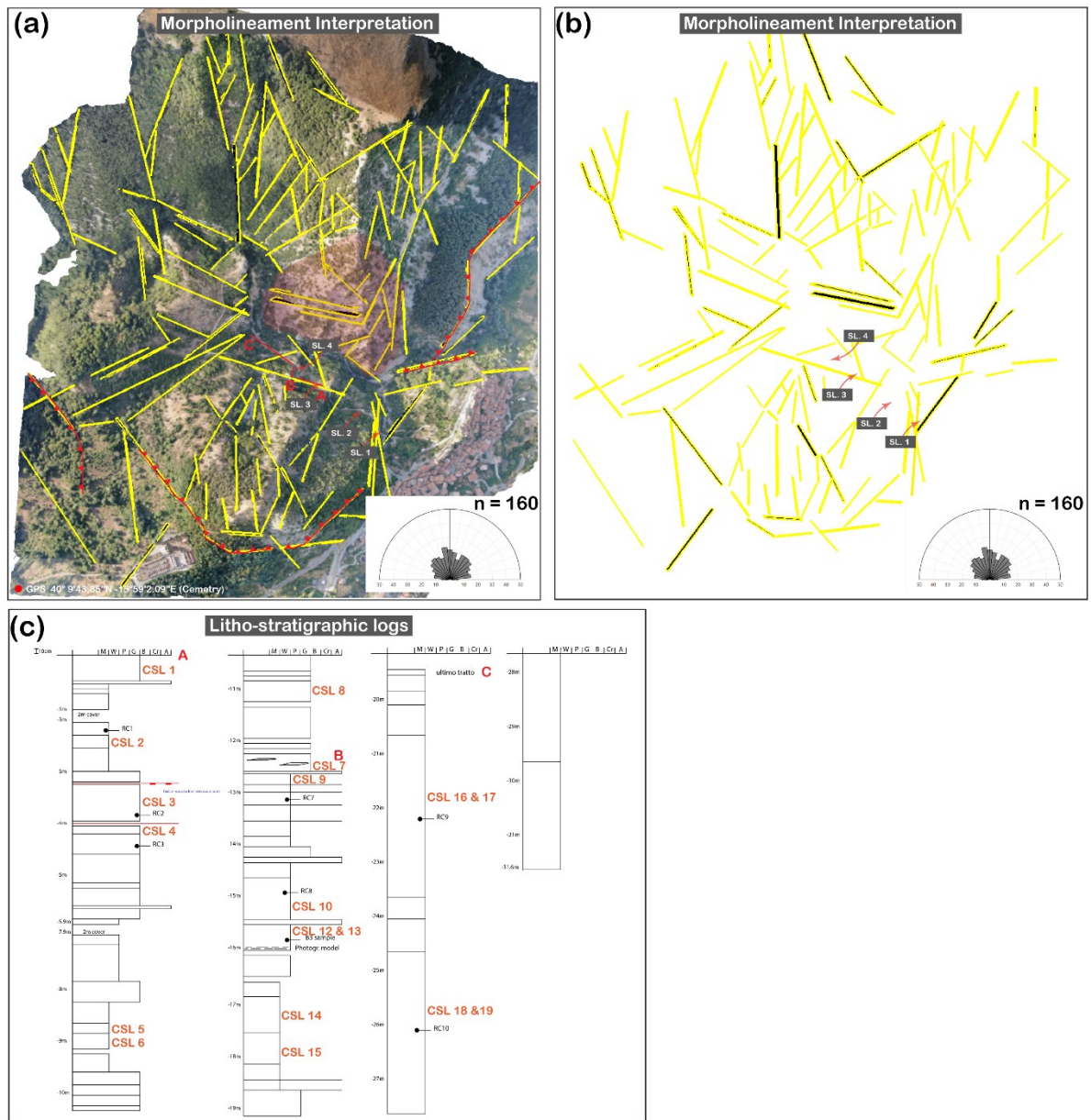
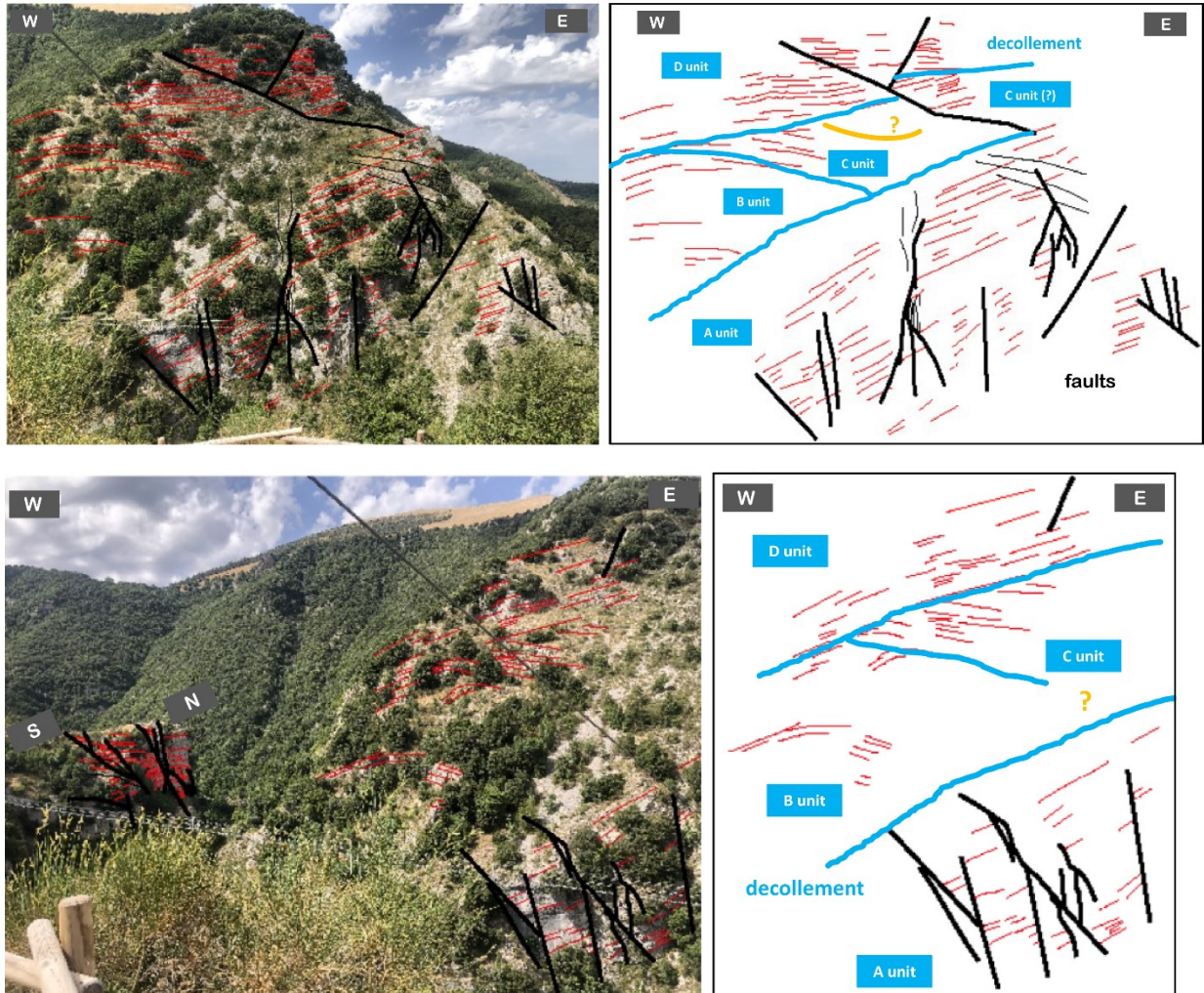


Figure A.18 (a) Morpho-lineament interpretation for the Castelsaraceno carbonates. Location of lithostratigraphic logs is shown, A to C. Linear scanline locations is indicated, SL 1, SL 2, etc. Orange marked region is the decollement sites from Figures. A.19a. Inset shows rose diagram for morpho-

lineament. (c) Lithostratigraphic logs according to certain portions of these carbonates, A to C. Location is shown in Figures A.18a.



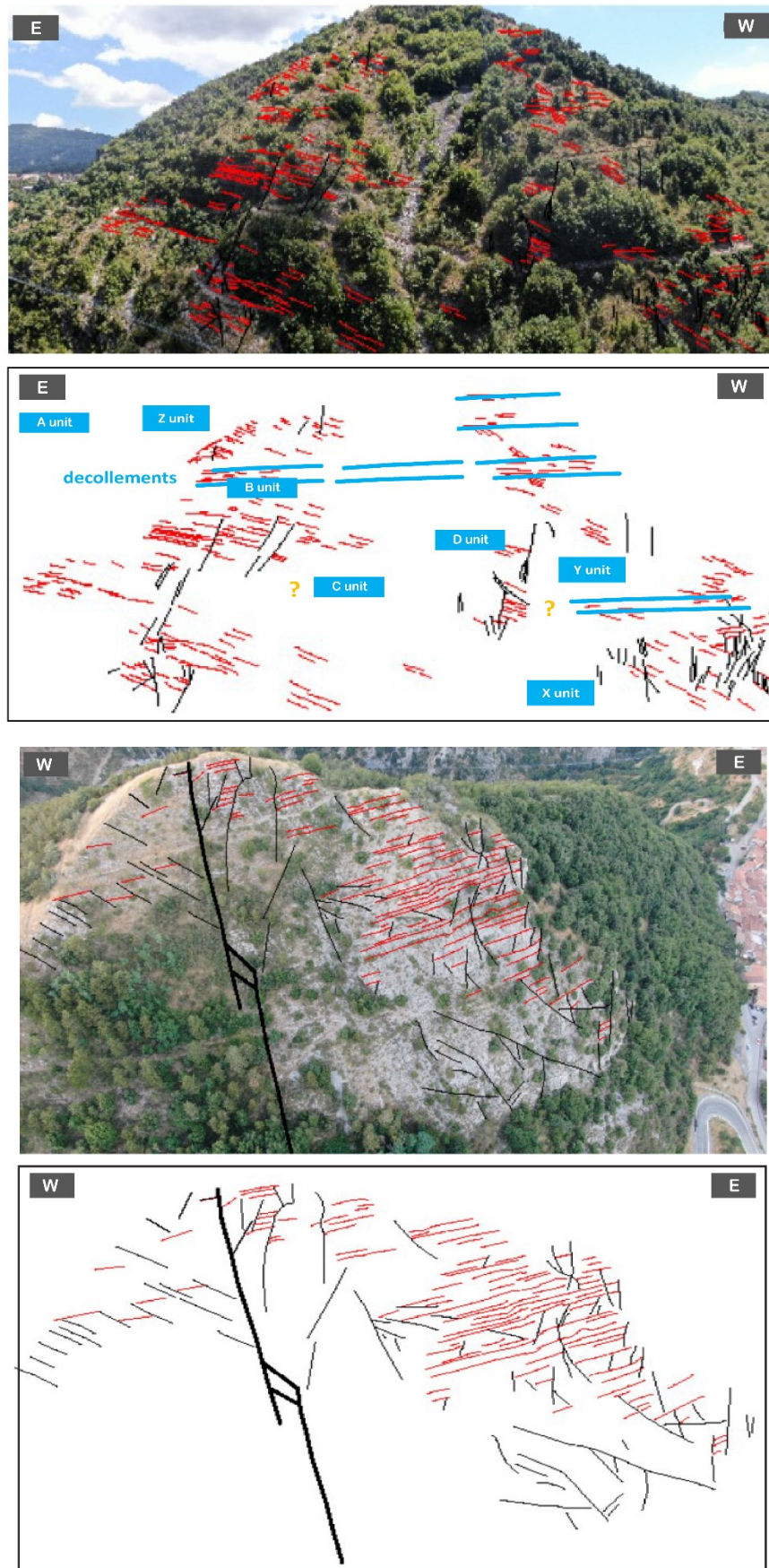


Figure A.19 (a) Castelsaraceno gorge – Northern flank. Site shown in orange (Figure A.18a). Faulted blocks are classified as decollements A to D. Block D overlies an interval bounding block A. (b) Castelsaraceno gorge – Northern flank. Central portion of the carbonate are shown. Sections of blocks B, C and D are shown. (c) Castelsaraceno gorge-middle ridge. Large scale E-W trending antiform, sub-

horizontal hinge. (d) Castelsaraceno gorge – southern flank (view from the north). Central and Western portions. Observed angular unconformities. Some sections of these block can be related to the Northern flank. (e) Castelsaraceno gorge – southern flank, cemetery cliff.

Thin sections of Castelsaraceno carbonates

The Castelsaraceno section consists of an alternation of calcareous horizons and clay horizons (Figure A.20a). The calcareous horizons consist of breccia bodies, with heterogeneous clasts up to 20 cm in size, and debris flow. The occurrence of Orbitolinids and *Salpingoporella dinarica* allow to correlate these deposits to Lower Cretaceous (Figure A.20b & c). On some levels, the calcareous horizons are organic-rich. The clay horizons have a variable thickness from about 10 cm to 40 cm. Sometimes, inside the clay levels, elongated clasts occur. Stylolites nucleated in the matrix follow the boundaries of clasts. These deposits can be attributed to a debris-mud flow occurred into a slope to base slope environments.

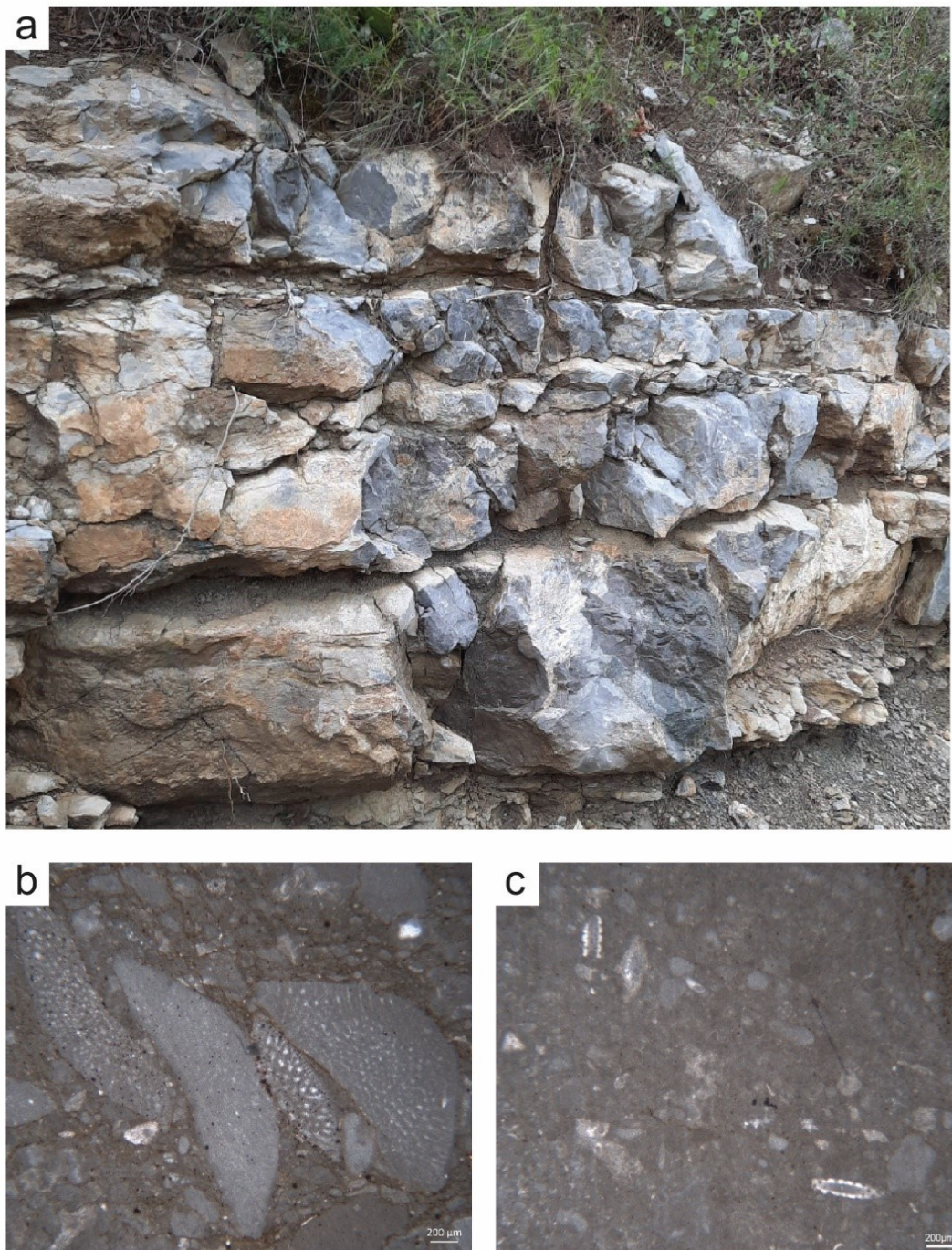


Figure A.20 (a) lithofacies observed in the Castelsaraceno outcrops (b) and (c) Microfacies association of the Castelsaraceno section.

Linear Scanlines

4 Linear scanline surveys were performed here that produced results on attributes related to 326 fractures (Figure A.21). Locations where scanlines were carried out are shown in Figure

A.18. Equal-area lower hemisphere projection fracture data are shown on the stereo plots (Figure A.21b). The multiscale fracture height distribution properties of these carbonates are shown (Figure A.21c). Here, fracture height data are best-fit both by negative exponential distributions at SL 1, SL 3, SL 4 and power-law distribution at SL 2.

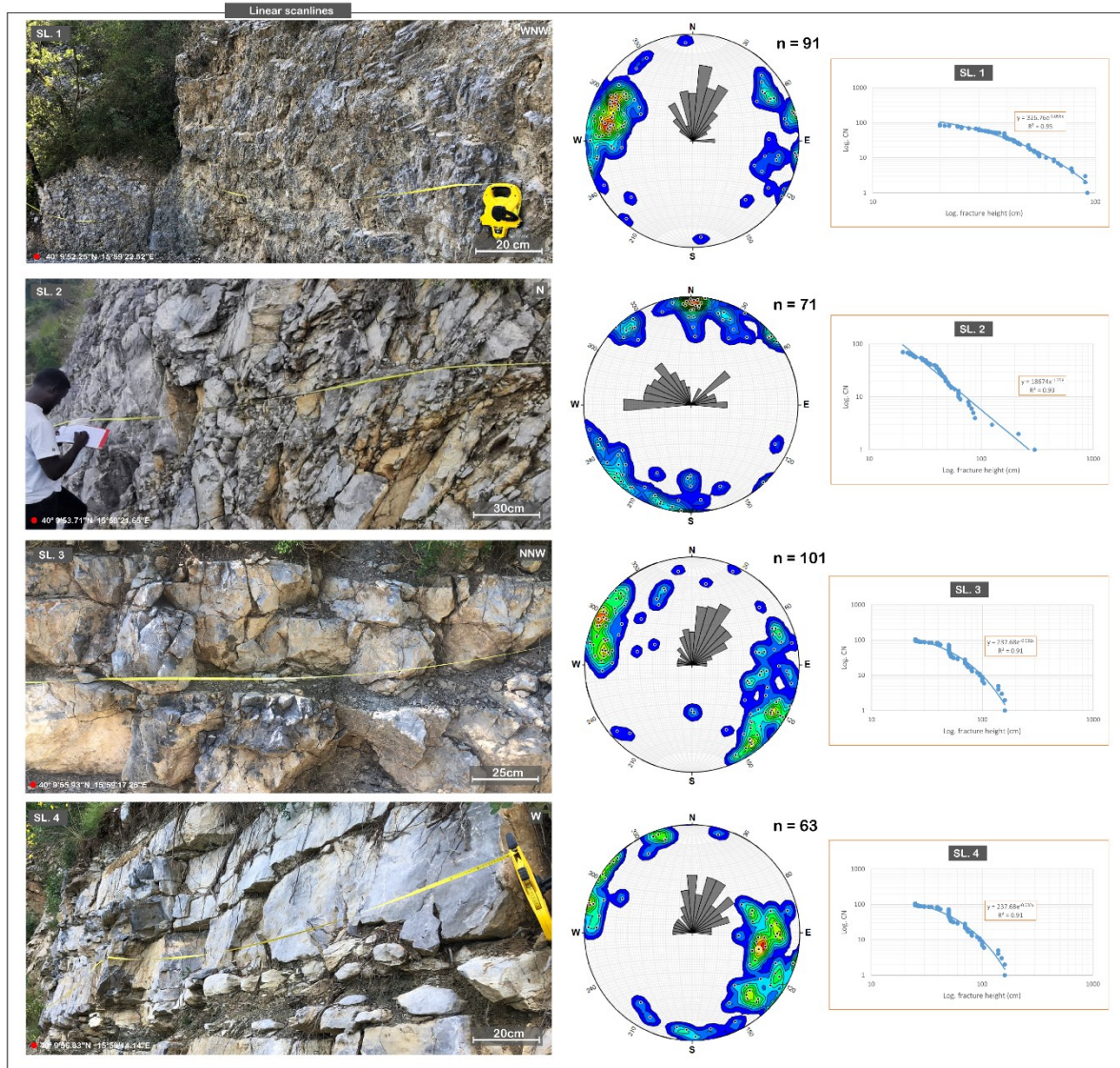


Figure A.21 (a) Linear scanlines measurements (b) Equal-area lower hemisphere stereo plot projection of fracture data for orientations from linear scanline measurements. (c) Multiscale fracture height distribution properties of these carbonates.

Circular scanlines

19 circular scanline measurements were carried out at the Castelsaraceno carbonates (Figure A.18c). Examples of some of the scanlines are shown (Figure A.22a). P20 and P21 results are

projected on histogram and box plot according to the different lithologies analysed (Figs. A.22b & c).

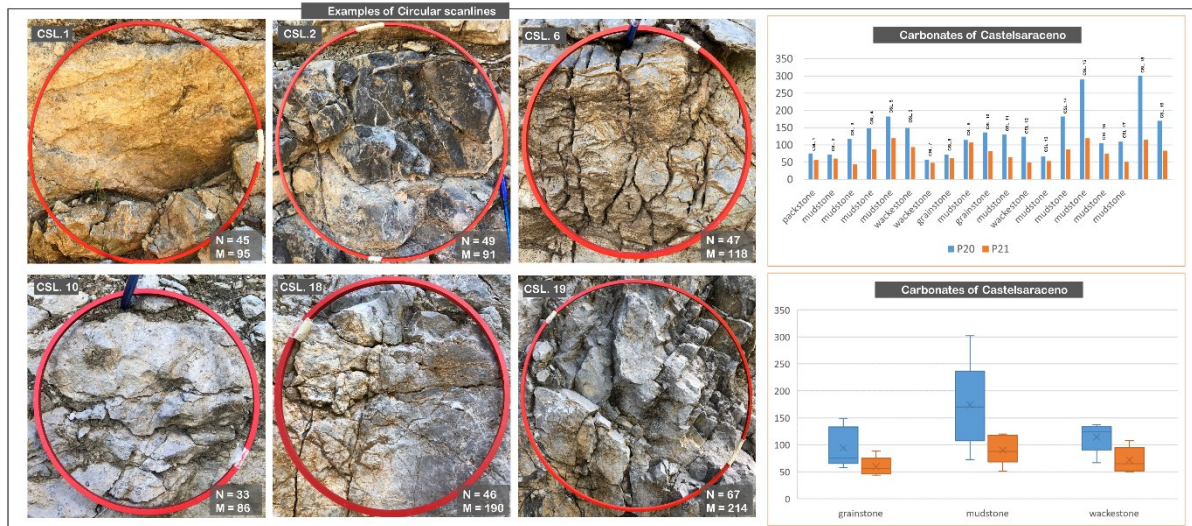


Figure A.22 (a) Examples of some of the circular scanlines from Castelsaraco are shown. (b) and (c) P20 and P21 results are projected on histogram and box plot according to the different lithologies analysed.

Other observations

1. We observed outcrop syn-sedimentary clasts (breccia) that were widely distributed, (Figure A.23, GPS. N40° 9' 55'' E15° 59' 17''). They resemble those documented within the intra-platform basin (Bonie et al., 1974; Italian Geological Bulletin), exposed at the Volle del Noce – Jurassic intra-platform basin with secondary dolomitization – Monte Foro Porta, Upper Triassic - Middle Jurassic.
2. Deformation related to large scale N20-N40 fault reported in the geological map were documented at Station 1. Small faults and associated fractures were measured and reported (Figure A.24). Circular scanlines, linear scanline and window sampling surveys were carried out applied here. Results are presented (Figure A. 24 and scanline 1 previously reported, Figure A.21). The trans-extensional fault with dextral component was oriented striking N220/74 (1) with a pitch of 172. Fractures here were oriented N158/56 (2), N135/40 (3), N152/72 (4), N210/71 (5), N240/44 (6), N242/30 (7), N35/75 (9), N20/40 (10) and N190/45. The bedding was about N355/10.

3. Evidence of flexural slip processes are documented along the trail that exposures the carbonates. We observed bed- parallel slip at station 2 (Figure A.25), and studied deformation at the hanging-wall flat, and foot-wall flat). Associated fractures and small faults fractures were also documented. Cleavages which could be reactivated later as reverse faults were also recorded. This site shows the flat geometry of a flat-ramp-flat thrust process (Savage & Cooke, 2003; Ehrlich & Gabrielsen, 2004). Measurements acquired here were for fractures - N236/12 (1), N70/62 (2), N62/72 (3), N190/55 (4), N205/6 (5), N52/82 (6) and N170/55; Reverse fault zone with measurement - N228/34 (7), the main fault planes - N120/25 (8), N152/45 and beddings orientated - N222/16 (10), N213/11 (11).
4. Another site showing evidence of flexural slip process was station 5, where we document flat-ramp-flat geometry of thrusting process (Figure A.26). Bedding measurements from the footwall and hanging wall of the thrust are recorded. High angle faults that cut across this structure are also documented.
5. We documented the architecture and deformation related to small extensional fault at station 3 and station 4 (Figure A.27 & A.28).
6. Similar to what was documented at Raparello, we observe dark coloured bitumen-rich carbonate rocks (smell of hydrocarbon), samples were collected for further analyses outside this scope of this study. (Figure A.29). Some of the earlier mentioned syn-sedimentary clasts have hairline veins infiltrated by Hydrocarbon.

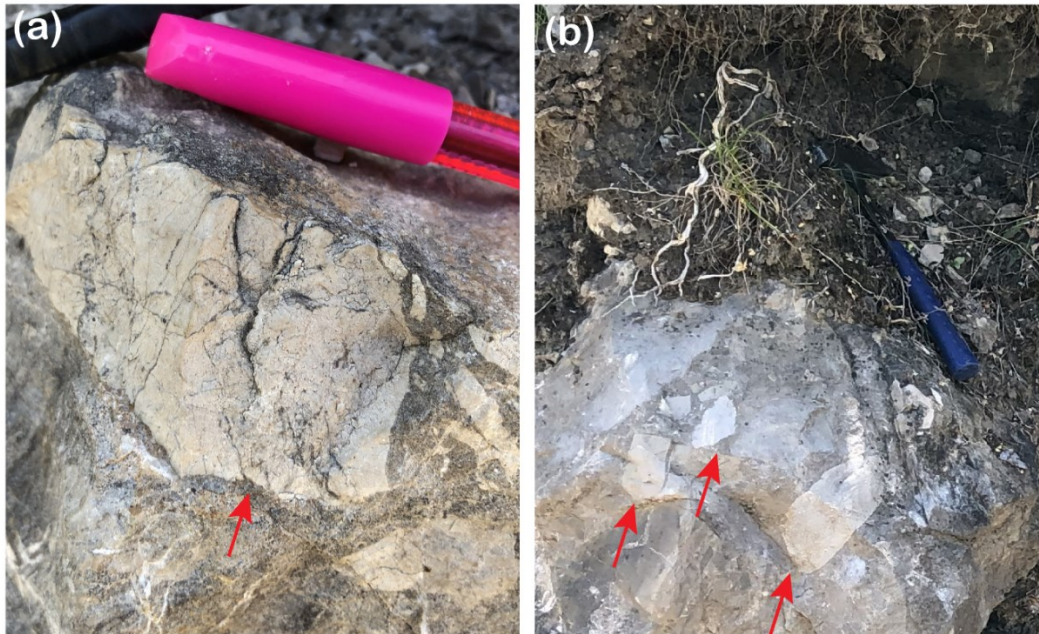
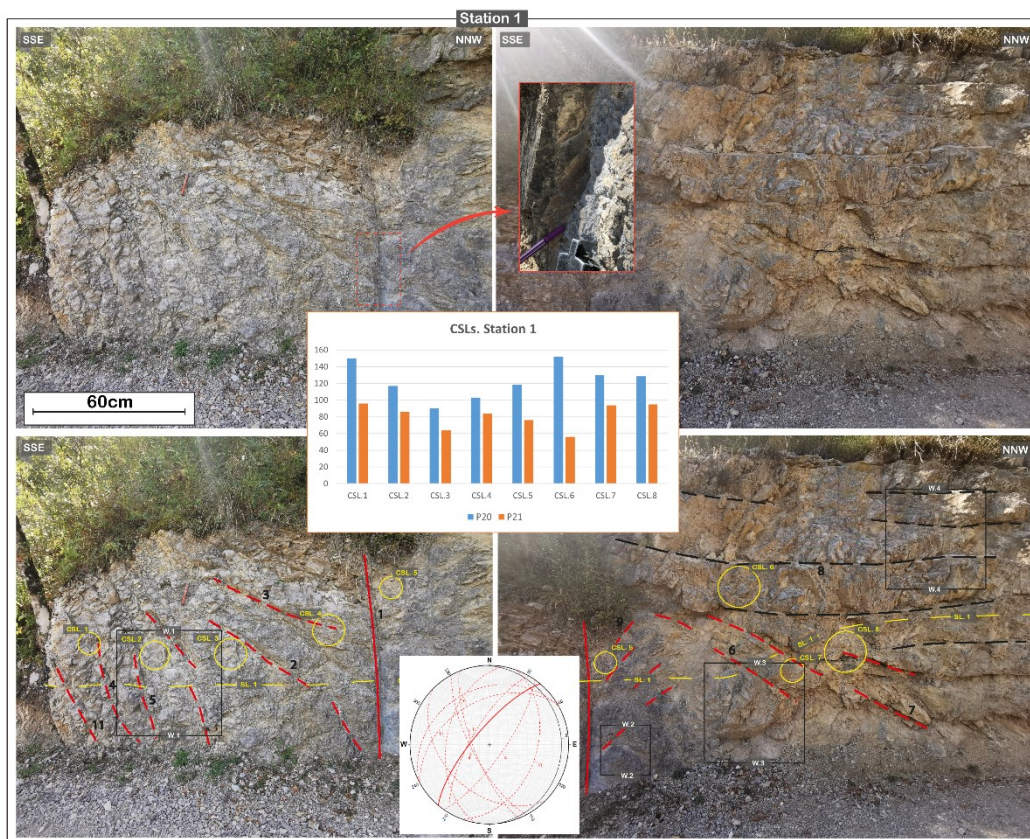


Figure A.23 Syn-sedimentary breccias with hairline veins infiltrated by hydrocarbon. GPS N40° 9' 55'' E15° 59' 17''



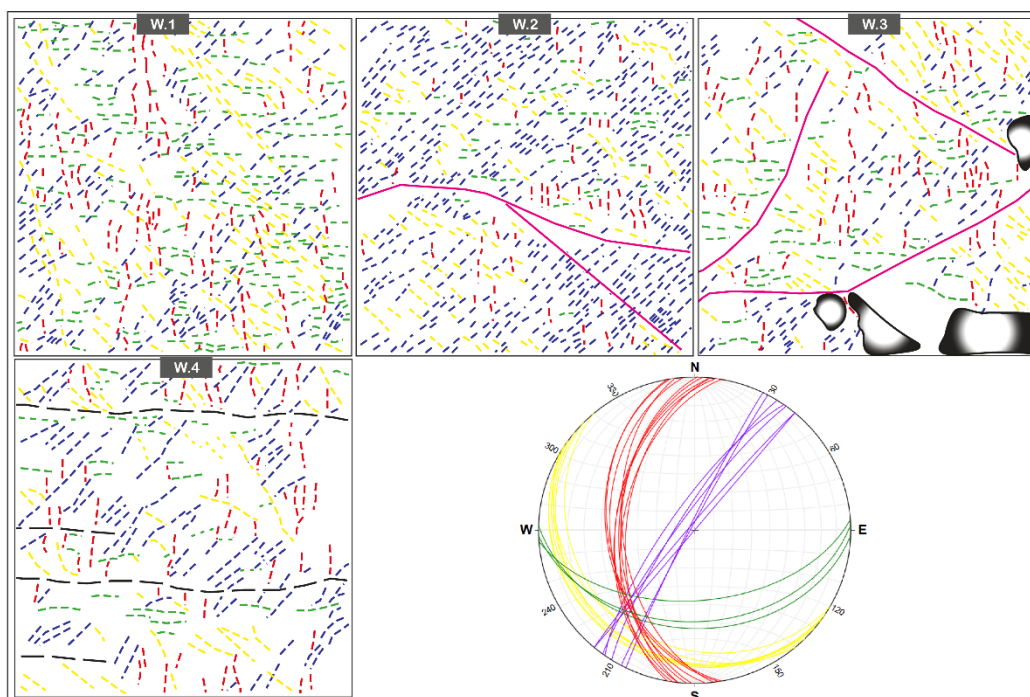
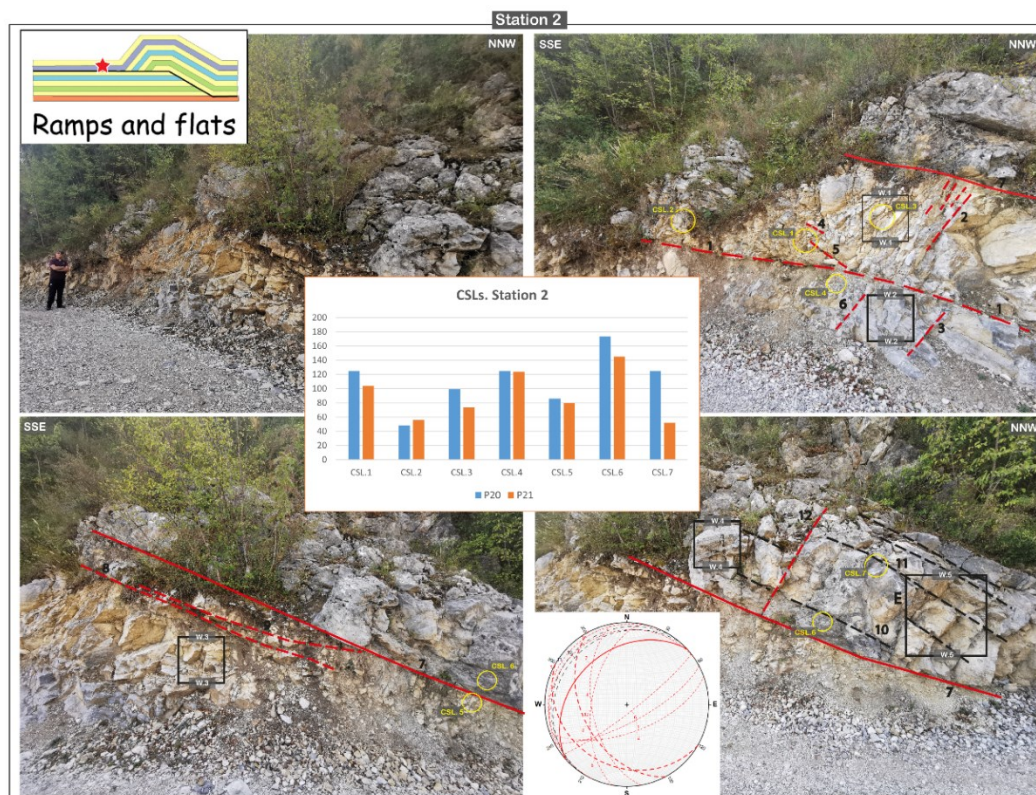


Figure A.24 (a) & (b) Fault damage zone related to the map scale N30-N40 fault. Architecture of the damage zone is studied, and results presented. $40^{\circ} 9'52.25''\text{N}$ $15^{\circ}59'22.53''\text{E}$. Location of scanline No. 1.



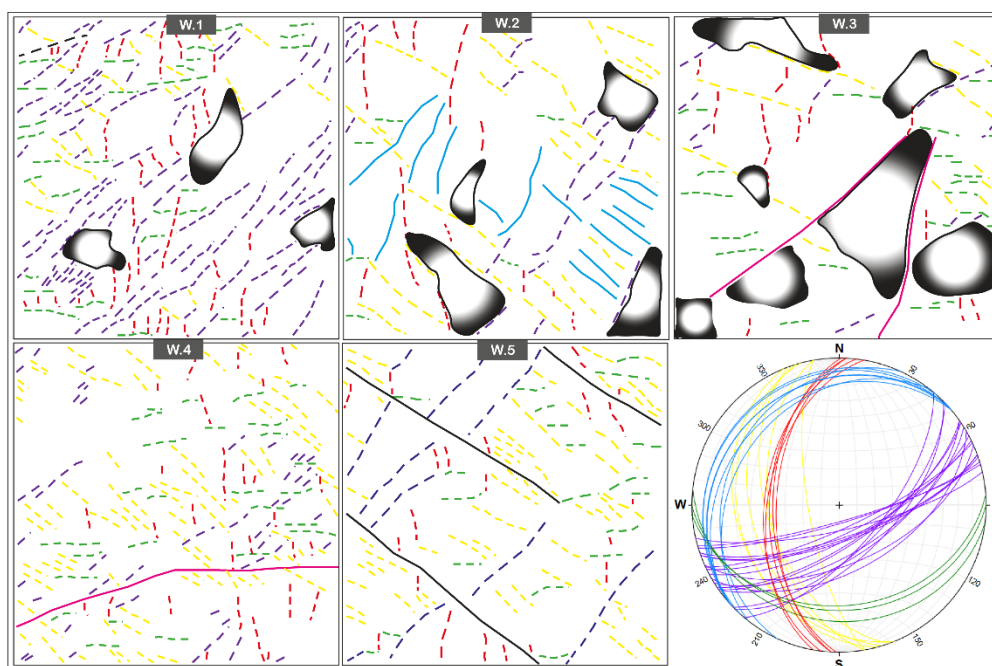


Figure A.25 Site showing evidence of flexural slip processes and its related deformation. GPS 40° 9'53.93"N 15°59'20.88"E

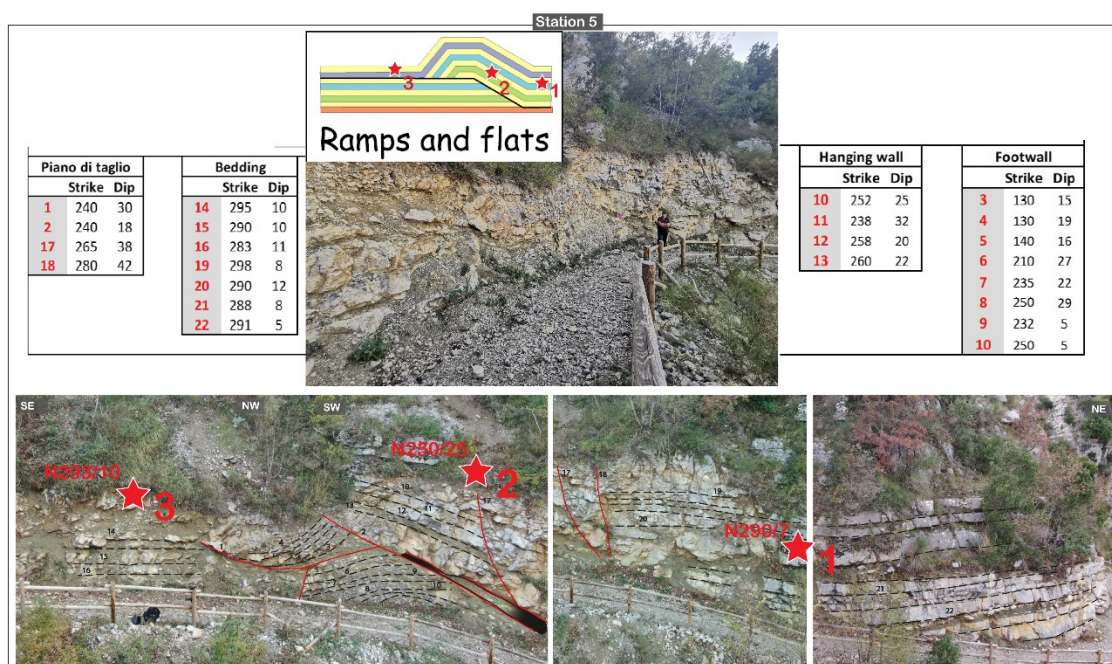


Figure A.26 Site showing evidence of flexural slip processes and its related deformation. The flat-ramp-flat geometry is studied. GPS 40° 9'57.23"N 15°59'14.30"E

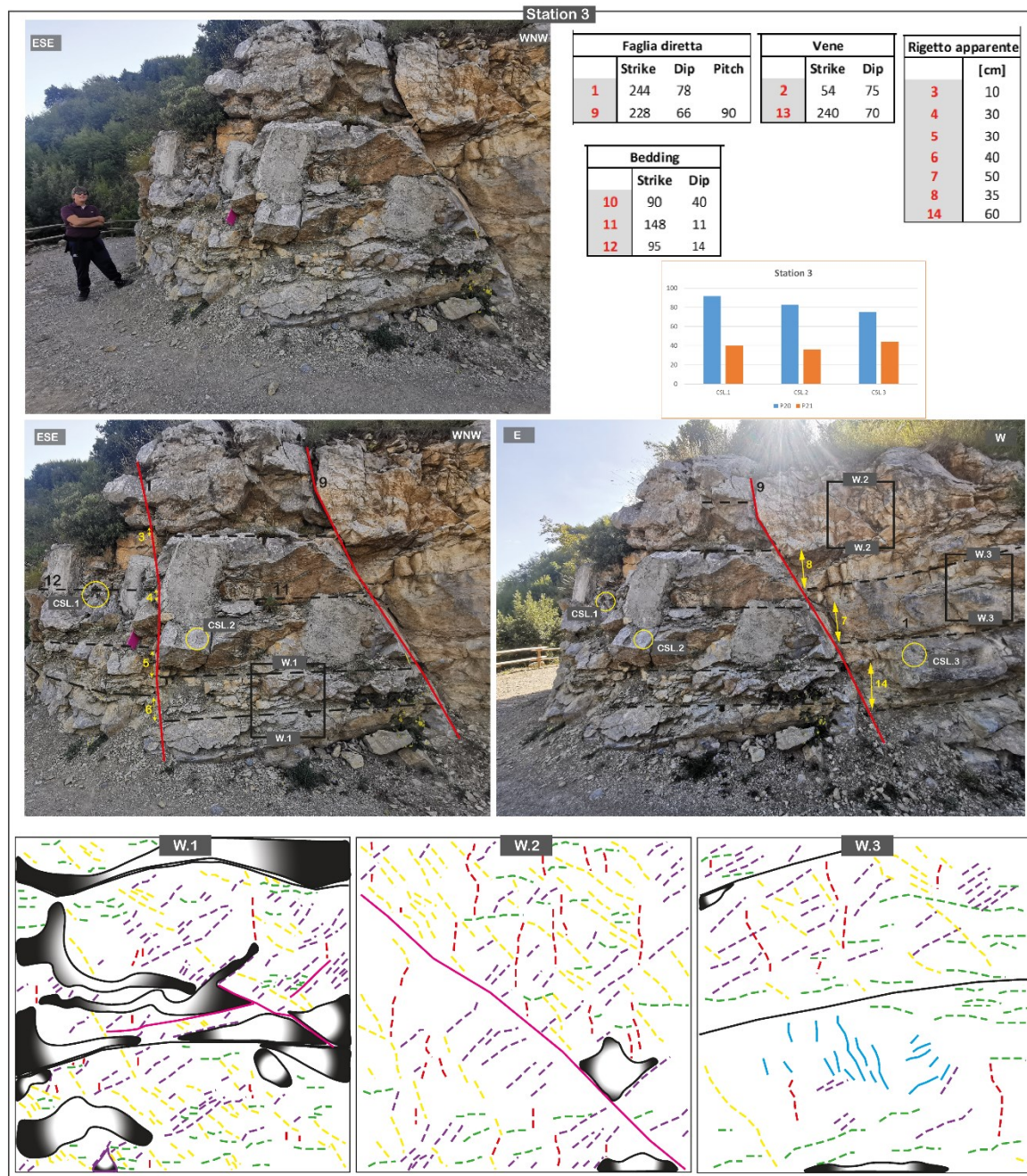


Figure A.27. Small fault zone and related deformation. GPS 40° 9'55.72"N 15°59'17.15"E

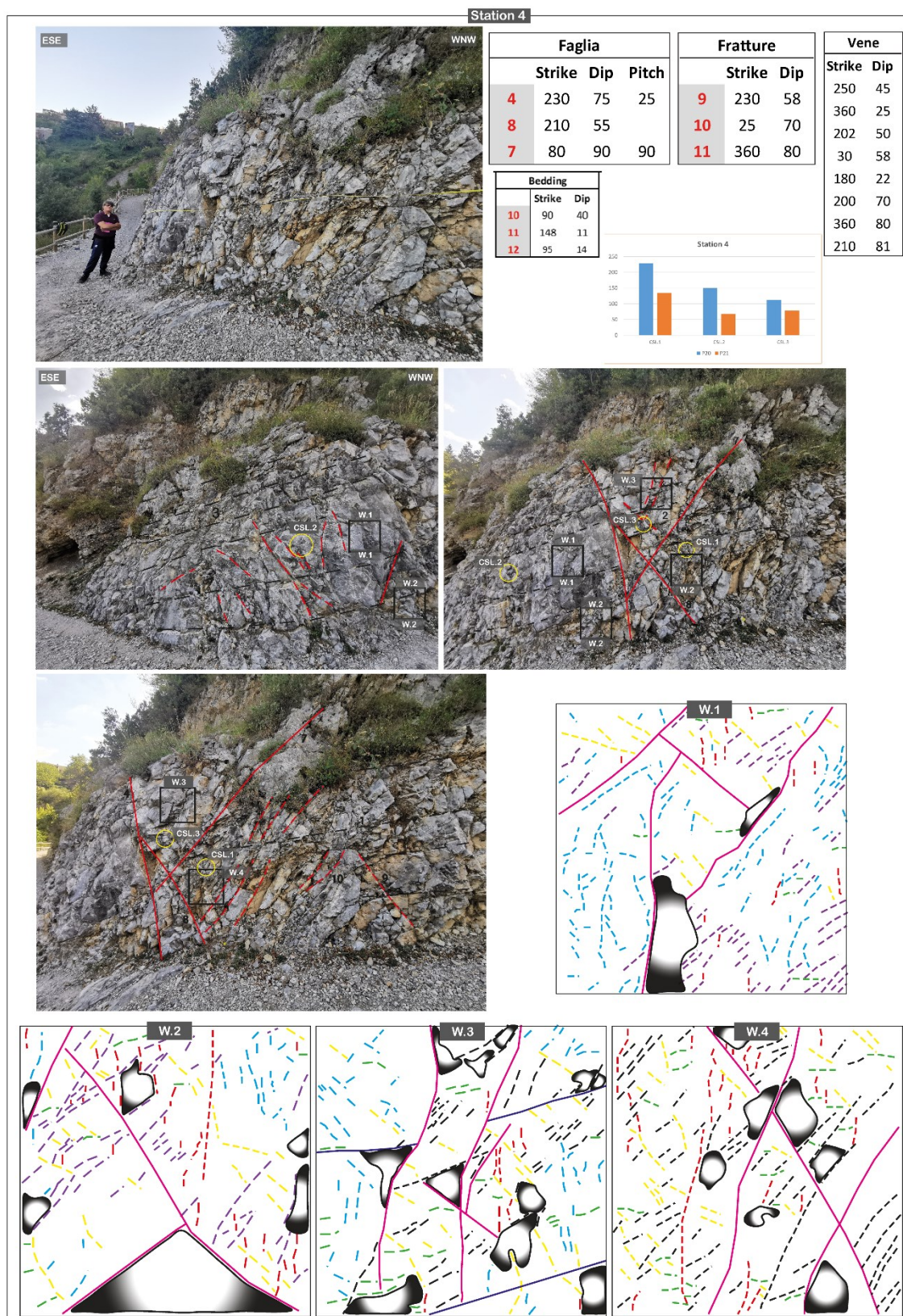


Figure A.28 Small fault zone with visible displacement in bedding and related deformation. GPS 40° 9'53.71"N 15°59'21.65"E



Figure A.29 Tar-rich mudstone

A.6 Discrete Fracture Network modelling for the Castelsaraceno carbonates

Discrete Fracture Network (DFN) modelling of these carbonates is to be carried out according to the earlier assessed decollements, A, B and D. Linear scanline 1 and linear scanline 2 by correlated bedding attitude belongs to decollement A. Linear scanline 3 belongs to decollement B and linear scanline 4 belongs to the D decollement, hence multiscale modelling for these three blocks is proposed.

Data collected from these sites are processed and used as input for the DFN modelling processes. DFN inputs are presented, for field and digital structural interpretations (Table A.1 & Table A.2). Two geocellular volumes are proposed to be constructed for each of the different decollements. One represents field data (fractures) and the other data extracted from 3D virtual outcrop models (fractures, faults). Here, we will build a 5m-side geocellular volume representative of several stacks of single carbonate beds with 10cm-cell-size, representing the smallest structural element assessed in the field. This geocellular volume will contain 10 sub-volumes, 50cm each representing the single carbonate beds, since the carbonates assessed in the field had beds ranging from 45cm – 65cm. For the digital outcrop sized model, we will build a 50m-side geocellular volume with 1m as cell size. This geocellular volume will contain 10 sub-volumes, 5m-each representing the stacks of single carbonate bed initially modelled.

The outcome will be multiscale modelling of these carbonates to assess their fluid storage and transport properties. The permeability results will be used to assess the 2D horizontal anisotropy ratio (eclipses) and hence tendency of fluid-flow within these rocks.

A.7 Results from DFN modelling

Based on the table presented, i.e., Table A.1 & Table A.2 from field data acquisition, we focused on the computation at first the field scale and then digital scale. Field fracture data are segregated and shown for SB and NSB fractures (Table A.1).

The graphical

For the field scale, fracture sets are presented together with multiscale fracture height distribution property graphs (Figure A.30). DFN graphical results are shown in Figure A.31 and A.32 and also in Table A.2.

For the large-scale analysis, the 3D virtual outcrops for the decollement A, B and D are presented (Figs. A.33a & b). There, 114 planes (block A), 54 (block B) and 84 (block D) fault planes were extracted for the large-scale geocellular volume computations. The planes were first processed by plotting the extracted data of their fault geometries on an equal area lower hemisphere stereo plot (Figure A.34). Multiple fault sets were extracted, and multiscale fracture height distribution property graphs were assessed according to the fault sets generated and stereo plots are shown for the different configurations/decollements (Figure A.34). Graphical results are shown in Figures A.35 and A.36. and in Table A.3. The ellipses (2D anisotropy ratios) for the computed permeabilities are shown in Figure A.37. In summary, moving average diagram (Munro et al., 2012) is shown for both field and digital fracture data (Figure A.38).

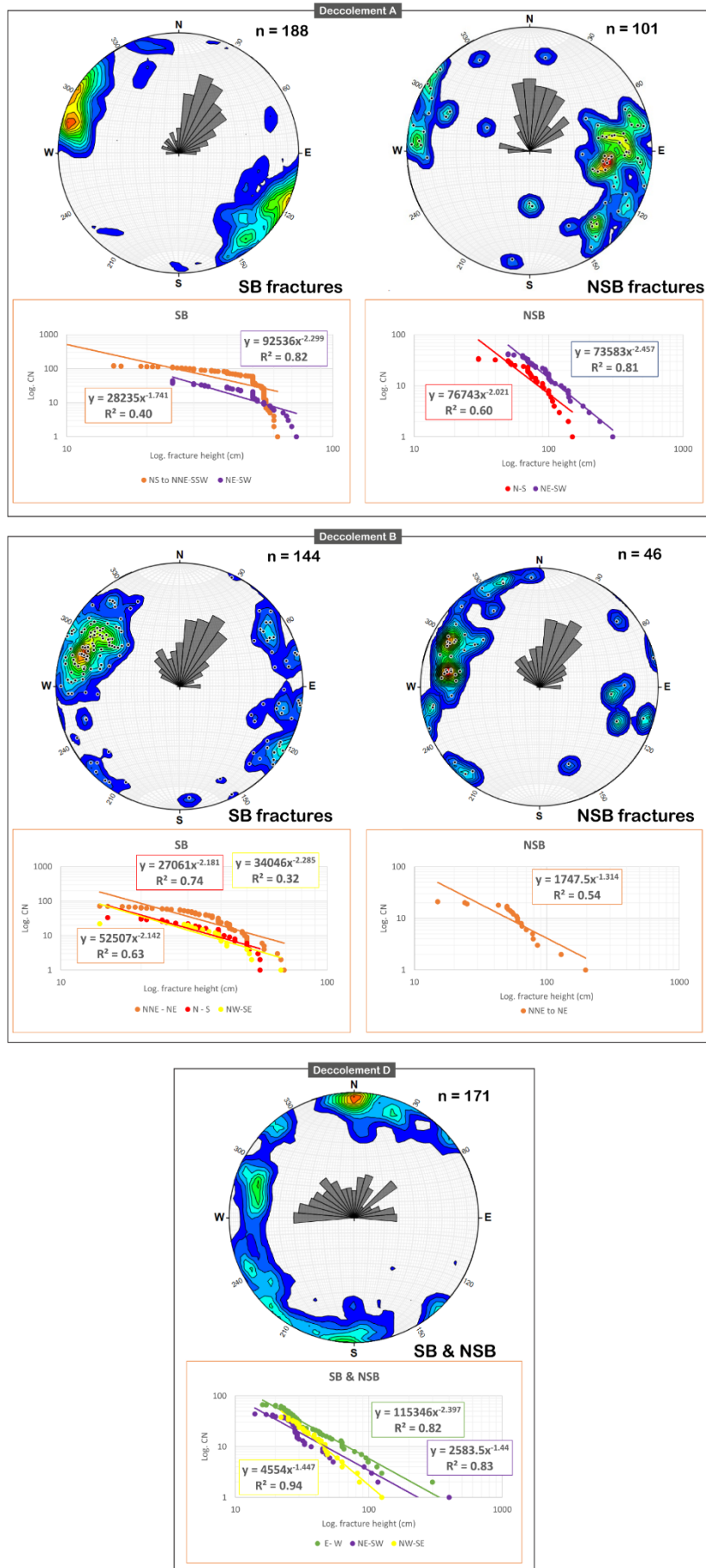


Figure A.30 Field data: stereoplots and multiscale fracture height distribution plots

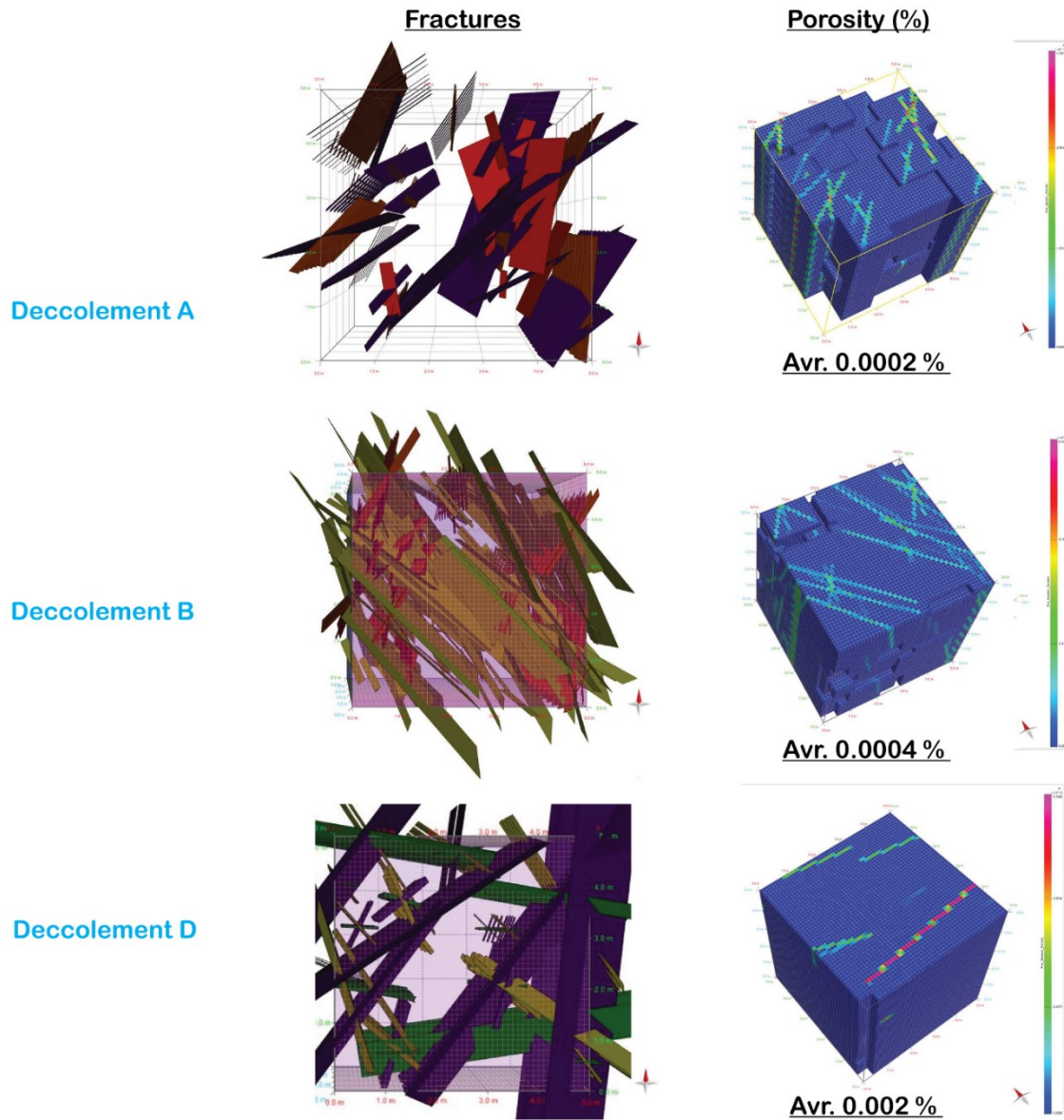


Figure A.31 Field scale: porosity results

Table A.1 Field data (5m scale) DFN inputs.

	Field										
Study Area	Decc. A_SB		Decc. A_NSB		Decc. B_SB			Decc. B_NSB	Decc. D_more SB (mixed)		
Input Parameters	SET N-S to NNE-SSW	SET NE-SW	SET N-S	SET NE-SW	SET NW-SE	SET N-S	SET NNE to NE	SET NNE to NE	SET NW-SE	SET NE-SW	SET E-W
Best-fit (strike, dip) RHR	N203/88	N231/78	N184/61	N221/81	N140/82	N8/80	N28/70	N30/69	N322/83	N31/76	N96/76
Fisher Distribution	32	35	31	25	25	65	44	23	32	20	52.7
Min Height (cm)	10	25	30	50	14	15	14	15	22	14	14
Max Height (cm)	62	73	150	300	67	56	69	196	125	400	400
Min Length (cm)	40	100	60	100	56	60	56	30	88	56	56
Max Length (cm)	248	292	300	600	268	224	276	392	500	1600	1600
Fractal D-value	1.74	2.3	2.02	2.46	2.29	2.18	2.14	1.31	1.45	1.45	2.4
Aspect Ratio	1:4	1:4	1:2	1:2	1:4	1:4	1:4	1:2	1:4	1:4	1:4
Mechanical Aperture, E (mm)	0.67	0.67	0.67	0.67	1.65	1.65	1.65	1.65	1.92	1.92	1.92
Hydraulic Aperture, e (mm)	1E-03	1E-03	1E-03	1E-03	6E-03	6E-03	6E-03	6E-03	1E-02	1E-02	1E-02
Average JRC	11.01	11.01	11.01	11.01	11.57	11.57	11.57	11.57	9.91	9.91	9.91
P30 (1/m ³)	1.17	1.06	1.05	1.06	1.04	1.06	1.13	1.04	1.06	1.07	1.11

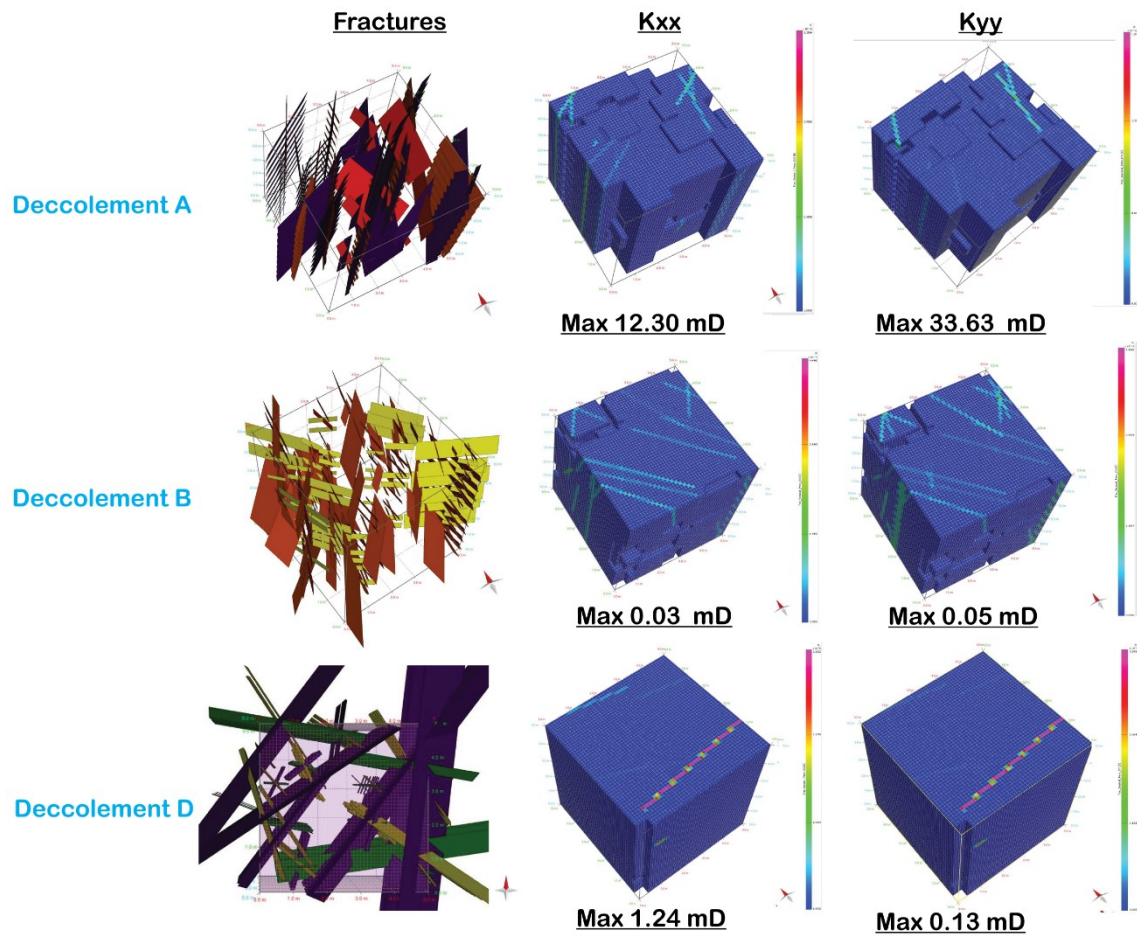


Figure A.32 Field scale: permeability results

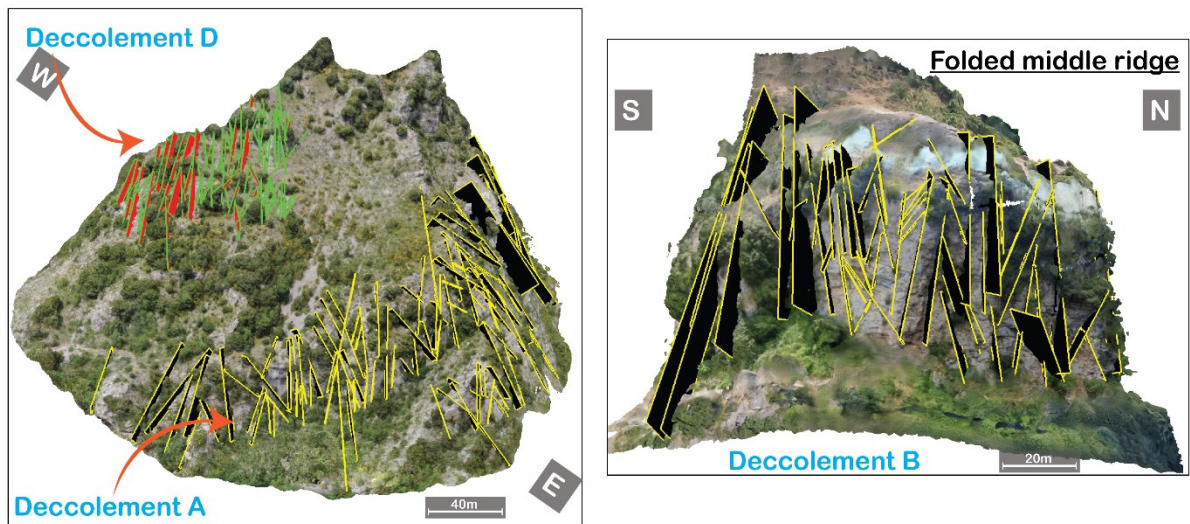


Figure 33 3D digital outcrop model shown according to respective décollements. (a) GPS 40°10'4.91"N 15°59'10.10"E (b) GPS 40° 9'59.47"N 15°59'20.68"E

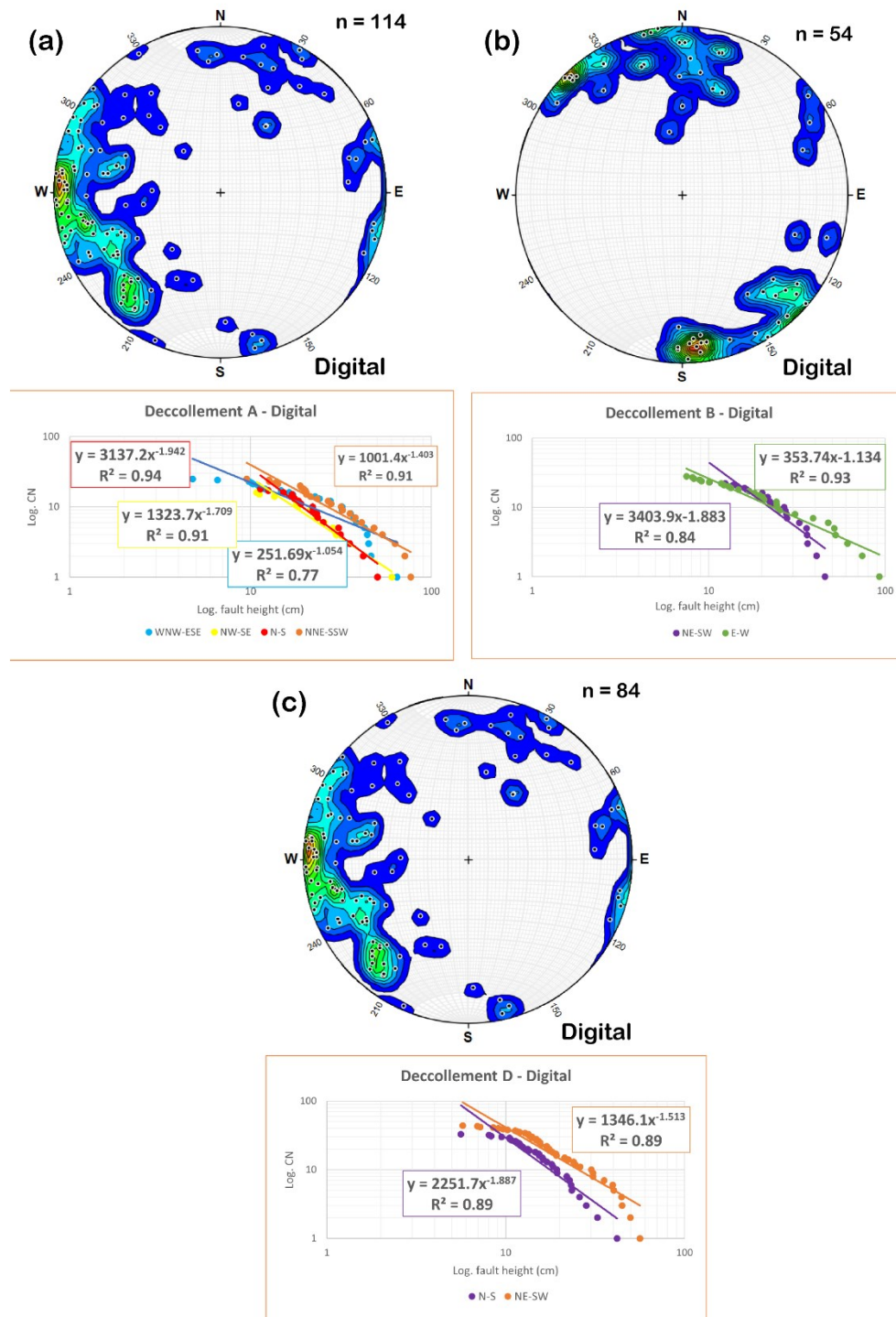


Figure A.34 Digital outcrop: stereoplots and multiscale fracture height distribution plot

Table A.2 Digital outcrop (50m scale) DFN inputs.

	Digital Outcrop							
Study Area	Decc. A				Decc. B		Decc. D	
Input Parameters	SET WNW- ESE	SET NW-SE	SET N-S	SET NNE-SSW	SET NE-SW	SET E-W	SET N-S	SET NE-SW
Best-fit (strike, dip) RHR	N310/70	N330/67	N357/81	N28/77	N47/82	N263/81	N4/85	N54/68
Fisher Distribution	123	52.5	58.6	83.5	77.5	82.6	89.3	39.7
Min Height (m)	4.79	10.8	11.4	9.5	7.5	10.1	5.6	5.7
Max Height (m)	64.4	60.5	50.4	76.5	92.7	45.7	41.8	56.4
Min Length (m)	9.58	21.6	22.8	19	15	20.2	11.2	11.4
Max Length (m)	128.8	121	100.8	153	185.4	91.4	83.6	112.8
Fractal D-value	1.05	1.71	1.94	1.4	1.88	1.13	1.89	1.51
Aspect Ratio	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2
Hydraulic Aperture, e (mm)	1E-03	1E-03	1E-03	1E-03	1E-02	6E-03	1E-03	1E-03
P32 (m ⁻¹)	0.06	0.03	0.03	0.08	0.04	0.09	0.03	0.07

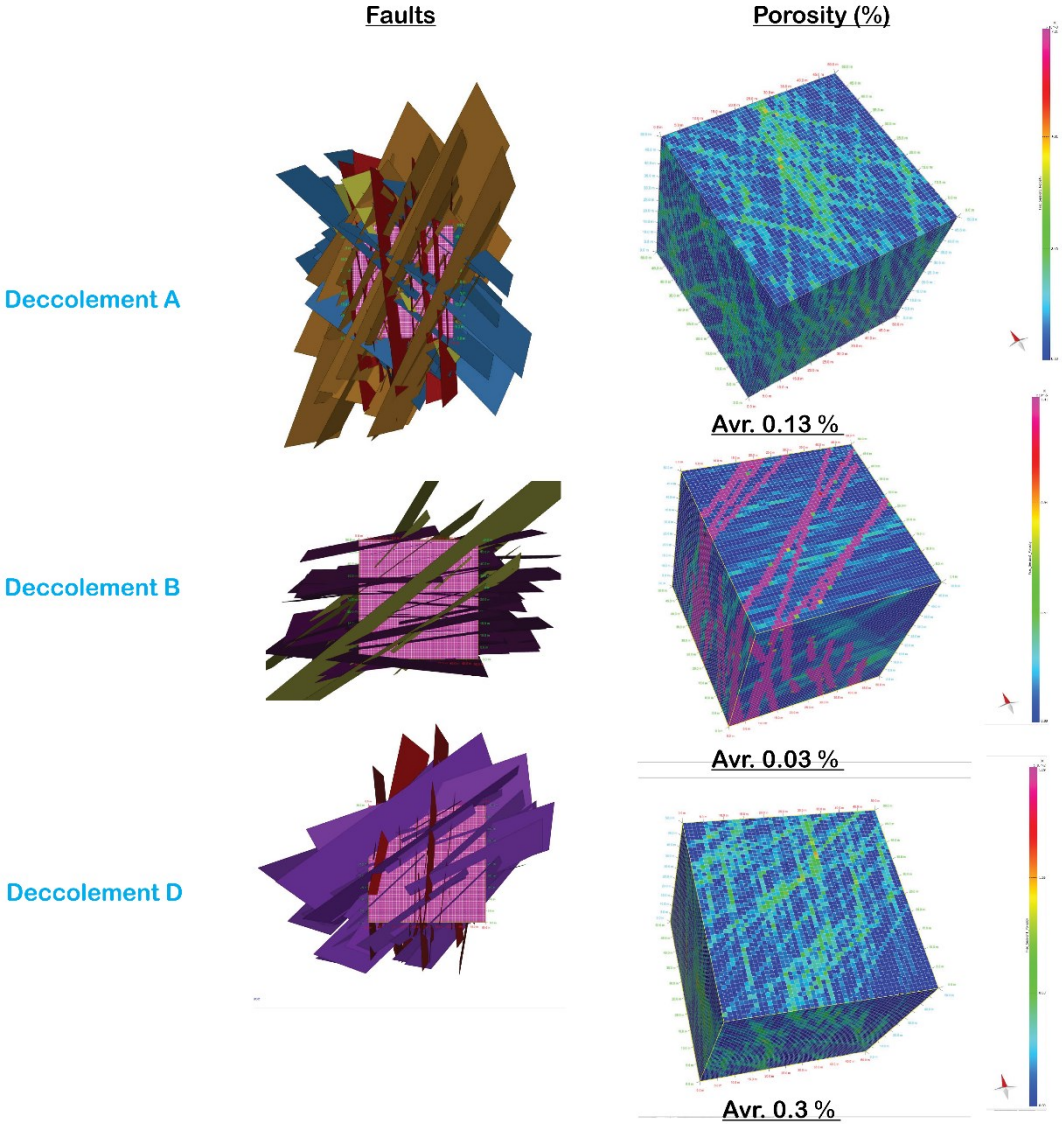


Figure A.35. Outcrop scale: porosity results

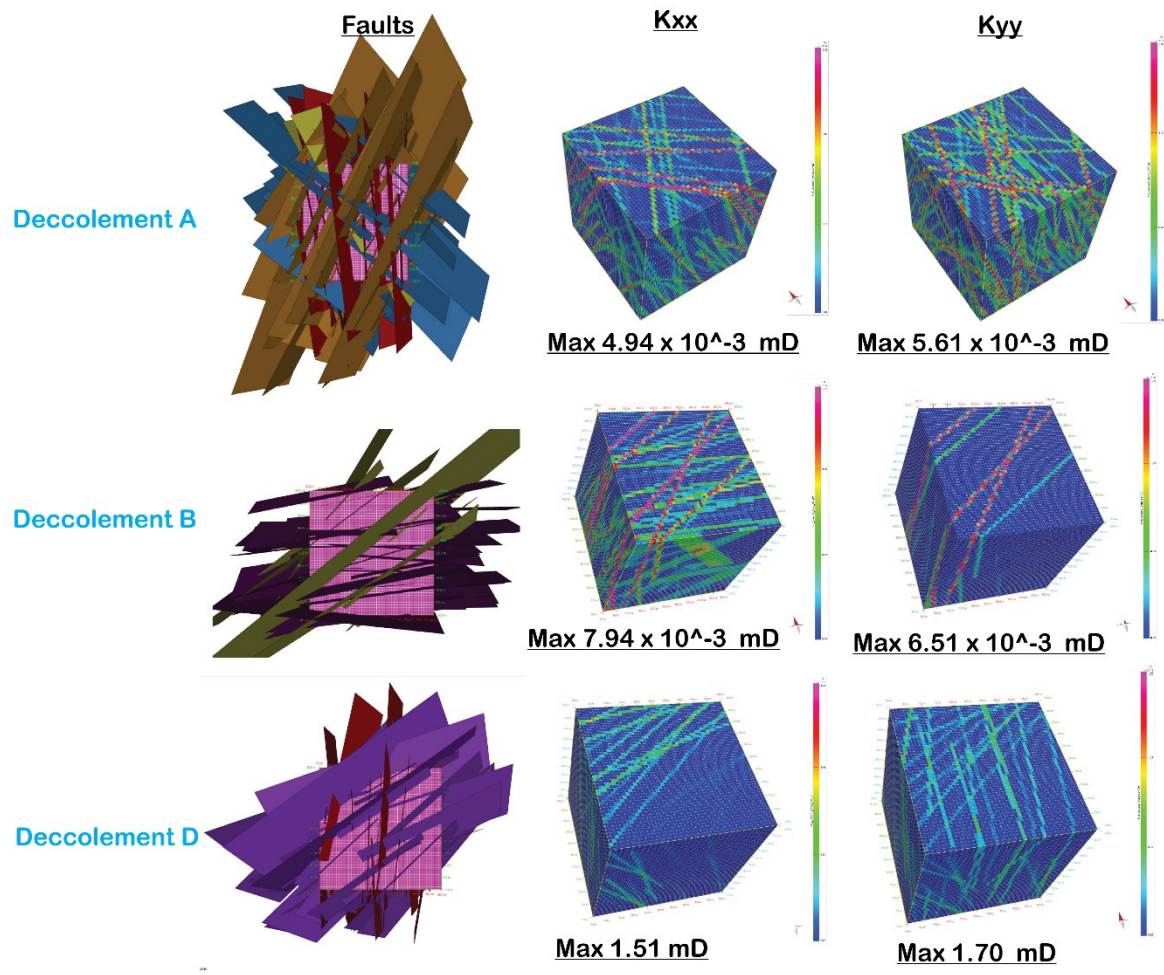


Figure A.36. digital outcrop scale: permeability results

Table A.3 DFN results.

		Field		
		Decc. A	Decc. B	Decc. D
Volumes		5m	5m	5m
Aperture Prop. L	Average porosity (%)	0.0002	0.0004	0.002
	Max porosity (%)	0.070	0.0114	0.015
	Max Permeability , Kxx (mD)	12.30	0.03	0.24
	Max Permeability , Kyy (mD)	33.63	0.05	0.13
	2D horizontal permeability tensor	2.73	1.72	1.80

		Digital		
		Decc. A	Decc. B	Decc. D
Volumes		50m	50m	50m
Aperture Prop. L	Average porosity (%)	0.13	0.03	0.31
	Max porosity (%)	0.72	0.34	1.89
	Max Permeability , Kxx (mD)	4.94E-03	7.94E-03	1.51E+00
	Max Permeability , Kyy (mD)	5.61E-03	6.51E-03	1.70E+00
	2D horizontal permeability tensor	1.14	1.22	1.13

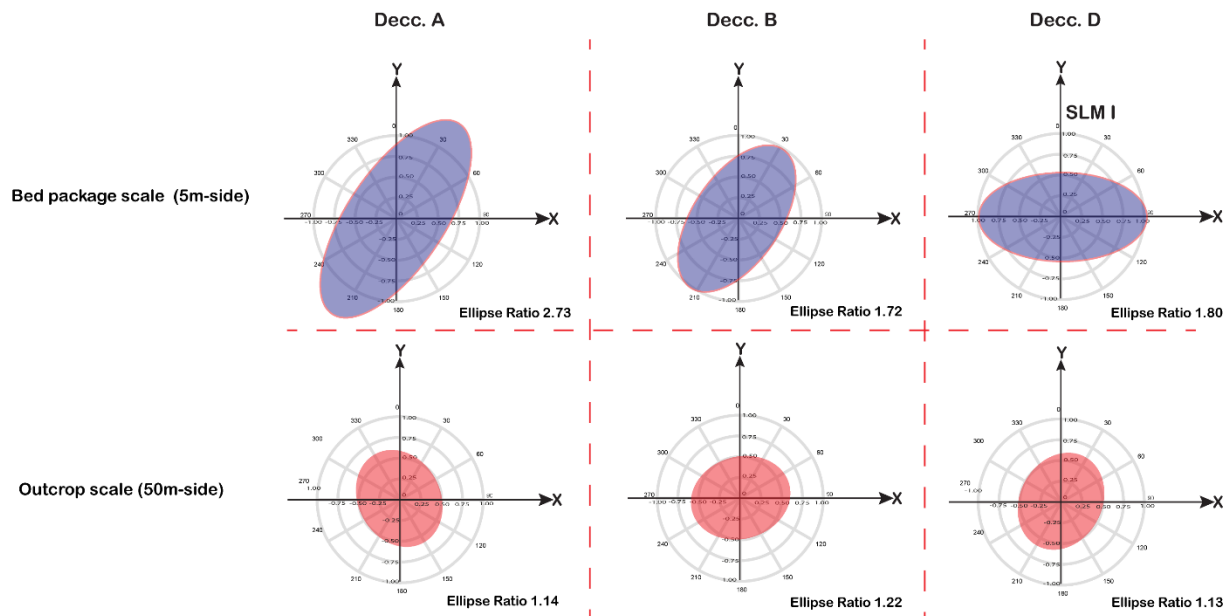


Figure A.37 2D permeability anisotropy ratios for field and outcrop scale

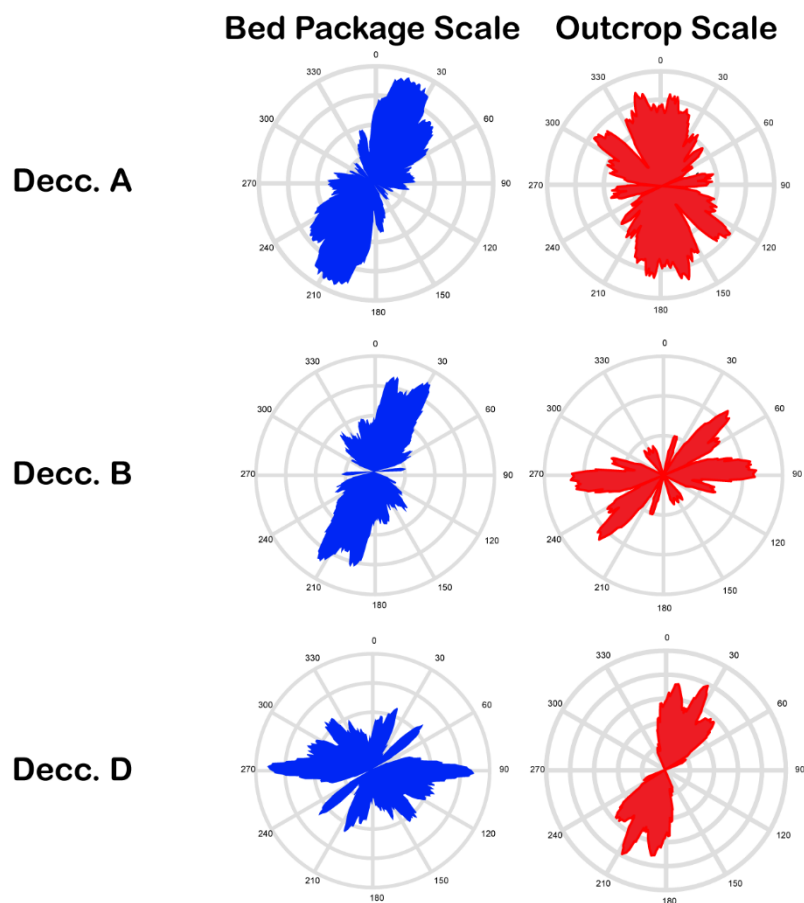


Figure A.38 Moving Average rose diagrams (equal area, aperture of 9°, weighing factor of 9; Munro et al., 2012), according to the scales and decollements investigated

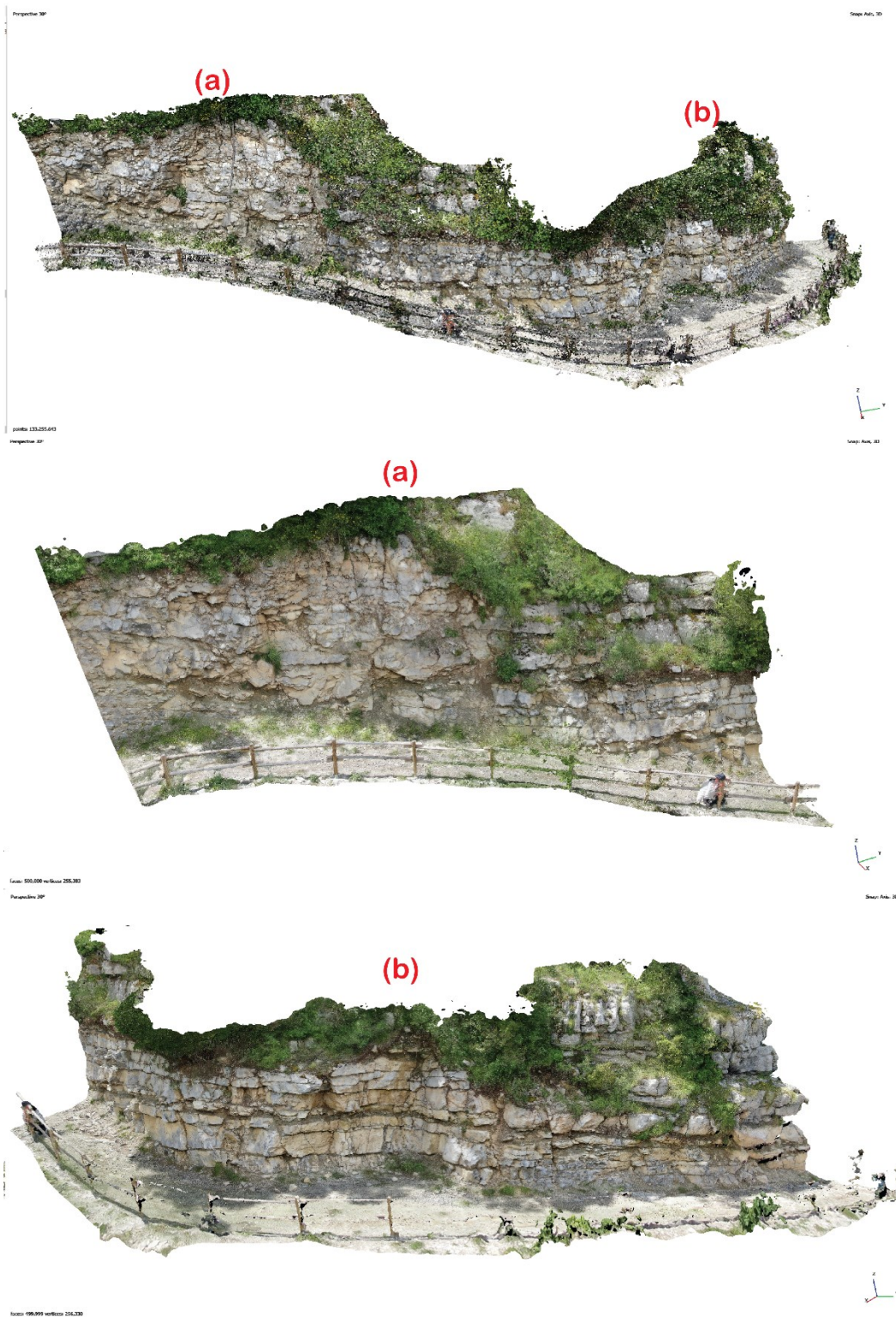


Figure A.39. Other 3D virtual outcrops from Castelsaraceno outcrops. GPS 40° 9'57.21"N 15°59'14.32"E

Perspective_30°

Snaps: Vertices, 2D

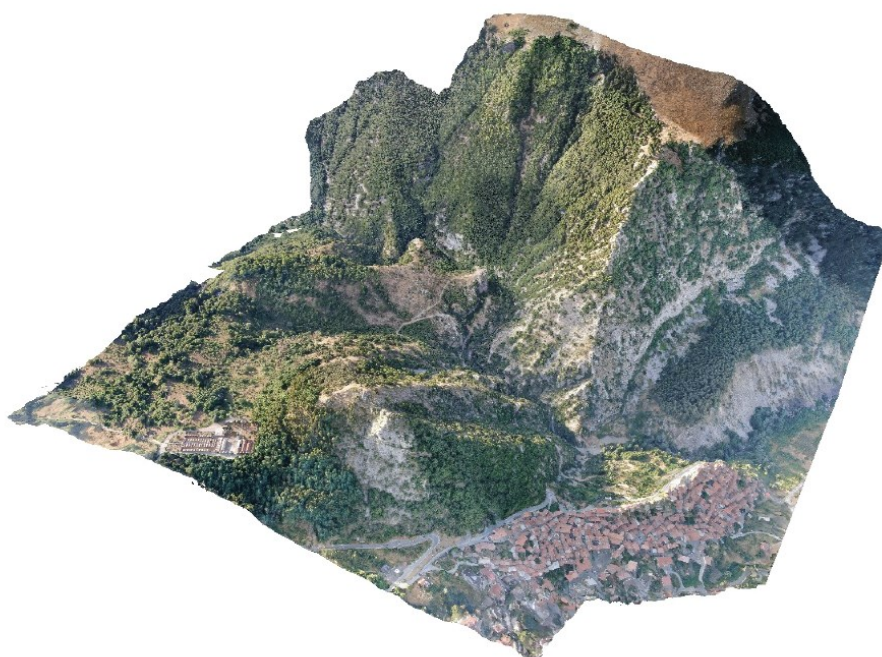


faces: 6,191,521 vertices: 3,105,160



Perspective_30°

Snaps: Vertices, 2D



faces: 6,191,521 vertices: 3,105,160



Figure A.40 Other 3D virtual outcrops from Castelsaraceno outcrops.

Python code for dfnWorks® (Working code)

```
"""
# :synopsis: Driver run file for TPL example
# :version: 2.0
# :maintainer: Jeffrey Hyman
#.. moduleauthor:: Jeffrey Hyman <jhyman@lanl.gov>
#"""

from pydfnworks import *
import os
import networkx as nx

jobname = os.getcwd() + "/output"
dfnFlow_file = os.getcwd() + '/dfn_explicit.in'
dfnTrans_file = os.getcwd() + '/PTDFN_control.dat'

DFN = DFNWORKS(jobname,
                dfnFlow_file=dfnFlow_file,
                dfnTrans_file=dfnTrans_file,
                ncpu=16)

DFN.params['domainSize']['value'] = [5, 5, 5]
DFN.params['h']['value'] = 0.01
DFN.params['stopCondition']['value'] = 0
DFN.params['nPoly']['value'] = 300
DFN.params['ignoreBoundaryFaces']['value'] = False
DFN.params['boundaryFaces']['value'] = [1, 1, 0, 0, 0, 0]
DFN.params['seed']['value'] = 1
DFN.params['orientationOption']['value'] = 2

#SLM I DFN model for Scarrone La macchia fractured carbonate outcrop (amalgamated beds) Lat
40°22'32.04"N Long 15°50'14.67"E

#Set WNW-ESE
DFN.add_fracture_family(
    shape="ell",
    distribution="tpl",
    alpha=1.24,
    kappa=72,
    family_number=1,
    probability=0.33,
    p32=1.75,
    number_of_points=8,
    aspect = 2,
    dip=80,
```

```

strike=289,
min_radius=0.12,
max_radius=2.5,
hy_variable='aperture',
hy_function='correlated',
hy_params={
    "alpha": 10 ** -4,
    "beta": 2,
})

```

#Set N-S

```

DFN.add_fracture_family(
    shape="ell",
    distribution="tpl",
    alpha=1.24,
    kappa=100,
    family_number=2,
    probability=0.33,
    p32=2.83,
    number_of_points=8,
    aspect = 2,
    dip=86,
    strike=356,
    min_radius=0.11,
    max_radius=2.5,
    hy_variable='aperture',
    hy_function='correlated',
    hy_params={
        "alpha": 10 ** -4,
        "beta": 2,
    })

```

#Set NNE-SSW

```

DFN.add_fracture_family(
    shape="ell",
    distribution="tpl",
    alpha=1.23,
    kappa=48,
    family_number=3,
    probability=0.33,
    p32=0.83,
    number_of_points=8,
    aspect = 2,
    dip=73,
    strike=20,
    min_radius=0.1,
    max_radius=0.75,

```



```

hy_variable='aperture',
hy_function='correlated',
hy_params={
    "alpha": 10 ** -4,
    "beta": 2,
})

DFN.make_working_directory(delete=True)

DFN.check_input()
DFN.create_network()
DFN.mesh_network(max_dist=20, max_resolution_factor=40)

# create values of the stress tensor
s1 = 7e6
s2 = 10e6
s3 = 13e6
sigma_mat = x = [[s1, 0, 0], [0, s2, 0], [0, 0, s3]]
DFN.dump_hydraulic_values()
DFN.add_variable_to_mesh("init_aper", "aperture.dat", "full_mesh.inp",
    "stress.inp")
# modify apertures based on the stress field
DFN.stress_based_apertures(sigma_mat)
# add final apertures to mesh
DFN.dump_hydraulic_values()
DFN.add_variable_to_mesh("stress_aper", "aperture.dat", "stress.inp")

# assign new names of aperture files
DFN.aper_file = "stress_aperture.dat"
DFN.perm_file = "stress_perm.dat"

DFN.dfn_flow()
DFN.dfn_trans()

DFN.effective_perm(2e6, 1e6, 'boundary_left_w.ex', 'x')
G = DFN.create_graph("fracture", "left_w", "right_e")
nx.has_path(G, "s", "t")
DFN.plot_graph(G, 's', 't', 'dfn_graph')

```


Original code for stress computation

```
import math as m
import numpy as np
# from pydfnworks
from pydfnworks.dfnGen.generation.hydraulic_properties import convert
def stress_based_apertures(self,
    sigma_mat,
    friction_angle=25.0,
    dilation_angle=5,
    critical_shear_displacement=0.003,
    shear_modulus=10.e9,
    min_b=1e-10,
    shear_stiffness=400.e9):
    """ Takes stress tensor as input (defined in dfn run file) and calculates new apertures based on
    Bandis equations. New aperture and permeability values are written to files.
    Parameters
    -----
    sigma_mat : array
        3 x 3 stress tensor (units in Pa)
    friction_angle : float
        Friction angle (Degrees)
    dilation_angle : float
        Dilation angle (Degrees)
    critical_shear_displacement : float
        Critical shear displacement
    shear_modulus : float
        Shear modulus (Pa)
    min_b : float
        Minimum aperture (m)
    shear_stiffness : float
        Shear stiffness (Pa/m)
    Returns
    -----
    None
    Notes
    -----
    For details of implementation see
    "Sweeney, Matthew Ryan, and J. D. Hyman. "Stress effects on flow and transport in three-
    dimensional fracture networks." Journal of Geophysical Research: Solid Earth 125.8 (2020):
    e2020JB019754."
    and
    Baghbanan, Alireza, and Lanru Jing. "Stress effects on permeability in a fractured rock mass with
    correlated fracture length and aperture." International journal of rock mechanics and mining
    sciences 45.8 (2008): 1320-1334.
    and
    Zhao, Zhihong, et al. "Impact of stress on solute transport in a fracture network: A comparison
    study." Journal of Rock Mechanics and Geotechnical Engineering 5.2 (2013): 110-123.
```

```

"""
print("--> Computing aperture based on stress tensor")
print("\n--> Stress Tensor (Pa):\n")
print(
    f"\t{sigma_mat[0][0]:0.2e} {sigma_mat[0][1]:0.2e} {sigma_mat[0][2]:0.2e}"
)
print(
    f"\t{sigma_mat[1][0]:0.2e} {sigma_mat[1][1]:0.2e} {sigma_mat[1][2]:0.2e}"
)
print(
    f"\t{sigma_mat[2][0]:0.2e} {sigma_mat[2][1]:0.2e} {sigma_mat[2][2]:0.2e}"
)
print()

# write stress to file.
with open("stress.dat", "w") as fstress:
    fstress.write(
        f"\t{sigma_mat[0][0]:0.2e} {sigma_mat[0][1]:0.2e} {sigma_mat[0][2]:0.2e}"
    )
    fstress.write(
        f"\t{sigma_mat[1][0]:0.2e} {sigma_mat[1][1]:0.2e} {sigma_mat[1][2]:0.2e}"
    )
    fstress.write(
        f"\t{sigma_mat[2][0]:0.2e} {sigma_mat[2][1]:0.2e} {sigma_mat[2][2]:0.2e}"
    )

# read fracture data:
initial_aperture = self.aperture
normals = self.normal_vectors
radii_frac = self.radii[:,
    0] #og in case of bugs np.genfromtxt('radii_Final.dat', skip_header=2)[: , 0]
num_frac = len(initial_aperture)
b = np.zeros(num_frac)

# Cycle through fractures and compute new aperture base on stress field and user defined
parameters
for i in range(num_frac):
    # Magnitude of normal stress
    sigma_mag = sigma_mat[0][0]*(normals[i][0])**2 + \
        sigma_mat[1][1]*(normals[i][1])**2 + \
        sigma_mat[2][2]*(normals[i][2])**2 + \
        2*(sigma_mat[0][1]*normals[i][0]*normals[i][1] + \
        sigma_mat[1][2]*normals[i][1]*normals[i][2] + \
        sigma_mat[0][2]*normals[i][0]*normals[i][2])

    T_1 = sigma_mat[0][0]*normals[i][0] + \
        sigma_mat[0][1]*normals[i][1] + \
        sigma_mat[0][2]*normals[i][2]

```

```

T_2 = sigma_mat[1][0]*normals[i][0] + \
      sigma_mat[1][1]*normals[i][1] + \
      sigma_mat[1][2]*normals[i][2]

T_3 = sigma_mat[2][0]*normals[i][0] + \
      sigma_mat[2][1]*normals[i][1] + \
      sigma_mat[2][2]*normals[i][2]

stress_sqr = (T_1)**2 + (T_2)**2 + (T_3)**2
# Magnitude of shear stress
shear_stress = np.sqrt(max(0, stress_sqr - (sigma_mag)**2))
# Critical normal stress (see Zhao et al. 2013 JRMGE)
sigma_nc = (0.487 * initial_aperture[i] * 1e6 + 2.51) * 1e6
# Normal displacement
normal_displacement = (9 * sigma_mag * initial_aperture[i]) / (
    sigma_nc + 10 * sigma_mag)
# Shear dilation
# print(normal_displacement)
shear_stress_critical = sigma_mag * m.tan(m.radians(friction_angle))
# Fracture half length
l = radii_frac[i]

# rock stiffness
rock_stiffness = 0.92 * shear_modulus / l
ks1 = shear_stiffness + rock_stiffness
ks2 = rock_stiffness
#
if shear_stress > shear_stress_critical:
    dilation_tmp = (shear_stress - shear_stress_critical *
        (1 - ks2 / ks1)) / (ks2)
else:
    dilation_tmp = 0

dilation = min(dilation_tmp, critical_shear_displacement) * m.tan(
    m.radians(dilation_angle))
#dilation = dilation_tmp * m.tan(m.radians(dilation_angle))
# take the max of the computed and provided minimum aperture.
b[i] = max(min_b, initial_aperture[i] - normal_displacement + dilation)

diff = abs(b - initial_aperture)
diff2 = diff**2
print(f"--> L2 change in apertures {np.sqrt(diff.sum()):0.2e}")
print(f"--> Maximum change in apertures {max(diff):0.2e}")

self.perm = convert(b, 'aperture', 'permeability')
self.transmissivity = convert(b, 'aperture', 'transmissivity')
self.aperture = b
# self.dump_hydraulic_values()
print("--> Computing aperture based on stress field complete ")

```

Original code for Mass balance equation

```
#!/usr/bin/env python

# Calculate mass balance across a boundary of a DFN mesh
# Make sure that you run PFLOTTRAN with MASS_FLOWRATE under OUTPUT
# Satish Karra
# March 17, 2016
# Updated Jeffrey Hyman Dec 19 2018
# Revision Jeffrey Hyman Oct 5 2020

import os
import numpy as np
import glob

__author__ = 'Jeffrey Hyman'
__email__ = 'jhyman@lanl.gov'

def check_inputs(direction, inflow_pressure, outflow_pressure, boundary_file, darcy_vel_file):
    """
    Checks that inflow pressure is greater than outflow pressure and that path to file paths are valid.

    Parameters
    -----
    direction : string
        Primary direction of flow (x, y, or z)
    inflow_pressure : float
        Inflow boundary pressure
    outflow_pressure : float
        Outflow Boundary pressure
    boundary_file : string
        Name of ex file for inflow boundary
    darcy_vel_file : string
        name of darcy velocity file (pflotran output file)

    Returns
    -----
    Boolean
        True if all tests passed, False if not
    """

    if direction not in ['x', 'y', 'z']:
        print(f"--> Error. Unknown direction provided {direction}. Acceptable values are 'x','y', and 'z'.\nExiting\n")
        return False
    ## Check Pressure
    if inflow_pressure < outflow_pressure:
```

```

    print(
        "--> Error. Inflow pressure is less the outflow pressure. Cannot compute effective
permeability.\n"
    )
    print(f"--> Inflow Pressure: {inflow_pressure}")
    print(f"--> Outflow Pressure: {outflow_pressure}")
    print("Exiting fucntion call.")
    return False

if not os.path.exists(boundary_file):
    print(f"--> Error. Boundary file: {boundary_file} not found. Please check path.\nExiting\n")
    return False

if not os.path.exists(darcy_vel_file):
    print(f"--> Error. Darcy velocity file: {darcy_vel_file} not found. Please check path.\nExiting\n")
    return False

return True

def flow_rate(darcy_vel_file, boundary_file):
    """Calculates the flow rate across the inflow boundary

    Parameters
    -----
    darcy_vel_file : string
        Name of concatenated Darcy velocity file
    boundary_file : string
        ex file for the inflow boundary

    Returns
    -----
    mass_rate : float
        Mass flow rate across the inflow boundary
    volume_rate : float
        Volumetric flow rate across the inflow boundary

    Notes
    -----
    None
    """
    # Calculate the mass flow rate
    mass_rate = 0.0 #kg/s
    volume_rate = 0.0 #m^3/s

    dat_boundary = np.genfromtxt(boundary_file, skip_header=1)
    dat = np.genfromtxt(darcy_vel_file)
    for cell in dat_boundary[:, 0]:

```



```

if (np.any(dat[:, 0] == int(cell))):
    ids = np.where(dat[:, 0] == int(cell))[0]
    for idx in ids:
        cell_up = int(dat[idx, 0])
        cell_down = int(dat[idx, 1])
        mass_flux = dat[idx, 2] # in m/s , darcy flux, right? m3/m2/s
        density = dat[idx, 3] # in kg/m3
        area = dat[idx, 4] # in m^2
        if (cell_up == int(cell)):
            mass_rate = mass_flux * area * \
            density + mass_rate # in kg/s
            volume_rate = mass_flux * area + volume_rate #in m3/s
        else:
            mass_rate = - mass_flux * area * \
            density + mass_rate # in kg/s
            volume_rate = -mass_flux * area + volume_rate #in m3/s
        #print cell_up, cell_down, mass_flux, density, area, mass_rate, volume_rate
if (np.any(dat[:, 1] == int(cell))):
    ids = np.where(dat[:, 1] == int(cell))[0]
    for idx in ids:
        cell_up = int(dat[idx, 0])
        cell_down = int(dat[idx, 1])
        mass_flux = dat[idx, 2] # in m/s
        density = dat[idx, 3] # in kg/m3
        area = dat[idx, 4] # in m^2
        if (cell_up == int(cell)):
            mass_rate = mass_flux * area * \
            density + mass_rate # in kg/s
            volume_rate = mass_flux * area + volume_rate #in m3/s
        else:
            mass_rate = - mass_flux * area * \
            density + mass_rate # in kg/s
            volume_rate = -mass_flux * area + volume_rate #in m3/s
        #print cell_up, cell_down, mass_flux, density, area, mass_rate, volume_rate
return mass_rate, volume_rate

```

```

def dump_effective_perm(local_jobname, mass_rate, volume_rate, domain,
    direction, inflow_pressure, outflow_pressure):
    """Compute the effective permeability of the DFN and write it to screen and to the file
    local_jobname_effective_perm.dat

```

Parameters

```

    local_jobname : string
        Jobname
    mass_rate : float
        Mass flow rate through inflow boundary
    volume_rate : float

```

```

    Volumetric flow rate through inflow boundary
    direction : string
        Primary direction of flow (x, y, or z)
    domain : dict
        Dictionary of domain sizes in x, y, z
    inflow_pressure : float
        Inflow boundary pressure
    outflow_pressure : float
        Outflow boundary pressure

Returns
-----
    None

Notes
-----
    Information is written into <local_jobname>_effective_perm.txt
'''

# Lm3 = domain['x'] * domain['y'] * domain['z'] #L/m^3
# if flow is in x direction, cross section is domain['y']*domain['z']
if direction == 'x':
    surface = domain['y'] * domain['z']
    L = domain['x']
if direction == 'y':
    surface = domain['x'] * domain['z']
    L = domain['y']
if direction == 'z':
    surface = domain['x'] * domain['y']
    L = domain['z']
# Print the calculated mass flow rate in kg/s
mu = 8.9e-4 #dynamic viscosity of water at 20 degrees C, Pa*s
spery = 3600. * 24. * 365.25 #seconds per year
# compute pressure gradient
pgrad = (inflow_pressure - outflow_pressure) / L
#darcy flux over entire face m3/m2/s
q = volume_rate / surface

output_string = f'''The mass flow rate [kg/s]: {mass_rate:0.5e}
The volume flow rate [m^3/s]: {volume_rate:0.5e}
'''

if direction == 'x':
    output_string += f'''The Darcy flow rate over {domain['y']} x {domain['z']} m^2 area
[m^3/m^2/s]: {q:0.5e}
The Darcy flow rate over {domain['y']} x {domain['z']} m^2 area [m^3/m^2/y]: {spery*q:0.5e}
'''
elif direction == 'y':

```

```

        output_string += f'''The Darcy flow rate over {domain['x']} x {domain['z']} m^2 area
[m^3/m^2/s]: {q:0.5e}
The Darcy flow rate over {domain['x']} x {domain['z']} m^2 area [m^3/m^2/y]: {spery*q:0.5e}
'''

    elif direction == 'y':
        output_string += f'''The Darcy flow rate over {domain['x']} x {domain['y']} m^2 area
[m^3/m^2/s]: {q:0.5e}
The Darcy flow rate over {domain['x']} x {domain['y']} m^2 area [m^3/m^2/y]: {spery*q:0.5e}
'''

    output_string += f'The effective permeability of the domain [m^2]: {q * mu / pgrad:0.5e}'
    print("\n--> Effective Permeability Properties: ")
    print(output_string)
    with open(f'{local_jobname}_effective_perm.txt', "w") as fp:
        fp.write(output_string)

    keff = q * mu / pgrad
    return keff

def effective_perm(self, inflow_pressure, outflow_pressure, boundary_file,
                  direction, darcy_vel_file = 'darcyvel.dat'):
    """Computes the effective permeability of a DFN in the primary direction of flow using a steady-
    state PFLOTTRAN solution.

    Parameters
    -----
    self : object
        DFN Class
    inflow_pressure: float
        Pressure at the inflow boundary face. Units are Pascal
    outflow_pressure: float
        Pressure at the outflow boundary face. Units are Pascal
    boundary_file: string
        Name of inflow boundary file, e.g., pboundary_left.ex
    direction: string
        Primary direction of flow, x, y, or z
    darcy_vel_file : string
        Name of concatenated Darcy velocity file
    Returns
    -----
    None

    Notes
    -----
    1. Information is written to screen and to the file self.local_jobname_effective_perm.txt
    2. Currently, only PFLOTTRAN solutions are supported
    3. Assumes density of water at 20c
    """

```

```

print("--> Computing Effective Permeability of Block\n")
if not self.flow_solver == "PFLOTTRAN":
    print(
        "Incorrect flow solver selected. Cannot compute effective permeability"
    )
    return 0

print(f"--> Inflow boundary file name:\t\t{boundary_file}")
print(f"--> Darcy Velocity File:\t\t{darcy_vel_file}")
print(f"--> Inflow Pressure:\t\t{inflow_pressure:0.5e} Pa")
print(f"--> Outflow Pressure:\t\t{outflow_pressure:0.5e} Pa")
print(f"--> Primary Flow Direction:\t\t{direction}")

if not check_inputs(direction, inflow_pressure, outflow_pressure, boundary_file, darcy_vel_file):
    return 1

mass_rate, volume_rate = flow_rate(darcy_vel_file, boundary_file)
keff = dump_effective_perm(self.local_jobname, mass_rate, volume_rate,
                          self.domain, direction, inflow_pressure,
                          outflow_pressure)
print("--> Complete\n\n")
self.keff = keff

```

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