

CONTROLS ON FRACTURE ABUNDANCE IN GENTLY DEFORMED CARBONATES

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Thesis submitted to the University of Oxford
for
the degree of Doctor of Philosophy



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Trinity, 2018

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and
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DECLARATION

The contents of this thesis are all my own work, except where otherwise stated. The views and opinions expressed herein are mine and not necessarily those of any other person or body unless so attributed.

Citation: Al-Fahmi, M. M. (2018), *Controls on Fracture Abundance in Gently Deformed Carbonates*, Ph.D. thesis, University of Oxford, Department of Earth Sciences, Oxford, UK.

Keywords: Fractures, Veins, Carbonates, Reservoirs

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Printed in the United Kingdom.

ABSTRACT

**Thesis Title: Controls on
Fracture Abundance in
Gently Deformed Carbonates**

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**Linacre College, Oxford
Doctor of Philosophy in Earth Sciences
Trinity Term 2018**

Fractures can profoundly affect the capacity of carbonate reservoirs to store and permeate fluids, depending on the properties and abundance of fractures. Fractures exist abundantly in carbonate outcrops; however, their abundance in subsurface carbonates is obscure because of the data shortages and uncertainties about the factors that drive fracturing in sedimentary basins. The objective of this research is twofold. The first is to study abundance of fractures in gently deformed carbonates, which were generally overlooked. The second is to address measuring fracture abundance using electrical borehole imaging, which is the mostly used method to describe reservoir fractures. Fractures were studied from areas in the gently folded and shallowly (less than 2 km depth) buried interiors of the Arabian Platform. The study areas include outcrops and reservoirs of the Late Jurassic Arab carbonates in the sprawling homocline of Central Arabia and a low-relief dome in Eastern Arabia. The Cenozoic Rus carbonates in the dome outcrops were also studied. Fracture abundance was measured from the outcrops using scanlines and from the reservoirs using core and borehole images of extended-reach drilling. Many systematic properties were drawn on

mineralization, orientation, and abundance of fractures. The fractures were found to be opening mode, mostly barren, and exist with subvertical dips, and some regional trends. The fractures display significantly differing ranges of abundance that were controlled by the subtle structural bending of the dome and homocline, carbonate lithofacies, and paucity of fracture mineralization. The borehole imaging was found to significantly lower fracture abundance. The detection of fractures was subject to several factors including size of fracture widths, nature of fracture roughness, and present-day stress field. The results have implications for modeling of fracture systems and tectonic regimes. For example, finding that fracture abundance varies drastically in such gently deformed regions indicates that carbonates are very sensitive to fracturing processes. Moreover, the borehole imaging limitations influence the models of fracture abundance and orientations, which are often used to deduce paleo tectonic regimes and present-day geodynamics in carbonate reservoirs.

To my mother Hillala H. Al-Fahmi, who I learnt from her the most, till I lost her to cancer in May 1st, 2015.

RIP Mom.

ACKNOWLEDGMENTS

My research would not have been accomplished without the kind help of many brilliant people. I am grateful, and will remain so, to the few I mention here and the numerous others who remain unnamed; I thank you all sincerely.

Foremost I thank my supervisors, Joe A. Cartwright and Richard Walker. I was privileged and rewarded to be guided and surrounded by global leaders in their fields of knowledge. While I am writing this acknowledgment after leaving to Saudi Arabia, I just cannot describe how I enjoyed my time working and discussing science with Joe and his team, John Hooker, Martino Foschi, Ben Manton, Claudia Bertoni, Micha Ruhl, Alex Dickson, Chris Kirkham, Qingfeng Meng, Matteo Paganoni, James Scaife, Isra'a Abu Mahfouz, Victoria Elliott, James King, Shahab Varkouhi, and others. Besides that they are influential scientists, they are friends who helped making life more fun in Oxford. Also, I would like to thank my college advisors, John Holmes and Asma Mustafa.

This research would not have been possible without the financial support of Aramco. I especially thank the following old friends that I rarely met them after leaving to Oxford: Abdullah Al-Shamsi, Jamil Al-Haghoug, Aus Al-Tawil, Mohammed Al-Ghamdi, Marwan Al-Thagafy, Mandefro Belayneh, Weihua Wang, Raji Mat Yacoub, Ahmed Hamidah, Khalid Al-Hawwas, Abdullah Al-Subaie, Mohammed Al-Ghamdi, Mohammed Ameen, Darryl Fischbuch, Hussain Bandah, Mohammed Al-Sarraj, Fahad Al-Khashrami, Mohammed Al-Masrahi, Sa'ad Al-Awwad, Fawaz Al-Khaldi, Ali Al-Saeed, and many others.

On a very special note, I would like to thank the following individuals. I thank Mohammed Al-Khalifa, a brilliant geologist who was my contact and support in Aramco in Dhahran. I thank Ismail Ozkaya and John Cole, who were great mentors since I joined them in 2008 to study reservoir fractures. I thank Khaled Shokair for sharing work and knowledge on the evolution of the Arabian sedimentary basin. I thank Abdullah Al-Mojel, an Aramco carbonate stratigrapher, who joined me in the field in the hot desert of Central Arabia. We promised we will do it again! I thank Aggie Cooper and her colleagues for their continuous support from Aramco London office. From Oxford, I thank Fiona Lerner and Chris Day for their lab work and education on isotopes. Also, I would like to thank Cristina Neagu, who excellently proofread the written work of this research.

I would like also to thank Ron Nelson, Nick Barton, Stephen Laubach, Mohammed Ameen, and other anonymous reviewers, who reviewed my submitted manuscripts and helped improving the contents of this research.

This acknowledgement would not be complete without thanking my new friends and officemates in Oxford and elsewhere. In particular, I thank Anna Rufas, Brook Keats, Tylor Ambrose, Brook Tozer, Naomi Sounders, Arola Moreras, Tin Naing, Anran Cheng, Julia Barrott, Luke Jenkins, Maeve, Peter Gyiring, Karrar, Amada Hughes, Caroline Mengeot, and many others. I thank my Saudi friends in Oxford, Abullah Alswied, Naif Al-Harbi, Abdossalam Al-Madkhali, and Farah Alammari.

The last, and certainly not the least, I thank my beautiful little family in Oxford, Wejdan, Sultan, and the lately arrived Jude, as well as my big family in Saudi Arabia. I would like to say to them “*I love you all so much*”, using Sultan’s British thick accent.

EXTENDED ABSTRACT

**Thesis Title: Controls on
Fracture Abundance in
Gently Deformed Carbonates**

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Fractures in carbonate reservoirs are among the crucial elements that are typically studied by earth scientists to maximize the benefits and mitigate the risks of costly industrial projects such as petroleum extraction and carbon dioxide sequestration. Fractures affect how rocks store and permeate fluids, depending on the properties of fractures and their abundance in rocks. The abundance of fractures in rocks requires modeling to understand how fractures govern, or influence, the thermal, hydraulic, mechanical, seismic, and electromagnetic properties of reservoir rocks.

Fractures exist abundantly in carbonate rock outcrops, but fracture abundance in subsurface carbonates is uncertain. Information about the abundance of fractures in subsurface rocks is often inadequate. The one method that can image large volumes of subsurface rocks is 3-D seismic reflection, but fractures are indiscernible on seismic reflection surveys. The observations from boreholes are commonly subject to the limitations of data recovery, resolution, and sampling dimensions. Furthermore, the geological models on the mechanisms that can cause and control

carbonate rock fracturing are mostly based on observations from outcrops as analogs to subsurface rocks. Nevertheless, the models are of wide-ranging probabilities to be reconciled for reservoir applications.

The objective of this research is twofold. The first, and foremost, is to identify the factors that control the abundance of carbonate fractures in regions of gentle deformation. Unlike regions of intense faulting and folding, gently deformed regions were often neglected by researchers. It is important to study carbonate fracturing in gently deformed regions to shed light on whether fracture abundance in carbonates is universally similar, with negligible differences, or rather substantially varying. The second objective of this research is to address measuring fractures by borehole imaging, which is the mostly used geophysical method for imaging reservoir fractures.

To address the first objective, fractures were studied from areas of the Late Jurassic Arab and Cenozoic Rus carbonates in the gently deformed and shallowly (less than 2 km depth) buried interiors of the Arabian Platform. The Arab carbonates were studied from outcrops in the Interior Homocline in Central Arabia, and from subsurface reservoirs in a low-relief dome in Eastern Arabia. The Cenozoic Rus carbonates were studied from the outcrops of the dome in which the Arab reservoirs were studied.

The study areas are of typical stratigraphic and structural analogies, displaying layer-cake stratigraphy and folds of very low curvatures, manifested in gentle structural dips in the Mesozoic and Cenozoic strata. The dome was formed by the slow rise of a deep-seated salt pillow, and the homocline was possibly formed in response to the reactivation of deep-seated basement faults. The two structures differ basically in shape and slightly in curvature magnitudes (degree of layer bending). The structural dips are very low: about $1^{\circ}.3'$ in the Rus outcrops in the dome area, 5° in the Arab reservoirs in the dome area, and $0^{\circ}.3'$ in the homocline. Furthermore, the Arab carbonates in the homocline and the dome display the same lithofacies and alternations of competent and non-competent layers.

The datasets of fracture abundance in the study areas were collected from outcrop using scanlines and from subsurface reservoirs using core and borehole images of extended-reach drilling. The geometry of the boreholes was ideally designed to intersect fractures in gently dipping

strata. Fractures were described, categorized, and correlated from the study areas. Fracture abundance was related to the thicknesses of host layers in the outcrops and lithological units in the reservoirs.

Many systematic characteristics were drawn on mineralization, orientation, roughness, and abundance of fractures, although some exceptions occur. The fractures were found to be opening mode, mostly barren, confined to layers, and exist with subvertical dips and sets of NE–SW and NW–SE orientations. The fractures display significantly differing ranges of abundance. On average, fractures are less abundant in the Rus outcrops in the dome than in the Arab reservoirs in the dome subsurface. Also, fractures in the Arab carbonate outcrops in the homocline are notably less abundant than in the Arab reservoirs in the subsurface beneath the dome. By comparing fracture spacing to the thicknesses of host layers and lithological units, fractures were found to be undersaturated in the Arab carbonate outcrops in the homocline, oversaturated in the Arab reservoirs in the dome, and balanced to undersaturated in the Rus carbonates in the dome outcrops.

Lithology and thickness of carbonate layers control fracture spacing in the Rus carbonates, whose thickness is mostly between 1 m and 5 m, and fracture spacing mostly between 2 m and 5 m. The controls of lithology on fracture abundance in the Arab carbonates are more recognizable in the reservoirs in the dome than in the outcrops in the homocline, possibly because of the low fracture abundance in the homocline outcrops. The major mechanisms that resulted in different abundance of barren fracture systems in these gently deformed carbonates are the structural development of the dome and homocline and the paucity of fracture mineralization. The dome curvature at the Arab reservoir level is higher than the subtle curvature of the nearly flat layers at the dome outcrops and the homocline outcrop. Yet, the Arab reservoirs in the dome experienced small (about 2%) tectonic extension resulted from the cyclic uplift and layer bending. The paucity of processes that mineralize fractures is indicated by the prevalence of barren fractures; the calcite and gypsum veins make up small percentages ranging from 0% to 10% in these carbonates. Other fracturing and controlling mechanisms (i.e., exhumation and hydraulic fracturing) are indiscernible from the nature of the described fracture systems, the level of sediment burial, and tectonic setting.

To address the second objective, the barren fractures and calcite veins in the core of the Arab carbonate reservoirs were described and directly compared to the corresponding intervals of borehole images. New results were obtained on the detection of carbonate reservoir fractures by electrical borehole imagers. The comparison resulted in a significant mismatch in measurements of fracture abundance. Many core fractures could not be seen in corresponding borehole images. The major influencing factor on fracture detection is imaging resolution, which reduces the identification of fractures of small width, below 2 mm. Most calcite veins were undetected because they exhibit widths less than 2 mm. Exceptions include a few calcite veins of 0.5 mm that were detected because of the strong data resistivity contrast between these resistive veins and conductive host rocks.

The shortcomings of borehole imaging were, nonetheless, useful to recognize some conditions that affect the size of reservoir fractures. The barren fractures that are aligned subparallel to the present-day S_{Hmax} were detected more abundantly than other non-aligned fractures. Consistent with this finding was another important finding: aligned fractures exhibit relatively large apertures in the borehole images. The apertures diminish in size as fractures gradually deviate in orientation from the S_{Hmax} . Most of the non-aligned barren fractures were undetected, except the fractures with rough walls. This indicates that the walls of the non-aligned fractures are mechanically closed by the normal S_{Hmax} , and that the remaining apertures were dependent on the availability of roughness mismatches between the closed fracture walls. The fractures display roughness, ranging between 5 and 14 on the joint roughness coefficient scale. The majority of fractures exhibit matching walls, and a minority with wall mismatches. Roughness and mismatch of fracture walls were found to reflect the fabrics of host carbonates and, hence, are potentially predictable from analyses of various carbonate lithofacies.

The results from this research have implications for geological modeling of fracture systems and tectonic regimes in carbonate reservoirs. For example, finding that fracture abundance varies drastically in such gently deformed regions indicates that layered carbonates are very sensitive to fracturing and that fracture oversaturation can happen under environments of shallow depths (<2 km) and low strain, below 2% of layer extension. This finding implicates invalidity of

using fracture abundance in relations to the strain intensity of folding and faulting in highly deformed outcrops. Moreover, relying on measurements of borehole imaging leads to biases in compiled fracture orientations in rose diagrams, which are often used to deduce paleo tectonic regimes. The borehole imaging remains indispensable to measure fracture orientations and present-day apertures and help identify the large (i.e., more conductive) fractures in reservoir rocks.

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1 INTRODUCTION

1.1 ROCK FRACTURES

Rock fractures are structural discontinuities of different shapes and sizes that embody losses of rock cohesion under loads. These loads mostly originate from gravity (overburden) and tectonic sources in the earth's crust (e.g., Fairhurst, 2003).

Fractures are categorized based on the crack mode of displacement into opening-mode fractures, compaction structures, and shear fractures (faults) (Fig. 1.1). This research is focused on opening-mode fractures, along which there has been little or no traverse (shear) displacement (e.g., Price and Cosgrove, 1990). Such fractures are visible with the naked eye in surface rocks (outcrops), and on drill core and borehole images in subsurface rocks. These fractures are sometimes called macrofractures to differentiate them from outcrop lineaments, seen in aerial photographs (e.g., Blanchet, 1957), and microfractures, seen under the microscope (e.g., Kranz, 1983).

The scale of individual fractures varies in the three dimensions (3-D) of space (Fig. 1.2). The range of fracture scales is roughly 0.1 mm to 1 cm for width, 10 cm to 10 m for height, and 1 m to 500 m for length (e.g., Bonnet et al., 2001). Their equivalents in subsurface rock formations are among sub-seismic fractures, a term coined in the last decade of the 20th century to define fractures, as well as faults with throws less than 30 m, which are undetectable on 3-D seismic reflection datasets.

Fractures can either be fully or partially filled with minerals, or barren. Mineralized and barren fractures in outcrops are often called veins and joints, respectively. Joints exist abundantly

in outcrops of many rock types (e.g., Pollard and Aydin, 1988). Carbonates are often broken up into blocks by several systems of nearly parallel joints (Fig. 1.1). Other terms that define the fractures under question include Mode I, dilatant, and tensile fractures—hereinafter called fractures except otherwise specified.

1.2 RESEARCH DOMAINS OF ROCK FRACTURES

The scientific literature on fractures of solid materials has dramatically expanded in the mid-20th century. This expansion resulted in the creation of many disciplines that generally address the phenomena of material strength, fatigue, and fluid flow. Fractures have been extensively studied from theories and experiments in engineering materials (metals, concretes, ceramics, polymers, and composites); geomaterials (rocks and sea ice); and biomaterials (woods and bones).

By the end of the 20th century, many problems in fracture mechanics of material sciences had been settled, at least for global theoretical solutions. Solid materials are recognized to fracture under loads that are much weaker than the theoretical strengths of materials, because of microflaws (e.g., Griffith, 1921). Nevertheless, the two exceptional unsettled areas of research are the perplexing dynamics of fracture and how a material breaks at atomic level (e.g., Fineberg et al., 1991). Many problems persist regarding fractures in semi-brittle, inhomogeneous geomaterials (rocks). Rock fracturing, whether it took place under natural geological conditions or by fluid injection into boreholes (i.e., fracking), is a major topic in current scientific research.

The geoengineering literature has been growing in volume and areas of applications. Recent publications cite rock fractures in relation to many industrial projects on rock masses at surface, near surface, and deep subsurface. For example, geotechnical research addresses rock fractures in connection to ground instability for the safety of civil engineering projects, such as mines, dams, and tunnels. Hydrological research is concerned about fractures as conduits and storage for water recourses. The research on deeper subsurface fractures is generally in the domain of engineering and geoscience of reservoir rocks—the buried rocks that typically store fluids (water, oil, and gas) in their voids (porosity). This is the domain under which this research may be catalogued. For convenience, this domain is referred to as “reservoir rock” in the text.

Reservoir rocks are domains of benefits and risks for the global economy and

environment. Fluids and rock fractures are crucial areas of research for petroleum extraction and safe sequestration of nuclear waste and carbon dioxide. The petroleum industry finds and extracts hydrocarbons by many processes that necessitate fluid injection into the subsurface to facilitate drilling, perform fracking, and increase the pressure of reservoir fluids for pressure-driven recovery.

1.3 ROCK FRACTURE PROPERTIES

Fractures are viewed in modern rock sciences as key parameters of the thermal, hydraulic, mechanical, and seismic properties of rock masses (e.g., National Research Council, 1996; Jaeger et al., 2007). These fracture effects (properties) are briefly mentioned here from their obvious domains of investigations.

Geological observations from outcrops indicate that fractures were conductive zones of fluid circulation in the past, and hence zones of heat transfer in the earth's crust (e.g., Lowell, 1975). The ability of a fracture to transmit fluid (moving under pressure) is known as fracture hydraulic conductivity, also called fracture transmissivity or fracture permeability. This is a rather complex fracture property that requires a set of assumptions in seeking a solution in any domain of investigation (e.g., Witherspoon et al., 1980; Zimmerman and Yeo, 2000).

In theory, the fluid flow is related to principles of fluid dynamics and descriptions of the void geometry (aperture) of the fracture. Quantifying the fluid flow is almost impossible without simplifications. Numerical models often disregard the terms of fluid acceleration, advection, and turbidity in the Navier-Stoke and Reynolds lubrication equations. The flow models can then be generally obtained for the simplest theoretical case of a single-phase laminar flow in a fracture of two smooth parallel and separated walls. The Reynolds equation shows that fracture permeability is proportional to the cube of the fracture aperture, and hence this relationship is known as the cubic law. However, this simple model is not conceivable for a natural system of fractures. In the 1960s, Snow (1965) and others obtained expressions for flow anisotropy of a fracture network from defining permeability tensors of each fracture. The current view is that isolated fractures resemble isolated rock pores, which do not contribute to the fluid flow. Accordingly, a fracture can only add to the rock permeability if the fracture intersects other fractures (Long et al., 1982) or is

connected to the matrix pores. Fluid flow in a fracture system is considered based on fracture connectivity, a topological property that is often described probabilistically from fracture intersections using the percolation theory (e.g., Robinson, 1983; Sahimi, 1994). Fracture connectivity is in many ways related to the measureable aspects of the geometry of individual fractures. These properties are enigmatic in buried rocks, and they are typically perceived from outcrop-based models on size, abundance, and orientation of fractures (see section 1.5).

The effects of fractures on the acoustic and electromagnetic properties of rocks are mostly related to the hydraulic properties of fractures. Laboratory and numerical investigations indicate that the presence of fluid in a fracture alters the transmission of acoustic waves (e.g., Pyrak-Nolte et al., 1990; Lockner, 1993) and electromagnetic fields (e.g., Yoshida et al., 1998). These physical properties have been used in the development of many geophysical tools for logging subsurface rocks. For example, fractures can be distinguished from rock fabrics in borehole images that are obtained using acoustic and electrical measurements (e.g., Lagraba et al., 2010).

The effects of fractures on rock mechanics are generally known from geotechnical studies on dry rocks and at low temperature. Rock joints are found to govern the strength of intact rock masses and their movement, according to the abundance, orientation, and shear strength of fracture surfaces (walls) (e.g., Hoek, 1983; Barton, 2013). The cohesive, tensile, and unconfined compressive strengths of a fractured rock mass are significantly weaker than the same strengths of the equivalent unfractured rock mass (e.g., Hoek, 1983; Barton et al., 1985; Schultz, 1996). In essence, joints have no tensile strength, and their shear (sliding) strength depends on the rock's internal frictions and on the roughness degree of the fracture surfaces (Barton, Bandis, et al., 1985).

The effects of fractures in rocks are expected to be dependent on the scale and size of fractures (e.g., Bazant and Planas, 1997; Nelson, 2001) and hydromechanical coupling (e.g., Zimmerman and Main, 2004). The interplay of these dynamic parameters is uncertain, especially in some large and concealed domains of investigation, such as a subsurface reservoir.

Hydromechanical models attempt to define the relationships between fractures in porous rocks (i.e., carbonates) from fracture properties such as size, aperture, and connectivity (Rutqvist

and Stephansson, 2003). These are additional to the reservoir matrix properties: porosity, permeability, stress fields, fluid multi-phase properties, and wettability (fluid-solid interactions) (e.g., Sahimi, 2011; Bear, 2013).

1.4 MODELS OF CARBONATE RESERVOIR FLUIDS

Carbonates are important reservoir rocks, especially for the hydrocarbon resources in the Arabian Plate region (e.g., Beydoun, 1991). Carbonates form within sedimentary basins by biological, chemical, and detrital processes. These processes produce skeletons, fecal pellets, lime mud, microbially mediated cements, lithified sediment (intraclasts), and reworked origin rock (lithoclasts) (e.g., Tucker and Wright, 1990; Ahr, 2008). In some settings, the grain size and stratification of carbonates are modified by biological activities such as organism consumption, burrowing, and boring. Diagenesis occurs in carbonates through their geologic history (e.g., Moore, 1989). Carbonate minerals are prone to rapid dissolution, cementation, recrystallization, and replacement in a variety of geological environments. The mixtures and varieties in size and shape of mud, grains, fossils, and pore spaces make carbonates complex to classify. Classifying limestones began in the 1960s (Folk, 1959; Dunham, 1962), lagging several decades behind the early grain-size based classifications of siliciclastic rocks in early 20th century (e.g., Udden, 1914; Wentworth, 1922).

Early in the 20th century, fluid flow in reservoir rocks was described from fluid pressure datasets using Darcy's law and models of rock matrix porosity. Not long after, in the mid-20th century, fractures were assumed to be among the factors causing heterogeneous fluid flow behavior in carbonate reservoirs (Pirson, 1953). Fractures were incorporated in the first theoretical dual-porosity (DP) model (Barenblatt et al., 1960), (Fig 3). Reservoir rock is perceived as a fluid-solid medium from applying the principles of continuum mechanics. The porosity of rock matrix and fractures is theoretically viewed as continua of overlapping and combined flow communications. The convention is that matrix porosity has a much greater capacity than fractures to store fluids, and fracture permeability is much greater than the equivalent matrix permeability.

The flow models of fractured porous reservoirs evolved from the DP model and earlier principles of continuum mechanics. Early methods were analytic until the technological

development of computers and central processing units permitted field-scale computations. Nowadays, fluid flow is typically described using 3-D computational models that encompass physical laws of rocks and fluids under subsurface conditions. Principal to the computational methods is the use of material balance equations in a 3-D numeric framework of grids. The computations are commonly based on the finite difference method (FDM), or the finite element method (FEM) (e.g., Smith, 1985; Brenner and Scott, 2007), and algorithms of high-performance computing (e.g., Bland et al., 2013). The fluid flow is estimated from Darcy's equation, fluid pressure measurements, and some hydromechanical relations. Observed reservoir behavior is used to estimate reservoir model variables that caused the behavior, in a type of inverse problem known as reservoir history matching (e.g., Oliver and Chen, 2011). Full details of these models can be found in reservoir flow simulation textbooks (e.g., Aziz and Settari, 1979; Aziz, 1993; Sahimi, 2011; Bear, 2013).

In general, fluid flow models require information on fracture size, aperture, abundance, and connectivity. However, such information is not directly obtainable from subsurface measurements. Limited fracture measurements compel modelers to adopt multiple-driver models, the sort of trial-and-error approaches for reservoir fractures (e.g., Sabathier et al., 1998; Al-Qassab et al., 2002). The modeler may combine statistical and stochastic methods for fracture properties that are not necessarily based on any particular geological model; rather, the modeler takes a wide range of possibilities for testing in models of reservoir history matching. This approach of fracture modeling may include “deterministic” information such as fracture measurements from core. The deterministic information remains unchanged when reducing or increasing fractures in the tested numerical models.

The borehole dataset, if available, is one of many drivers for fracture modeling (e.g., Bisdorf et al., 2014). Fractures observed in well datasets are statistically extrapolated to inter-well regions, and superimposed on the fractures derived from models, pressure datasets, or seismic attributes. Some reservoir models start with a 3-D numerical representation of fractures called discrete fracture network (DFN) based on some deterministic and stochastic attributes (e.g., Long et al., 1982; Cacas et al., 1990). The stochastic models can be useful in the absence of datasets on

subsurface reservoirs, or when the effects of fractures are expected to dominate, as in rocks of low-matrix permeability. However, the case of porous reservoirs such as carbonates is different. According to Nelson (2001), a fractured reservoir is one in which fractures have a significant effect on fluid flow, reflecting unexpected magnitudes and directions of permeability and porosity in the reservoir. Nelson proposed four types of reservoir rocks (Fig. 1.3). The varieties in carbonate lithological fabrics (matrix) can produce varying hydromechanical relations, but these relations are difficult to describe without some basic information on fracture properties. For informed decisions on reservoir development, it is imperative to understand if fractures contribute to, or dominate, porosity and permeability systems.

In summary, this research is motivated by three main considerations:

- 1) Carbonates are important rocks for the world economy. There is more oil in carbonates than in any other rock type (Schlumberger, 2007), and they also host enormous reserves of gas and water.
- 2) Carbonates are expected to be fractured in the subsurface (see geomodels in section 1.5). There are, however, uncertainties about fractures and their properties in the subsurface. Generally, data on reservoir rock fractures are indirect and subject to the limitations of data resolution, sampling dimensions, and calibrations (e.g., Nelson, 2011).
- 3) Carbonates are heterogeneous. Though fractures may influence or govern the hydraulic, mechanical, and seismic properties of reservoir rocks, these properties are major uncertainties in the subsurface, particularly for carbonate reservoirs. Carbonate reservoirs typically exhibit heterogeneous pore systems that challenge predictions (e.g., Ahr, 2008). Carbonates may include as many as 14 types of matrix porosity in addition to fractures (e.g., Philip W. Choquette, 1970). Today is no different from the mid-20th century, when reservoir characterization was developing as a new field of application. Warren and Price (1961) expressed their frustration that “it is possible to compute the effect of reservoir heterogeneity on behavior, but it is not possible to specify the heterogeneity itself”. This uncertainty continues to prompt multidisciplinary research on carbonate fractures and other subjects related to subsurface dataset collection, processing, and modeling.

1.5 MODELS OF FRACTURES IN CARBONATES

This research pursues a theme to contribute to the knowledge of fractures in subsurface carbonate reservoirs. The main aim of this research is to study fracture abundance for subsurface reservoir modeling. Fracture abundance is an umbrella term for the amount of rock fractures (Mauldon and Dershowitz, 2000). The term is associated in the geotechnical literature with other quantitative and qualitative terms such as intensity, density, frequency, persistence, and spacing (Mauldon and Dershowitz, 2000).

Abundance is one of the most important, and probably least characterized (Dershowitz and Herda, 1992), properties of fracture spatial distributions, such as orientation, size, shape, and spatial location (Dershowitz and Einstein, 1988; Dershowitz and Herda, 1992). Measuring fracture abundance is important to characterize the hydraulic, mechanical, and seismic properties of carbonate reservoirs. In this research, fracture abundance refers to fracture spacing, which is the mean distance between all fractures (Priest and Hudson, 1976). In essence, the shorter the spacing between fractures, the more fractures are in rock masses.

Fracture spacing can be measured along sections of layers using scan lines, or in boreholes using core and borehole images. Borehole images can be acquired using three types of borehole measurements: optical, acoustic, and electrical. Optical tools, including the optical digital scanner and other borehole cameras, capture true-colored images of borehole walls with high resolution, but they cannot be used in boreholes drilled with mud. Acoustic (or ultrasonic) tools, such as the borehole televiewer (BHTV) have been used since their introduction in the 1970s (Zemanek et al., 1970). The BHTV has a radially mounted rotating transducer that emits in the transmit mode a high-frequency pulse that is reflected by the borehole wall back to the transducer in the receive mode. The BHTV can measure the borehole diameter by using the acoustic transit time between transducer and borehole wall and the amplitude of acoustic signals reflected by the borehole wall. Electrical tools were introduced in the 1980s, starting with the Formation MicroScanner (FMS) (Chen et al., 1987; Ekstrom et al., 1987). The electrical tools have arrays of buttons positioned on pads that are orthogonal to each other. The electrical imagers have seen radical advancements and applications in the petroleum industry over the years (e.g., Prensky, 1999; Pöppelreiter et al., 2010).

The FMS was followed by generations of the Formation Micro Imager (FMI) and High-definition Formation Micro Imager (FMI-HD).

The models for predicting the existence of subsurface fractures, or some of their properties, are numerous in the geological literature. These models are mostly based on outcrop observations and empirical relations. The lack of direct measurements and modeling on fracture abundance in carbonate reservoirs is remarkable. Cores have been used in a few studies, such as Narr and Burruss (1984), Narr (1991), and Sagi et al., (2014), to measure fracture abundance in carbonate reservoirs. The main source of many measurements is electrical borehole imaging, a geophysical technology invented in the 1980s as an economic and practical substitution to cutting core samples from subsurface reservoirs (see chapter 5). Borehole imaging is more practical than coring for many reasons related to the design, execution, and completion of boreholes, especially geometrical (directional) boreholes (e.g., Paillet, 1993). Other geophysical methods of borehole logging and seismic imaging were not apparently used, but were not expected to identify fractures useful for abundance measurements.

The extensive publications on the following models give them a merit to be discussed in length in relation to modeling fracture abundance in carbonate rocks. The sketch in Fig. 1.1 provides a useful reference regarding the terminology and geometry of fractures (joints and veins), faults, layers, spacing, width, height, and length in the 3-D space of a layered rock.

1.5.1 Fracture Spacing and Layer Thickness (FSLT) Model

Rock layering of carbonates, and some siliciclastics, has been observed in outcrops to control the spacing and height of fractures. Fracture spacing has been related to the thickness of host layers by some linear and nonlinear relations. For brevity, these relations are referred to as the fracture spacing and layer thickness (FSLT) model. This is probably the most widely known model describing fracture abundance in layered carbonates. The observations fed in the model are quite old in the geological literature. For example, geologists in the late 19th and early 20th century mentioned some aspects of the uniform distances (spacing) between rock joints (e.g., Goodchild, 1883; Scott, 1914).

In the late 1940s, Bogdanov, Novikova, and Kirillova, cited by Price and Cosgrove (1990),

proposed a linear relationship between spacing and layer thickness. A large volume of research on the FSLT model has followed since the 1960s. Over decades, this model has been derived, modified, and even debated in theories from outcrops and experimental observations.

The following publications give thorough outlooks on the model from outcrop measurements: McQuillan (1973) on the Asmari carbonates in Zagros; Ladeira and Price (1981) and Huang and Angelier (1989) on carbonates in the Gulf of Suez and southeastern France; and Narr and Suppe (1991) and Gross et al. (1995) on the Monterey Formation in California. Many other publications proposed models that are based on physical and theoretical techniques (e.g., Rives et al., 1992; Mandal et al., 1994; Wu and D. Pollard, 1995; Bai and Pollard, 2000; Underwood et al., 2003; Tang et al., 2008; Schöpfer et al., 2011). For example, Rives et al. (1992) carried out four-point bending experiments on polystyrene plates subjected to traction in the presence of alcohol to facilitate polymer chain breaking. Mandal et al. (1994) generated fractures by extending rigid layers of plaster of paris resting on a viscous substratum. Wu and Pollard (1995) tested layering control using four-point bending experiments with brittle coating materials. Bai and Pollard (2000) used the finite element technique to study stress distribution between two adjacent fractures, using a three-layer elastic model with a fractured central layer.

The linear relationship was first explained by Price (1966), Hobbs (1967), and Sowers (1972). Their theoretical treatments are different, but the conclusions are generally similar (Price and Cosgrove, 1990). The simplest (and ideal) form of this model is that the spacing (S) between fractures is related linearly to the thickness (T) of the host layer. Measurements of S and T from outcrops can be then related by fitting a line with this formula: ($S=kT$), where k is some constant related to the layer lithology (Price and Cosgrove, 1990) (Fig. 1.4) According to this model, the spacing increases with increasing layer thickness, so fractures in thick layers are less abundant than they are in thin layers. The spacing is inversely proportional to the square root of the elastic modulus of the competent layer and the square root of the shear modulus of the adjacent ductile layers (Hobbs, 1967). Fracture abundance increases in layers with increasing tectonic deformation (Hobbs, 1967).

The fundamentals of the linear relations between fracture spacing and layer thickness are

that a fracture grows in a layer by layer-parallel stretching (tensile stress) in extensional regimes, such as within bending (folding) strata. The rock layers are assumed to be homogenous plates. They differ in their elastic strengths between a middle fracturing layer and two non-fracturing bounding layers, assuming different interactions to the remote loads. The layer contacts are treated as planes of elastic behavior to the shearing stress to prevent layer-parallel slips. The development of a single fracture under the tensile stress represents an initial condition in the model. The tensile stress, then, drops to zero at the developed fracture, as this free surface (or boundary condition) hinders the stress transmission in the rock layer continuum. The stress then ranges from zero at the fracture to an equivalent value to the remote stress at an infinite point away from the fracture. The development of more fractures redistributes the stress in the layer continuum, resulting in stress reduction in the vicinity of the fractures, and stress concentration in the central region between the fractures. The stress reduction is called the stress shadow. The stress shadow around developing fractures extends laterally according to the fracture height (layer thickness) (Gross et al., 1995). Increasing remote stress decreases fracture spacing, by new fractures nucleating and propagating between earlier formed fractures. This is called the “fracture sequential infilling”, or the “fracture saturation”, process (Gross, 1993). Fractures get closely spaced in the layer, to a degree that no further fractures develop with increasing strain, but the fractures continue to dilate in the models (as the two walls move away from each other).

The results from previous studies indicate that fracture spacing evolves with time, strain magnitude, strain rate, and loading cycle. Under these processes, new fractures nucleate and infill the layer where stresses can overcome local tensile strength of the unfractured part of the layer. The numerical simulations of Bai and Pollard (2000) reveal that when the ratio of fracture spacing to layer thickness exceeds a critical value, the normal stress (perpendicular to the fractures) changes from tensile to compressive in the region between developed fractures. This stress transition precludes further fracturing, except maybe at existing flaws or fracturing by internal fluid pressure (Bai and Pollard, 2000).

Rock layering has been observed to control the height of fractures in layered rocks. Many fractures (joints and veins) can be observed in outcrops terminating at the upper and lower

contacts of host layers. In recent years, such fractures have been designated as layer-confined fractures to be discriminated against throughgoing fractures, which cut through multiple layers (e.g., Gillespie et al., 1999; Gross and Eyal, 2007). The layering controls on fracture abundance and height can be explained by the general theories of mechanical stratigraphy and fracture stratigraphy.

Fractures typically develop in the brittle layer and terminate at the contact with ductile layers (e.g., Cook and Erdogan, 1972). Carbonates, however, do not invariably display this sort of end member of interbedded brittle–ductile layers, except when dolomite is interbedded with marl (e.g., Wennberg et al., 2006).

Mechanical stratigraphy divides layered rocks according to the mechanical properties of layers and layer interfaces (contacts). In a sequence of varying carbonate lithology, the layers are independently fractured, where the fractures terminate at weak interfaces and cut through strong interfaces (e.g., Cooke and Underwood, 2001).

Mechanical layering of rocks can be modeled from averaging measures of rock rigidity, which can then be related to the core lithological descriptions, geophysical logging data, porosity, and mineral composition (e.g., Nelson, 2001). As breaks in lithological properties are expected to coincide with a change in mechanical properties, logging lithological stratigraphy can reveal rock mechanical layering that can also coincide with change in fracture properties (Nelson, 1992; Lockman et al., 1995). These dependencies led to the emergence of the term fracture stratigraphy in the 1990s (Nelson, 1992; Lockman et al., 1995). But as fractures may have occurred in layered rocks with mechanical properties that are different from what we measure today in outcrop or subsurface rocks (e.g., Shackleton et al., 2005), fracture stratigraphy deviates from mechanical stratigraphy in that fracture stratigraphy must define intervals in layered rocks according to fracture properties such as height and abundance (e.g., Laubach et al., 2009).

The two theories are not equally applicable for subsurface models. Mechanical stratigraphy is obtainable from measuring rock properties and, hence, has the potential to be a useful theory under the assumptions that the diagenetic effects on fracture properties are limited or irrelevant. Fracture stratigraphy, however, is not obtainable from measuring rock properties, because fracture

size, particularly height, is beyond boreholes and, therefore, the theory is limited to outcrops and their validity as reservoir analogues.

The FSLT model seems to have propelled a number of studies that validate, invalidate, or restrict the model applications. Like many models, it has a defensible use, but with some serious caveats. The FSLT model is apparently selective in reducing the datasets, choosing the settings where fractures show a linear relation with layer thickness, or both. Importantly, many field studies have demonstrated that there are no obvious relations between fracture spacing and layer thickness (Fig. 1.5). Some points can be summarized here on the invalidity of the model:

- 1) The relations between fracture spacing and layer thickness are only valid in well-layered sequences of contrasting brittleness, such as limestone interbedded with ductile shale layers (e.g., Wennberg et al., 2006).
- 2) The model is limited for thicknesses up to few metres (e.g., Price, 1966; Ladeira and Price, 1981), (Fig. 1.5). Gross et al. (1995) reported from the Monterey Formation that in a succession of different rock types with thin layers (e.g., layers ranging in thickness from about 1 to 100 cm), the ratio of fracture abundance to layer thickness is approximately 1.0. The thicker layers do not display this relation, either because of a mechanical control on the driving stress field or of biases of measurements. Most measurements were from sequences that did not exceed 1.5 m (Price and Cosgrove, 1990).
- 3) Reporting fracture abundance is not always consistent. For example, Narr and Suppe (1991) used a new technique called the fracture-spacing index (FSI), which is the slope of the trend of layer thickness to joint spacing. Gross (1993) introduced the fracture spacing ratio (FSR), which is the mean mechanical layer thickness divided by the median fracture spacing. Tan et al. (2014) introduced a new parameter called the joint-saturation ratio (JSR), which equals size of the stress shadow divided by average joint spacing and multiplied by 100%.
- 4) The model is based on selective cases in outcrops. Wennberg et al. (2007) suggested that the model is derived for a simple case where a single fracture set is generated during one phase of extension and, therefore, the model cannot predict fracture abundance in layers

with multiple deformation.

- 5) The model is focused on joints, or particular sets of joints, and disregards veins and throughgoing fractures.

The validity of the linear FSLT model for outcrops, and hence for subsurface predictions, is limited. The model is obviously specific to particular types of fractures (joints), unit thicknesses, rock formation mechanics, and extensional tectonic setting.

1.5.2 Models of Fractures in Folded, Faulted, and Nearly Flat Strata

Folds and faults are deformational rock structures that have been extensively studied for almost two centuries, from outcrops, physical lab replicas (i.e., clay box), and mathematical simulations. The earliest studies on folds include the work of Hall (1815) on the Berwickshire coast of Britain and the reputable studies of Willis and Van Hise in the late 19th century on fold mechanics in the Appalachian Mountains (Willis, 1894; Van Hise, 1896).

Folds and faults vary in shape, size, and origin in sedimentary, metamorphic, and igneous rocks. Descriptions and classifications of folds and faults can be found in many textbooks (e.g., Ramsay and Huber, 1987; Price and Cosgrove, 1990; Pollard and Fletcher, 2005).

Fractures in folds have drawn increasing research attention since the 1960s to derive models predicting fractures in hydrocarbon reservoir rocks in which the hydrocarbons are trapped in folds (Harris et al., 1960; Murray, 1966, 1968; Price, 1966; Stearns, 1968). Folds have received great consideration to study their fracture patterns from outcrops (see Cosgrove and Ameen, 1999). Fold-fracture models were studied from layered sedimentary rocks, where folds typically occupy large geographic areas of several square kilometers. The geological literature is reviewed for fold-fracture studies to note geographic regions, tectonic deformation history, lithology, and fractures.

Publications include many examples of folds from many places around the world (Fig. 1.6). Mostly studied folds are of anticlinal types and carbonate lithology, and much fewer examples are on synclines and siliciclastic lithology. The fold-fracture model was conceived from fractures in anticlines. The model has three interrelated theories that will be given here the following terms: *fold-fracture development (FFD)*, *fold-fracture orientations (FFO)*, and *fold-fracture abundance (FFA)*. The

outcrop observations upon which the three theories are established differ, and so the applicability of one theory does not necessarily translate to the applicability of others. This note will be discussed further here.

The FFD theory is not geological in its origin and development. It is based on the beam bending theory, which derived from Galileo's beam experiments in 1638. In the late 17th century, Edme Mariotte and Gottfried Wilhelm Leibniz found out that fractures occur in bending beams after some elastic strain, from stretching of one half and contraction of the other (see Todhunter, 1886; Love, 1892; Timoshenko, 1953). The mathematical models of bending beams evolved over centuries to describe tensile, compressive, and shear stress-strains relations in materials (Timoshenko, 1953). Fractures in folded layers can develop in a manner that can be theoretically explained by the bending plate theory (Timoshenko and Woinosky-Krieger, 1959).

Rock layers (as experimental plates) experience longitudinal stretching at the outer arc and shortening at the inner arc, and a neutral unstrained surface separating the outer-extended and inner-contracted parts. The FFD theory often explains the longitudinal (tensile) stresses at the accessible top of fractured rock layers. The bending theory is apparently appropriate, except that fractures in folds are not a single event of rupture. Also, fractures may have developed prior to the fold growth in the rock layers. This condition compelled structural geologists to develop the second theory: the FFO. Fundamentally, the FFO theory correlates general trends of fracture orientations with the fold extensional field. Such use of orientation data had become fundamental to relate joints (and faults) to the stress field since the late 19th and early 20th centuries (Daubrée, 1879; Van Hise, 1896; Price, 1966). In essence, the FFO theory was a normal progression from early theories relating fractures to rock extension. The first examples of the FFO theory were published in Harris et al. (1960), Price (1966), Stearns (1968), and Stearns and Friedman (1972), and they were later modified in many publications (Stearns and Friedman, 1972; Cosgrove and Ameen, 1999; Fischer and Wilkerson, 2000; Bergbauer and Pollard, 2004; Cooper et al., 2006; Savage et al., 2010; Cosgrove, 2015).

The Stearns model, as it has become known, proposes that two sets of fractures are sufficiently common for incorporation into a generalized model for fold-related fractures (Stearns

and Friedman, 1972). The model includes both fractures and faults (namely conjugate shear fractures) that were described in the Teton anticline (Fig. 1.7). The two sets are suggested to be formed by folding because they have consistent orientations with respect to bedding and anticlinal structure, and accommodate bedding-parallel shortening across the anticline. A third set of fractures was also interpreted to accommodate extension because of anticlinal bending of the formations. Fracture abundance, according to Stearns and Friedman, was mostly affected by rock type and layer thickness.

The rationale of the FFO theory is that the stress field of the fold must dominate in a manner that the orientations of developing fractures reflect the fold shape. Fractures are viewed as bending strains, although this view violates the bending theory. This view, however, gives the FFO theorists an entry to describe fractures from the fold shape, following the Euler-Bernoulli bending theory, which mathematically relates the bending moment to the beam curvature. The present-day mathematical treatments are different. Fracture orientations are predicted from curvature properties, from the assumption that fractures open parallel to the maximum instantaneous stretch of a layer and trend parallel to the minimum curvature (e.g., Fischer and Wilkerson, 2000; Özkaya, 2002) (Fig. 1.7).

The pitfalls of the FFO theory are obvious from the view that existing fractures and other rock heterogeneities can disturb folding-ensued stresses. Existing fractures may be reactivated (sheared), and new fractures (due to folding) may develop in directions controlled by existing fractures and other flaws instead of propagating according to the systematic stress field of the fold. The other view is that a fold grows in shape and size in 3-D space, with many observed examples in outcrops of vertical migration and lateral propagation of fold hinges and limbs (e.g., Savage et al., 2010). Accordingly, the present-day fracture patterns do not necessarily match with the present-day fold geometry (curvature). Some pitfalls of the FFO theory may be avoided by adopting the third theory: the FFA.

The FFA theory correlates the abundance of fractures with the magnitude of fold curvature (Harris et al., 1960). The model suggests that the tighter and sharper the fold curvature, the higher the extensional strain which can be translated into more fractures (e.g., Lisle, 1994;

Mynatt et al., 2007). The FFA theory is often referred as the “structural position” control on fracture abundance. It draws many aspects of the FFA and FSLT models, because fracture abundance is mostly measured for certain sets in layers using scan lines. The FFA theory is slightly different from the FSLT model, in the sense that fracture abundance reflects the magnitude of folding. The folding-related strain must reach higher degrees in folds than otherwise nearly flat layers; hence, folds generate more fractures than do flat layers. This implies that fractures away from folds are less abundant than are fractures near folds. Yet, the FFA theory shares some pitfalls of other fold-fracture theories.

It is difficult to derive a framework for fracture abundance from fold-fracture models. Folding is not well defined for fracture abundance, as folds could develop at different scales, shapes, and magnitudes (e.g., Ramsay, 1967). The stress-strain relations of curvature properties are too simple to predict fracture abundance. Many presented cases of outcrop fractures are debatable if they were products of the host fold or other deformation, such as faulting and regional tectonics.

Models of fault-related fractures assume major change in fracture abundance and orientation along isolated linear zones of shear zones. The relations between fractures and faults are generally more complex than those between fractures and folds. Outcrop-based studies demonstrate two important aspects of fault-related fractures.

Firstly, fracture orientations in shear zones differ from fracture orientations in regions away from shear zones. Kattenhorn et al. (2000) found that joints have high angles to normal faults in a field location in Arches National Park in Utah. In Anderson’s theory, dykes (opening-mode fractures) follow the trends of faults (Anderson, 1951). Although fracture orientations in fault zones can be explained by the stress field being perturbed by fault growth (e.g., Rawnsley et al., 1998), it is difficult to predict fracture orientations from fault geometry. Fractures may have pre-dated faults, post-dated faults, or synchronically developed with faults under the controls of local stress, remote stress, and other influencing factors of layer extension, bending, twisting, and damaging (e.g., Cooke, 1997; Kattenhorn et al., 2000; Peacock, 2001; Bastesen et al., 2009).

Secondly, fracture abundance increases drastically in shear zones. Agosta and Aydin (2006a) found that the degree of deformation generally increases towards the fault core in a basin-

bounding normal fault in a Mesozoic carbonate platform in Italy. They recognized three domains: (i) pulverized, (ii) intensely fractured, and (iii) moderately fractured carbonates (Agosta and Aydin, 2006). In general, the properties of fractures and their abundance are more complex in shear zones than elsewhere, where layers are simply folded or nearly flat (e.g., Skar et al., 2016). The theory that fracture abundance is very high in faults is often employed in mechanics-based subsurface models (e.g., Childs et al., 1990; Maerten and Maerten, 2006; Wilkins, 2007). Fracture abundance may indeed be higher in faults than elsewhere. However, fractures can be re-activated (i.e., become faults); therefore, fractures are challenging to be related from mechanics-based models.

Away from faults and folds, fractures are common in layered, nearly flat rocks. Some fractures form systematic trends over large areas, so they are called regional fractures. Regional fractures are proposed in many case studies where the fracture trends match fold model predictions almost nowhere (e.g., Lorenz et al., 1991). Regional fractures (mostly joints) were observed in large geological terrains such as the Arabian Platform (Hancock and Kadhi, 1978; Hancock et al., 1984), the Appalachian Plateau (Hall, 1815; Parker, 1942; Engelder and Geiser, 1980), the Colorado Plateau (Verbeek and Grout, 1984; Garrett and Lorenz, 1989; Hennings et al., 2000; Bergbauer and Pollard, 2004), and southeast England and northeast France (Hancock and Engelder, 1989).

The notion of regional extension of these fractures is very old, although mostly known today from publications of John M. Parker, Paul L. Hancock, and Terry Engelder. Fractures are noted in the literature of the 19th and early 20th centuries as regional features of topography. At that time, geological theories were explaining joints on a global scale. This was before the fracture models in folds and faults started to dominate the geological literature, in the last four decades of the 20th century. Regional fractures are studied as lineaments of dominant trends and explained as parallel to the direction of regional horizontal tectonic compression (e.g., Lorenz et al., 1991). Regional fractures originate with tectonic processes that could be associated with sedimentary rocks, from burial to exhumation. The load paths may include thermoelastic contraction, burial mechanical compaction, and unloading effects with uplift and erosion. Other possible load paths account for high fluid pressure under regional compression. Elevated fluid pressure creates low

effective confining stresses to permit rock fracturing, according to the theory of Terzaghi (Terzaghi, 1943).

It is doubtful if regional fractures have specific spacing. The publications on regional fractures provide no clear measures for fracture abundance in relatively undeformed layered rocks (i.e., neither faulted nor folded). Though these publications are mostly concerned with systematic trends and origins of fractures, they indicate that increasing fracture abundance can reflect the intensity of fracturing stresses and rock mechanical controls (e.g., Lorenz et al., 1991; Palaz and Marfurt, 1997). The spacing of regional fractures is embedded or mixed with the FSLT models, which do not generally specify the mechanism through which fractures are developed. There is, however, an emphasis in these publications that the unloading (with the stress relief due to erosion) of sediments generates fractures (e.g., Price, 1966; Voight and St Pierre, 1974; Engelder, 1985; Narr and Suppe, 1991). This theory apparently limits the use of outcrops as analogues to subsurface reservoirs. If we interpreted fracture abundance in outcrop fractures as being the product of an unloading mechanism, we would infer little abundance of fractures in subsurface rocks, because their load paths are different or deprived of this tensile mechanism.

1.5.3 Fracture Scaling Models

Analyses of fracture sizes emerged in the mid-20th century, and have become very active in the last three decades. The earliest example is perhaps Blanchet (1957), who presented spatial analysis of fractures (and faults) from aerial photographs. Blanchet stressed that fractures are abundant and systematic in the earth crust. He, however, attributed their origin to external planetary forces (of tides), one of many old theories on joint origins that became obsolete after the theories of rock mechanics and plate tectonics were formulated. Previous work on fractures and faults covered a wide range of micro-, meso-, and macro-scales, from thin sections to boreholes, outcrops, and aerial photographs (Fig. 1.2). The scaling laws are statistical and stochastic methods used to predict the probability of fracture (and fault) length, height, aperture, linkage, roughness, and many others properties (e.g., Cartwright et al., 1995; Bonnet et al., 2001; Li and Zhang, 2015). The size of fractures varies in width, length, and height over several orders of magnitude. The frequency distributions of fracture properties include the power, log-normal, gamma, and

exponential laws (e.g., Bonnet et al., 2001).

The scaling models also adopt fractal methods that emerged in the work of Mandelbrot in the 1960s (Mandelbrot, 1967; Mandelbrot and Pignoni, 1983). The core philosophy of a fractal system is that the system displays self-similarity, in which small segments of the system reflect its larger segments, and hence this self-similarity can be quantified by the fractal dimension. Fractal analysis has been applied to fracture systems to describe various scale-invariant distributions of fracture length and spacing (Bonnet et al., 2001).

The scaling models carry a potential for subsurface predictions to substitute limited datasets by proposing models on styles and relations of fracture systems. The scaling models reflect a trend that is deviating in philosophy from the rigid mechanical theories of rock deformation. Mechanical theories typically require descriptions of rock mechanical properties, structures, and stress fields as a priori input for fracture prediction. The scaling methods avoid conflicts of geological interpretations. Undeniably, many geological studies differ in fracture interpretation even for the same location. The advantage of the scaling model is that it is not exclusive to a specific rock or fracture type, but rather general to the wide range of rocks, faults, and microfractures (e.g., Marrett et al., 1999).

Applications of the scaling laws, however, vary because none is expected an appropriate model in all rock and fracture cases (Bonnet et al., 2001). The physical factors controlling the model parameters (exponents) of statistical distributions are always subject of debate. Although fractures can appear to extend in an outcrop, fractures are discontinuous at a particular scale of observation (Pollard and Aydin, 1988). The size of fracture systems must have upper and lower bounds that can be related to the length scale of the system, driving mechanism, or controlling mechanism. The lower bound of fracture size is not established. It is difficult to make observations at the level of atomic bonds. The upper limit is sometimes extended to the brittle part of the earth crust for all types of discontinuity networks (fractures and faults).

Fracture confinement by layers is considered a boundary condition (upper bound) for scaling relationships (Gillespie et al., 1999). Fractures also terminate at other (pre-existing) fractures. The scaling laws for fractures in layered rocks are possible but with some limitations that

can affect the general distribution of fracture observations. In particular, fractal analysis is apparently useful in absence of mechanical controls, such as fractures in non-layered massive rocks (Riley et al., 2011), in which the system obeys an internal mechanism rather than the mechanical boundary conditions.

1.6 RESEARCH OBJECTIVES AND STRUCTURE

1.6.1 Research Scope

Fractures, especially joints, are renowned for their ubiquity and abundance in carbonate outcrops. The abundance and properties of fractures in subsurface carbonates is subject for many-faceted debates; chief among them is the shortage of direct observations from subsurface, discrepancy of outcrop-based models, and validity of outcrops as reservoir analogues. Nonetheless, the aforementioned models provide useful frameworks that can be summarized in the following points:

- 1) Fractures can develop in rocks because of the weak tensile strength of rocks and availability of many loading paths that can produce fractures in different tectonic environments (Price, 1966; Engelder, 1985; Cosgrove et al., 2004).
- 2) The publications that support the regional fracture theory acknowledge that increasing fracture abundance can reflect the regional stress intensity and the local controls of rock lithology (Lorenz et al., 1991; Palaz and Marfurt, 1997).
- 3) Fractures can form and evolve in rock layers under the loads that led to the development of folds and faults, or the loads that were directed or ensued by the growth of folds and faults. The models generally agree that intensity of folding and faulting can generate more fractures in all, or part, of the deformation area. Some of these concepts are employed in geomechanically based methods to relate fracture abundance, although there is no agreeable scale for rock strains. The geomechanical models are generally viewed as testable to outcrops and subsurface alike.

The review above outlines the reasons that provided the inspiration for this research. The research scope can be well-defined if we first realize that previous studies are mostly (i) based on

outcrops and empirical relations, (ii) based on outcrop cases located in highly deformed regions of the Variscan, Alpine, Alleghanian, Laramidian, and other orogens (Fig. 1.6), and (iii) presented models that are not universal, and can be debated even within highly deformed regions. Fracturing developed through geological histories under many possible load paths associated with rock burial, uplift, erosion, folding, and faulting processes. In some outcrop cases, fracturing changed mode, where rock blocks were displaced to turn fractures into faults.

This research is exploratory; it is not designed to credit or discredit previous models, but rather to investigate the problem from a different perspective and develop simple models.

The scope of this research is to study carbonate fractures from subsurface and outcrops in regions of gentle deformation that are buried at relatively shallow depths (less than 2 km) see (Fig. 1.8, Fig. 1.9, and Fig. 1.10). Gentle deformation is introduced in this research to qualitatively define areas lacking faults and folds, except a very low-amplitude folds on a regional scale. Such a geologic setting is treated as if were a natural laboratory for fracturing in layered carbonates. Case studies from such regions can shed light on how carbonates are sensitive to fracturing.

The main aim of this research is to address controls on fracture abundance in gently deformed carbonates. A simplified version of the FSLT model is used in this research as an important framework to relate fracture abundance (Fig. 1.11). In the framework of the FSLT model, fracture abundance is divided into three categories: (i) undersaturated for $S > T$, (ii) balanced saturated for $S \approx T$, and (iii) oversaturated for $S < T$. Other aims of this research are to address the following issues: (i) values of subsurface datasets for modeling reservoir fractures, (ii) methods of reservoir fracture interpretation and modeling, and (iii) validity of outcrops as reservoir analogs.

1.6.2 Research Design

The research aims are based on four case studies in the interior of the Arabian Platform (see Fig. 1.8 and Ch. 2).

The research objectives are as follows:

- 1) The first objective is to describe fractures, identify their systems, and measure their abundance in the same exhumed and buried multilayered carbonate platform. This approach is best for studying outcrop-reservoir analogues despite its inherent difficulties.

The approach has been rarely explored from the exhumed and buried parts of a carbonate platform (e.g., Narr, 1991), due to either lack of outcrops for reservoir rocks or lack of direct datasets on reservoir fractures.

- 2) The second objective is to illustrate a context for fracture abundance in gently deformed carbonate strata of a tectonic history at contrast with that in polyphase and complex tectonics.

This approach can help provide insight to frame whether fracture abundance in carbonates is universally similar, with negligible differences, or rather substantially varying. For example, this research can demonstrate how fractures in the interior of the Arabian Platform differ from the fractures in the Asmari carbonates at the platform margin.

Fractures were studied and correlated from what can be considered as “stratigraphic” and “structural” analogues. Stratigraphically, fractures are in the reservoirs and outcrops of the Late Jurassic Arab carbonates, the world’s most oil-productive rocks. The Arab carbonates display the same lithofacies with their alternations of competent and non-competent layers, and comparable layer thicknesses. Structurally, the abundance of the Arab reservoir fractures in the dome structure is correlated with the outcrops on top of the dome and with the outcrops of the homocline. The dome and homocline are gentle forms of folds in the Arabian sedimentary basins. The dome outcrops belong to the Cenozoic carbonates of the Rus Formation.

1.6.3 Outlines of Research Chapters

This research is organized in eight chapters. The contexts of the study areas, datasets, and methods are introduced in Ch. 2 and Ch. 3. The systematic properties of the fractures in the Arab carbonates are presented in Ch. 4. New results were obtained on the mineralization, orientation, and abundance of the fracture systems in the Arab reservoirs and their equivalent outcrops. A comparison between fractures in the core and corresponding borehole images is presented in Ch. 5, which also includes new results on the factors influencing the detection levels of reservoir fractures by modern electrical borehole imagers. Among the influencing factors of fracture detection were fracture roughness and wall mismatch, two properties that are described in Ch. 6. Ch. 6 presents new insights on the nature of roughness and wall mismatch, which were measured

using a novel combination of measuring techniques, described in Ch. 3. Ch. 7 includes comparisons and discussions on the factors that control fracture abundance in gently deformed carbonates. Ch. 8 presents the summary of the research findings and some ideas of potential for future work.

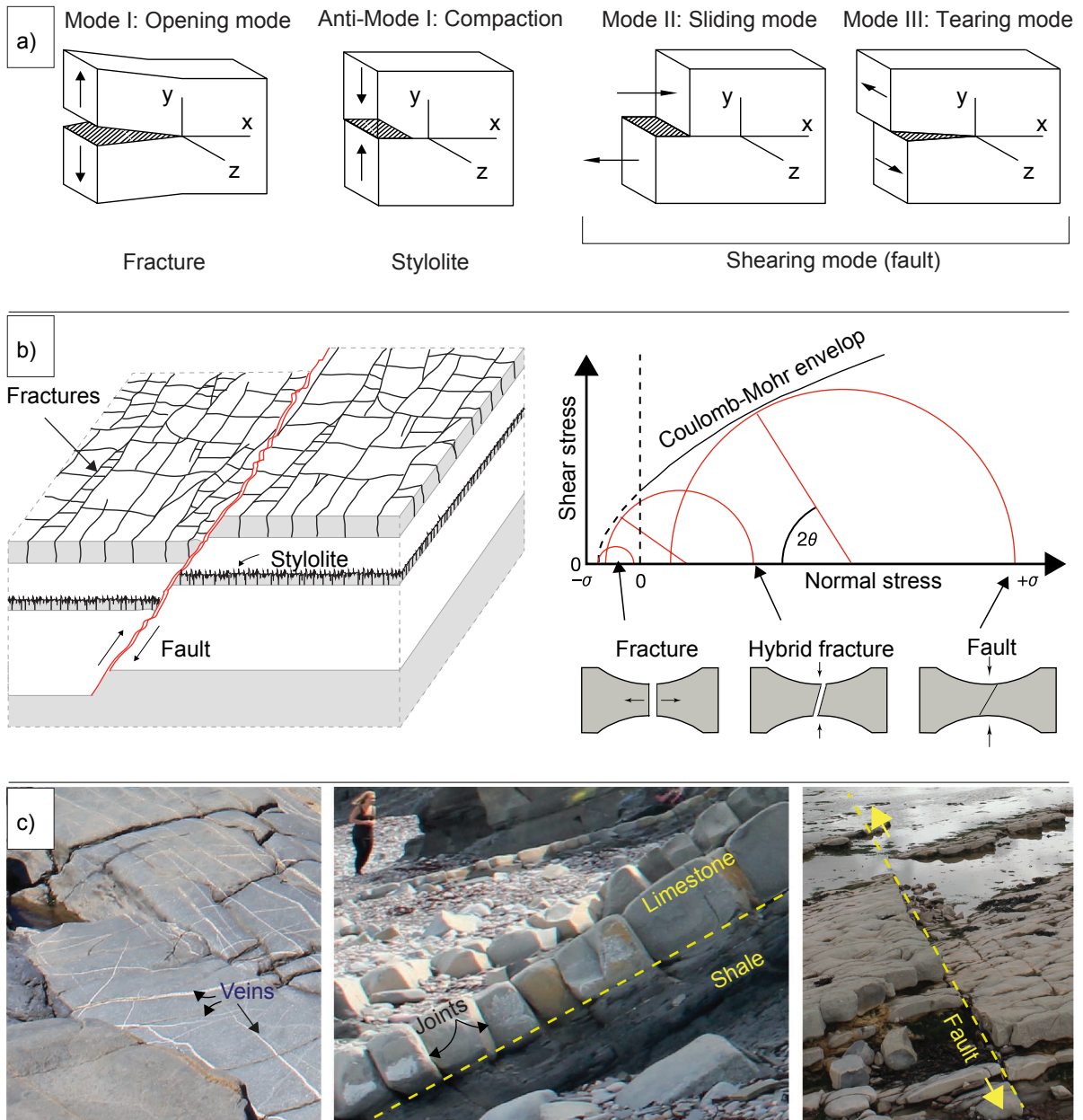


Fig. 1.1: Typical modes of crack tip displacements.

a) Mode I, outward normal to the fracture plane; Anti-Mode I, inward normal to the fracture plane, and parallel to the fracture plane in Mode II and Mode III, but perpendicular in II and parallel in III to the leading tip of the crack; b) a model displaying the setting of fractures (joints and veins), a bed-parallel stylolite structure, and a fault in flat layered rock; and the Coulomb-Mohr failure criteria explaining development of fractures under normal and shear stress fields in rock formations; and c) examples of calcite-filled fractures (veins), barren fractures (joints), and a fault in the carbonates exposed along Kilve Beach in the Bristol Channel, UK.

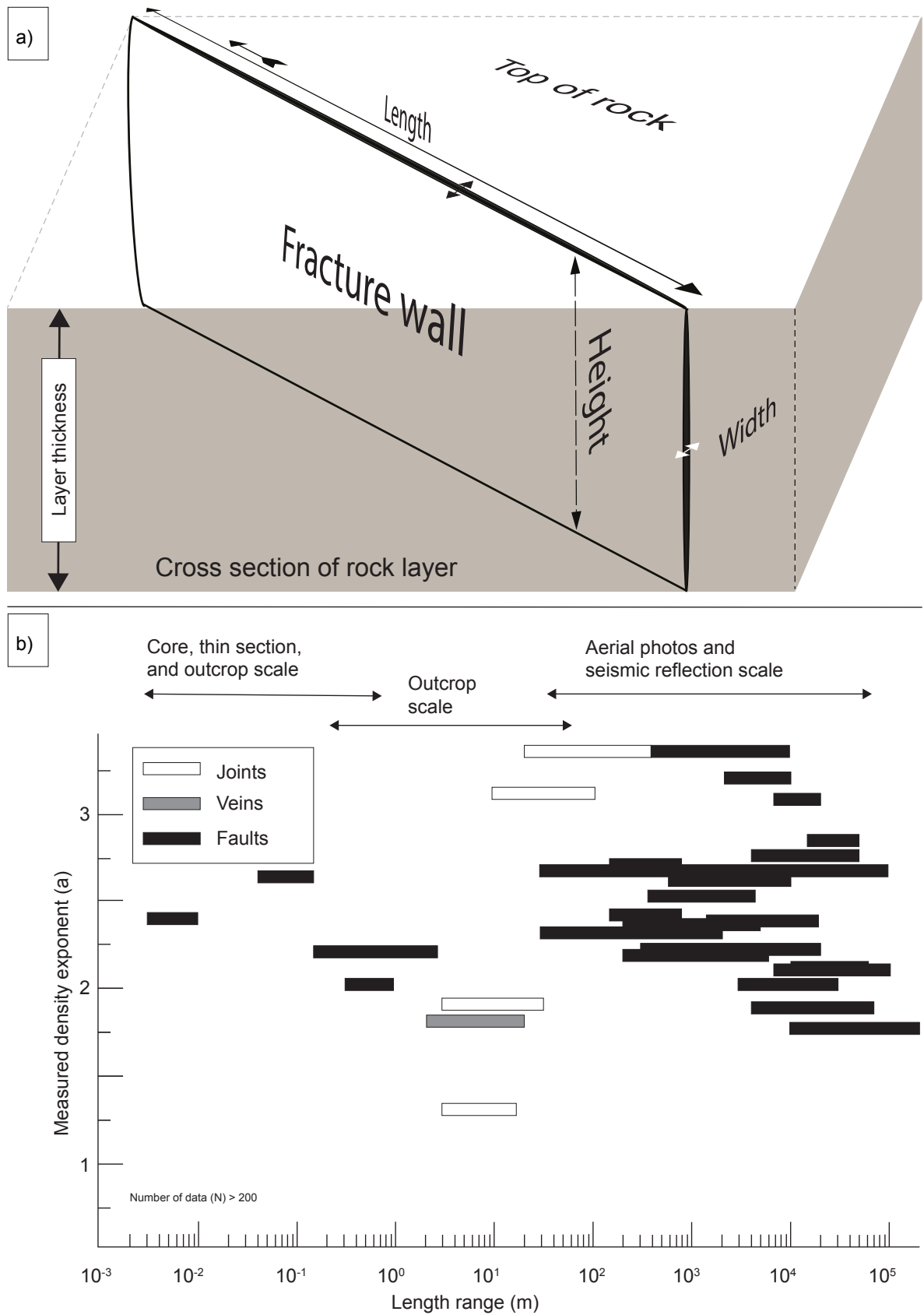


Fig. 1.2: a) Typical 3-D geometry of a fracture in layers; b) ranges of fracture lengths, modified from (Bonnet et al., 2001).

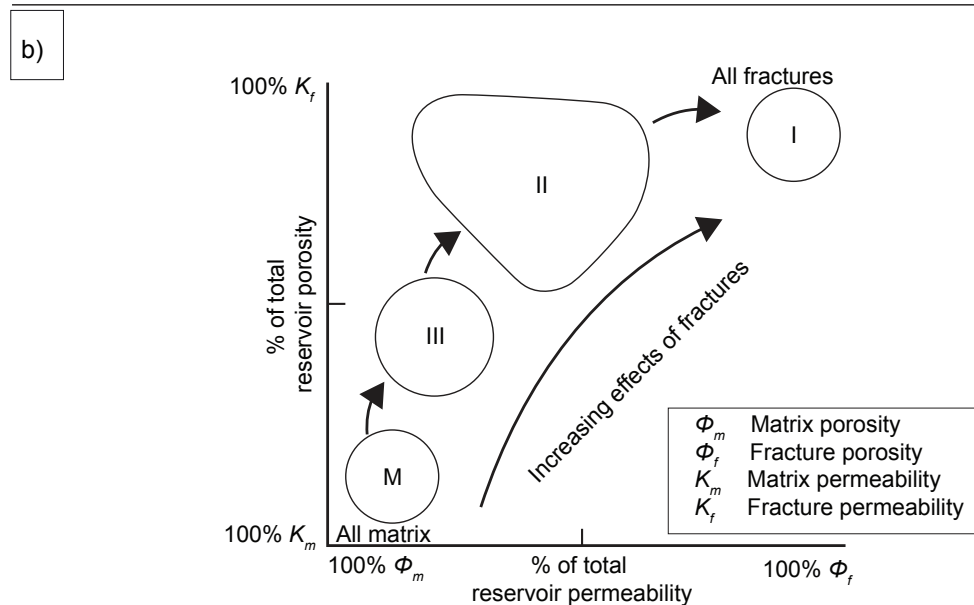
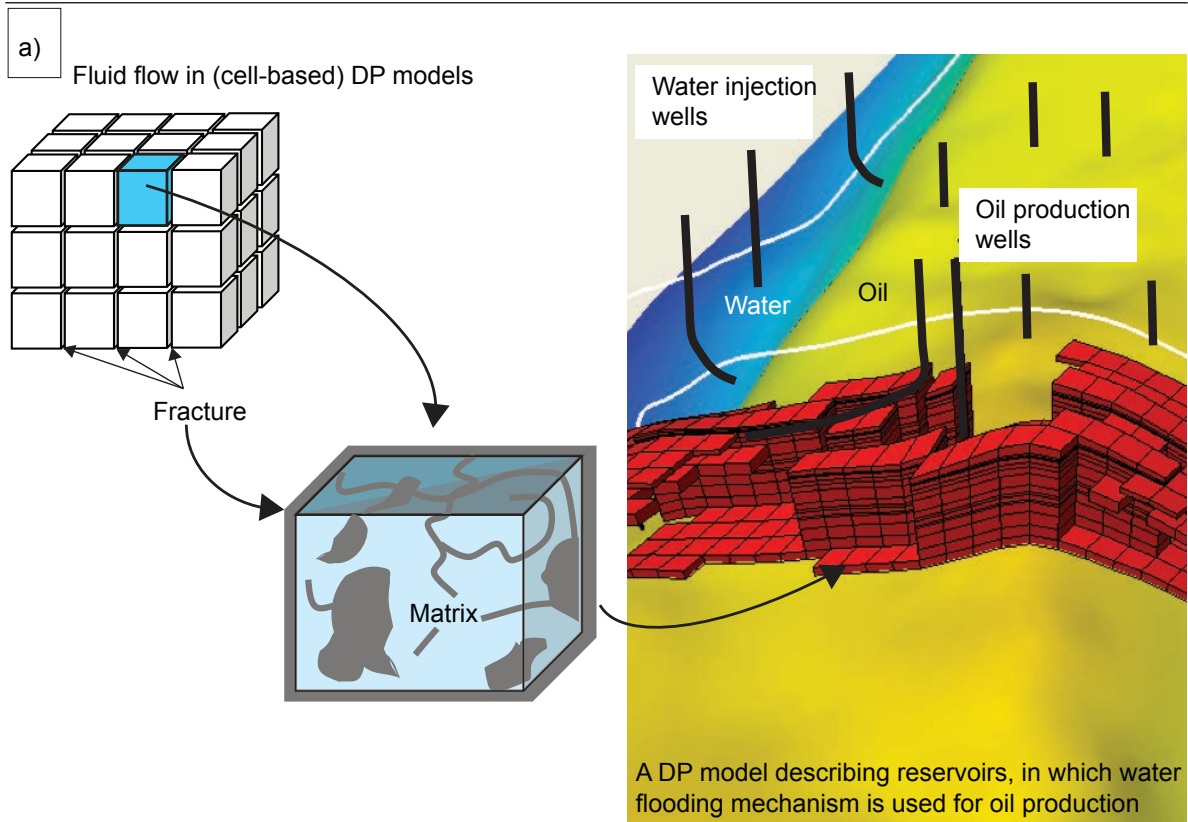


Fig. 1.3: a) Basic concepts of 3-D numeric simulations of fluid flow, incorporating porosities of matrix and fractures in a dual-porosity (DP) model, where fractures are sometimes modeled using the method of discrete fracture network (DFN); b) classifications of oil reservoirs based on reservoir rock porosity and permeability, adapted from Nelson (2001).

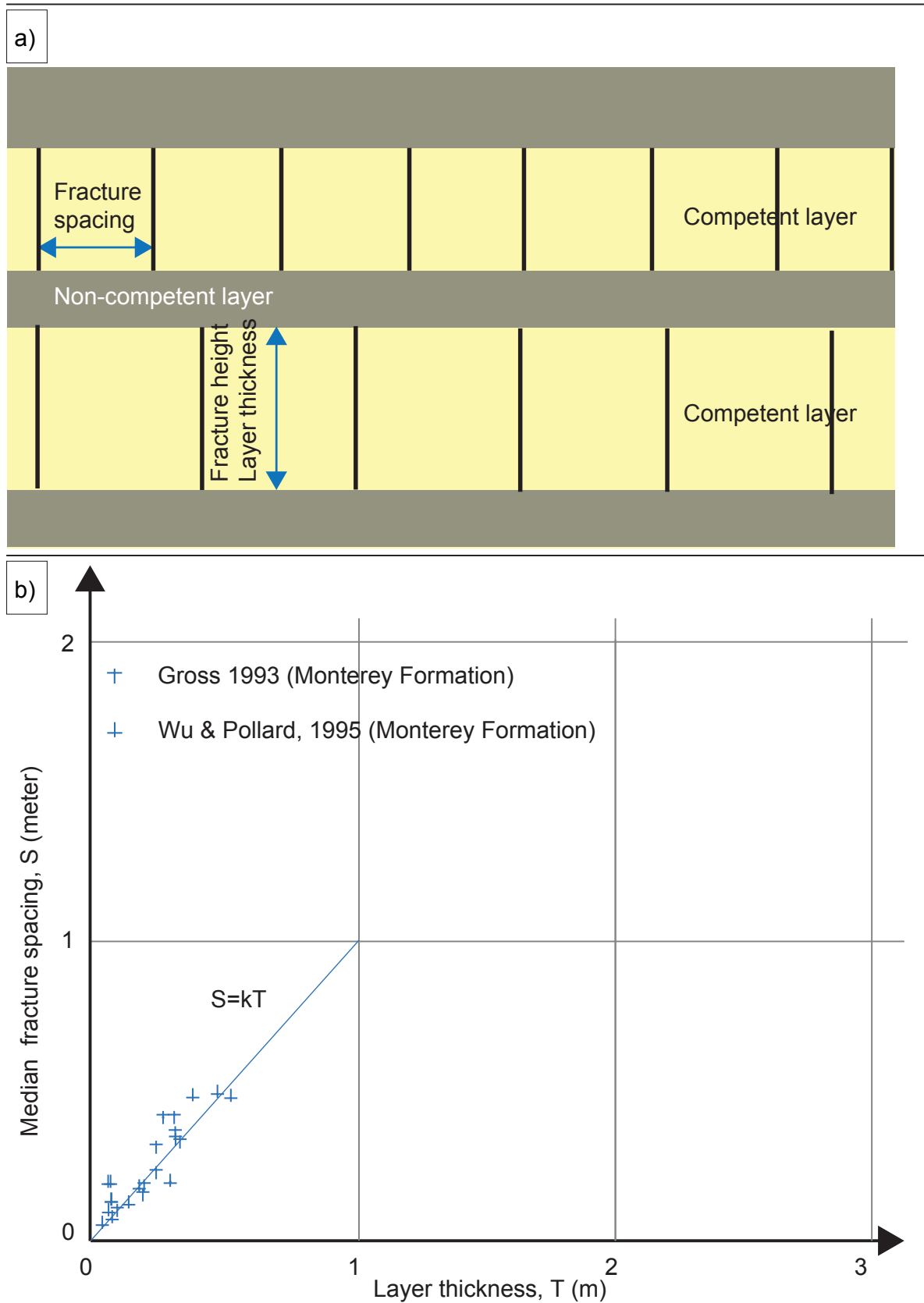


Fig. 1.4: a) cross section of a layered rock with regularly spacing fractures in competent layers terminated at non-competent layers, b) example of outcrop measurements from Monterey Formation in California showing the FSLT model that relates the spacing (S) between fractures in a layer to the thickness (T) of the layer in a linear relationship dependent on some constant (k) of the layer lithology.

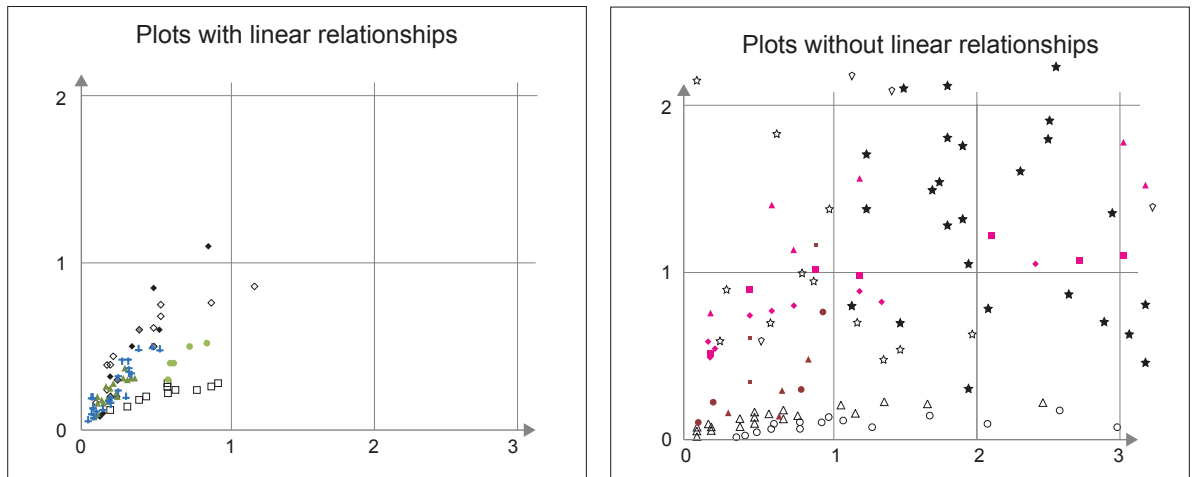
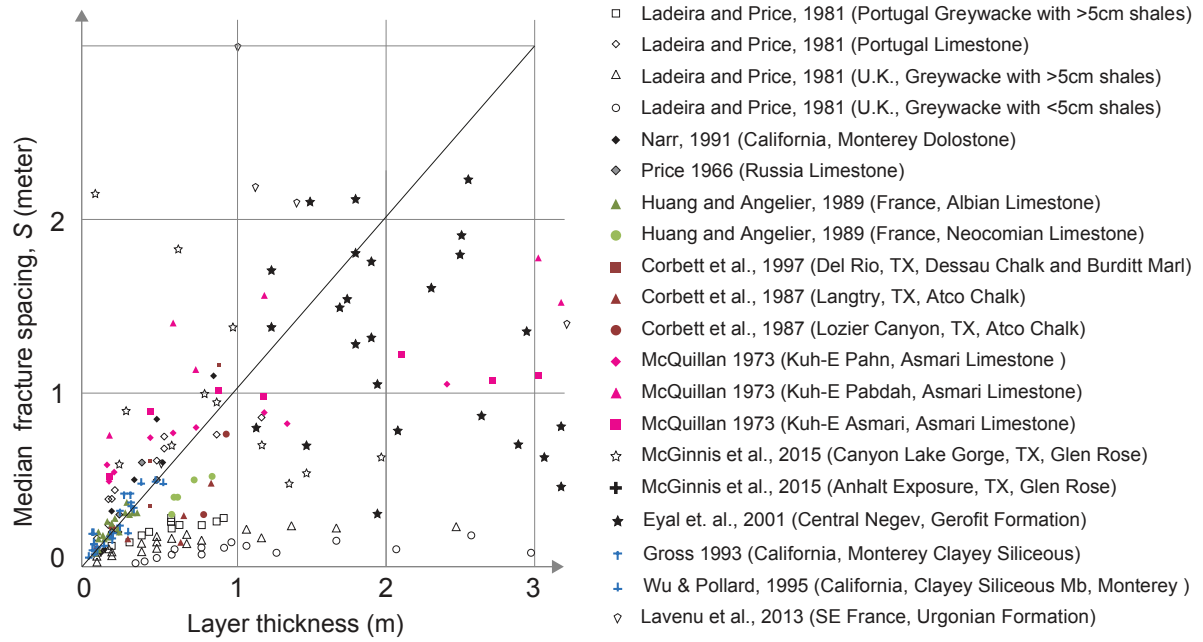


Fig. 1.5: Some of the publications that presented measurements for fracture spacing (S) with and without linear relations to host layer thickness (T).

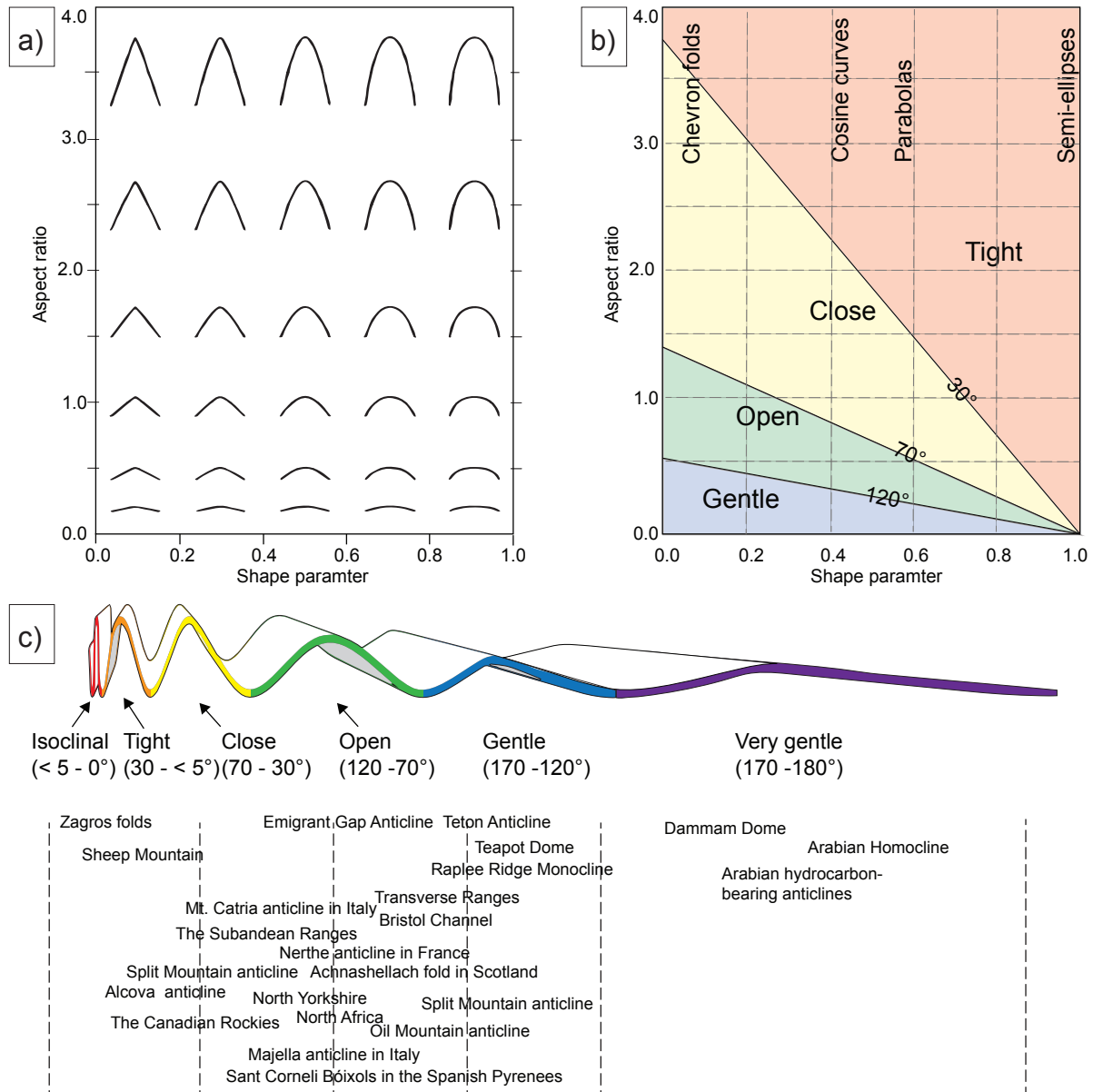
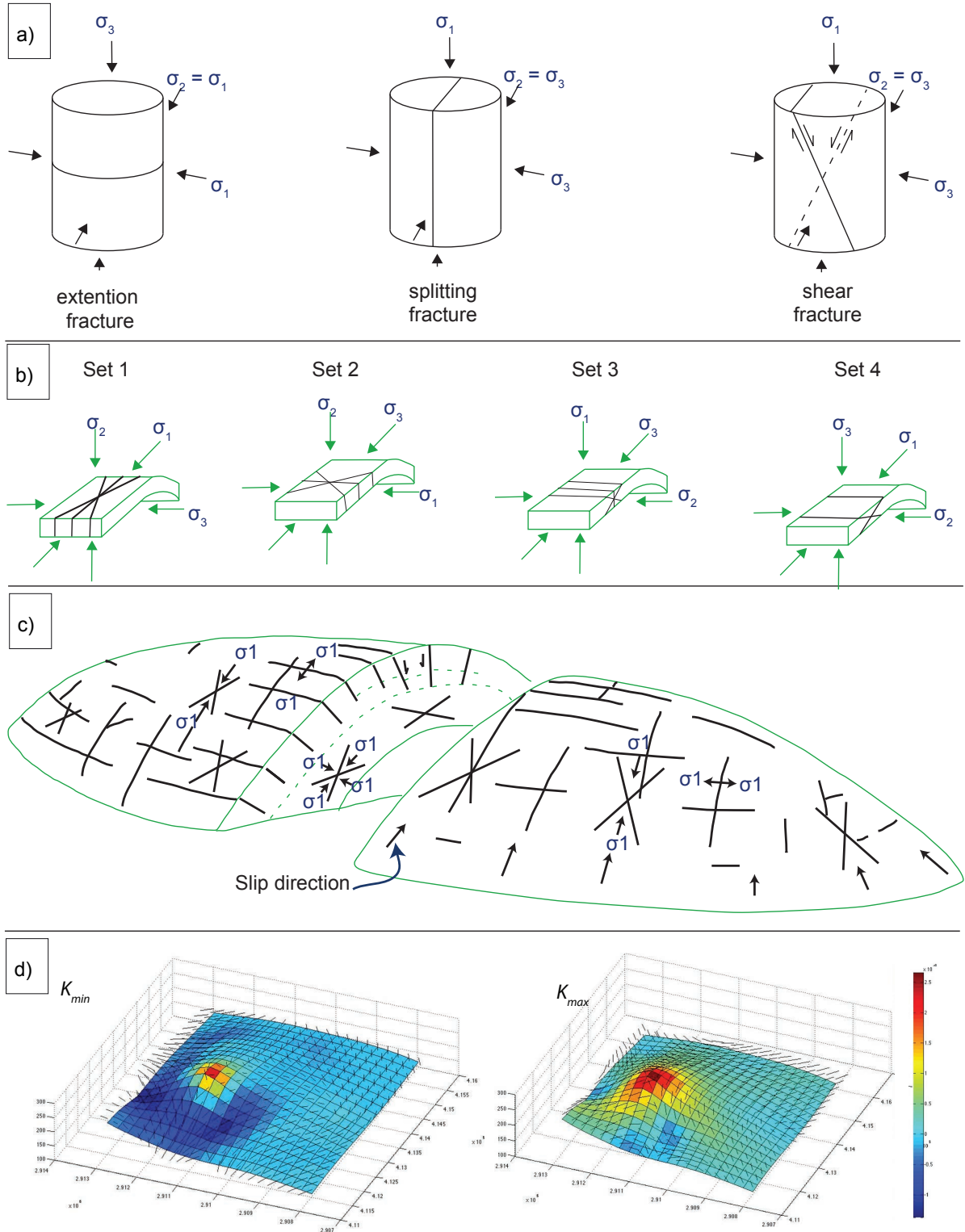


Fig. 1.6: a), b) Classification of folds based on the shape parameter of fold tightness and aspect ratio between fold amplitude and base length, modified from Ramsay and Huber (1987); and c) a sketch demonstrating the magnitudes of layer dips on fold wings, with the following examples of folds, in which carbonate fractures were studied:

From the USA, the Teton Anticline (Stearns and Friedman, 1972), Sheep Mountain (Harris et al., 1960; Bellahsen et al., 2006), Teapot dome (Thorn and Spieker, 1931; Cooper et al., 2006), Emigrant Gap anticline (Bergbauer and Pollard, 2004), Grand Hogback Monocline (Murray, 1966; Garrett and Lorenz, 1989), Raplee Ridge Monocline (Mynatt et al., 2009), and the Transverse Ranges in California (Narr and Suppe, 1991). From the United Kingdom, Bristol Channel (Hancock, 1969; Rawnsley et al., 1998; Belayneh and Cosgrove, 2004) and North Yorkshire (Milodowski et al., 1998). From Europe, Sant Corneli Bóixols in the Spanish Pyrenees (Shackleton et al., 2011; Tavani et al., 2011), Mt. Catria anticline in Italy (Tavani et al., 2008), Majella anticline in Italy (Agosta et al., 2010), and Nerthe anticline in France (Lamarche et al., 2012). From Zagros Mountains, Kuh-e Asmari, Kuh-e Pahn, Kuh-e Pabdeh-Gurpi, Khaviz, Sim, and Meymand (McQuillan, 1974; Ameen, 1991; Wennberg et al., 2006; Stephenson et al., 2007; Ahmadhadi et al., 2008; Mobasher and Babaie, 2008; Lacombe et al., 2011; Awdal et al., 2016). From the Canadian Rockies, (William R. Jamison, 1997), the Subandean Ranges (Iñigo et al., 2012), the North Sea (Sagi et al., 2014), North Africa (Ismat, 2008; Kjelkenes, 2015), East Oman (Mercadier and Makel, 1991; Bertotti et al., 2005), and Eastern Arabia (Al-Fahmi, Cooke, et al., 2014).



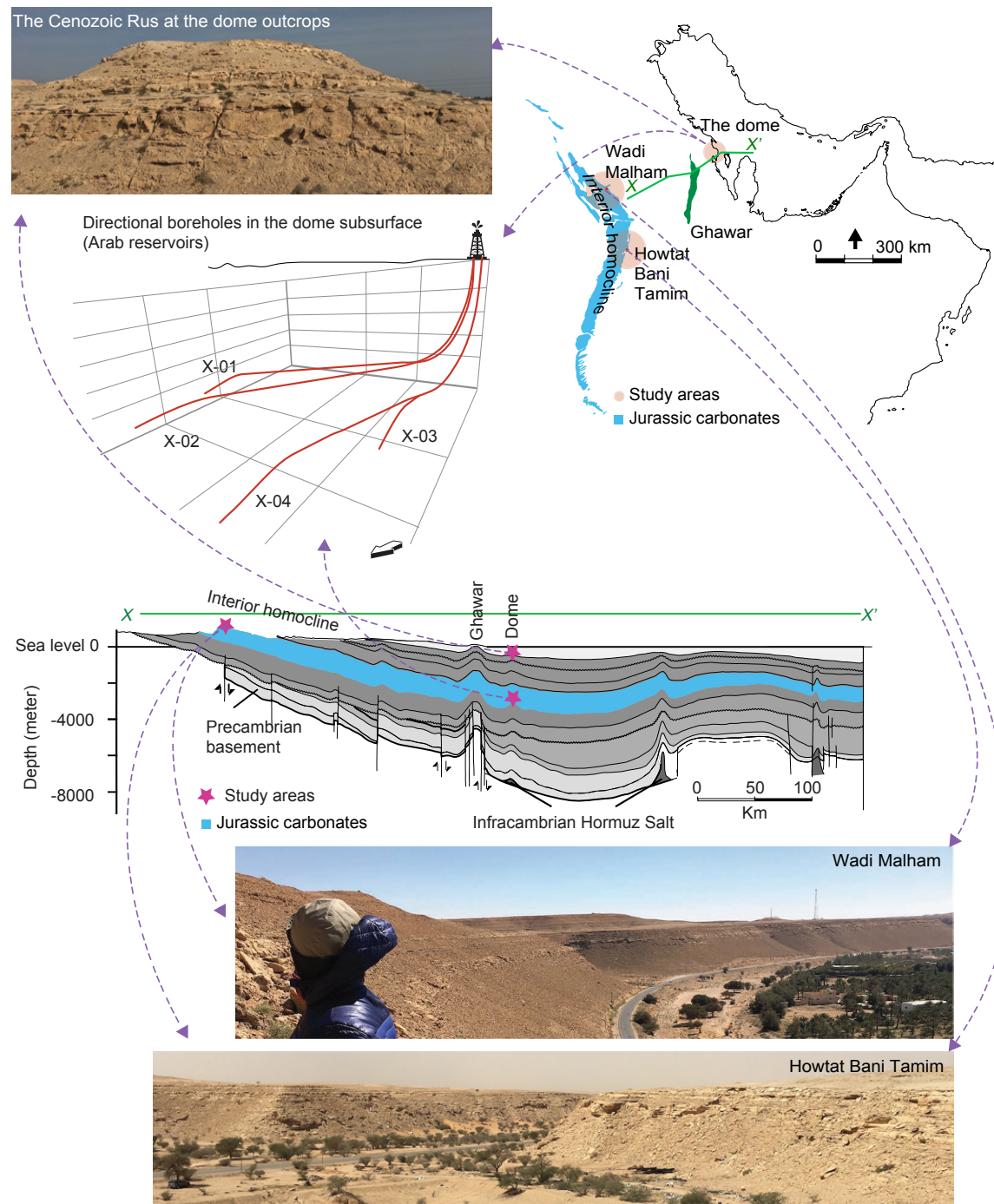
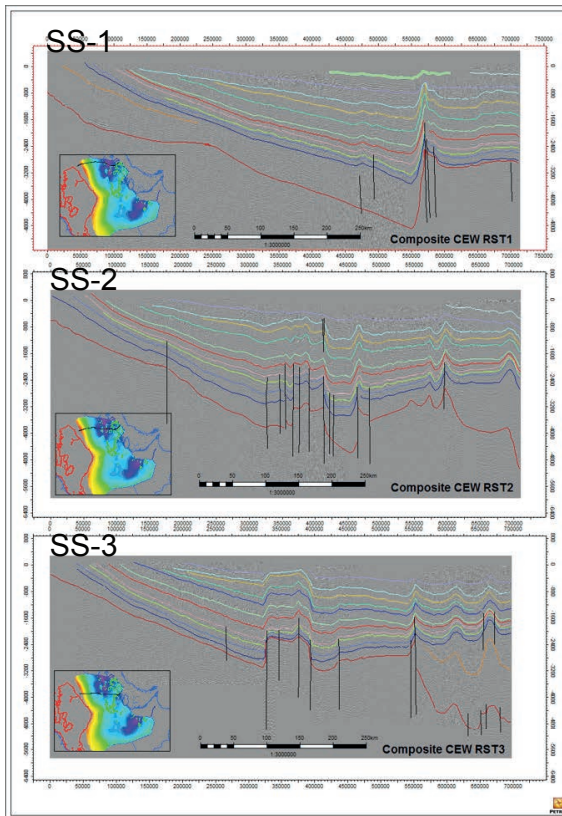
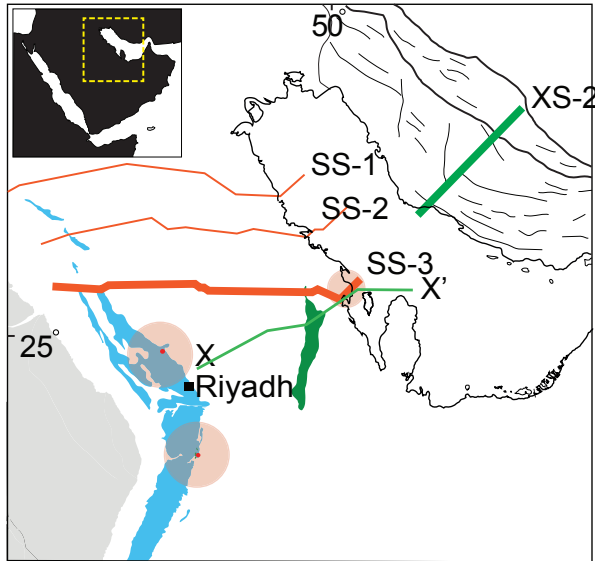


Fig. 1.8: Fractures are studied from three geographic areas in the Arabian Platform, two areas of the Jurassic Arab carbonate outcrops in Central Arabia, and one area of a dome structure in Eastern Arabia, in which fractures are described from the outcrops of the Cenozoic Rus Formation and the reservoirs of the Arab carbonates, using borehole datasets of core and borehole images (Ch. 2).



Burial analyses

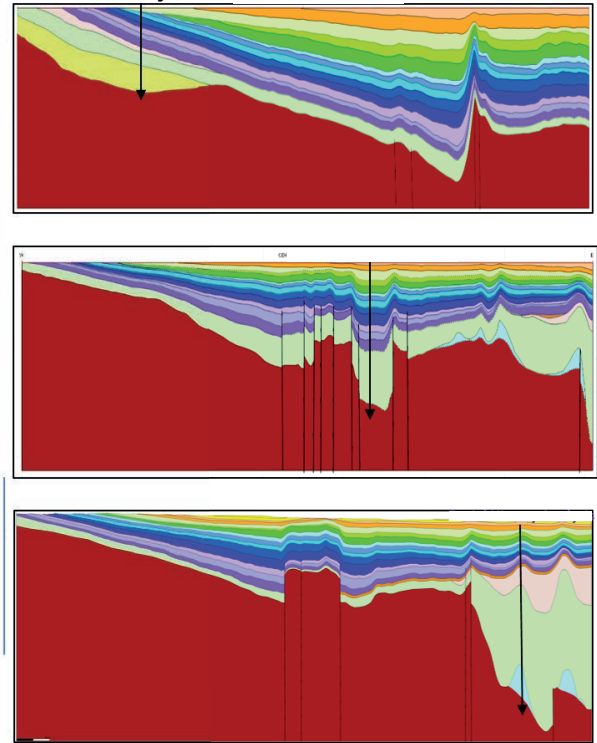


Fig. 1.9: Seismic reflection sections of the Arabian Platform interior (SS-1, SS-2, and SS-3) display gentle deformation of low-curvature folds developed by movement of Hormuz Salt and basement faulted blocks. X-X' cross section Fig. 1.9. The seismic sections are adapted from Aramco. See depths of the Arab carbonates in the next figure.

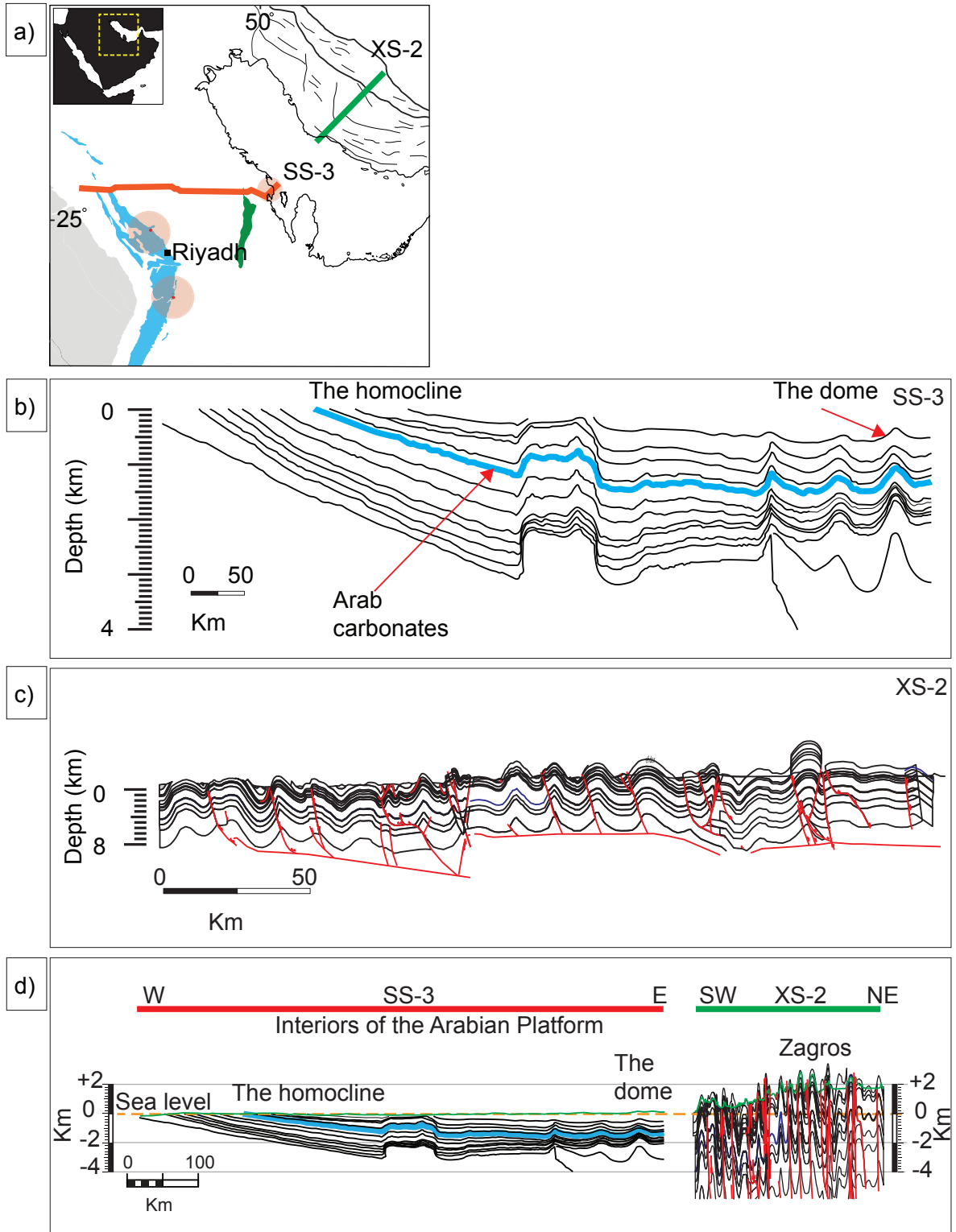


Fig. 1.10: Cross-sections of the Arabian Platform interior. a) and b) Seismic reflection section (SS-3) displays gentle deformation of folds in contrast with the sharply folded and intensely faulted margins of the platform in the Zagros Mountains, see cross-section XS-2, modified from Bigi et al. (2018); d) the two sections in (b) and (c) are combined to see the degree of shortening in the Arabian Platform. Note that the burial of the Arab carbonates (light blue) is less than 1.6 km.

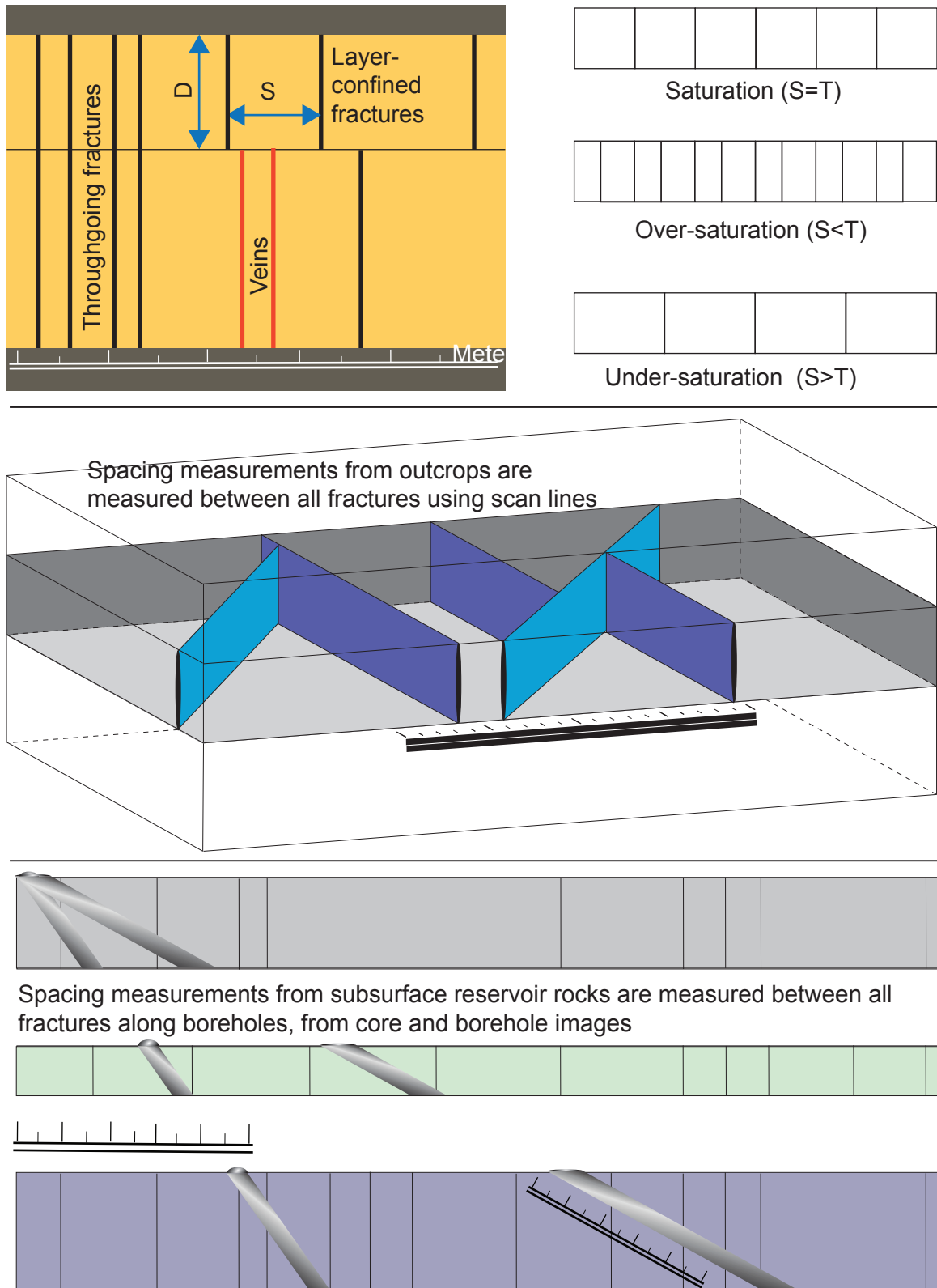


Fig. 1.11: The methods used in this research to describe fracture abundance.

Fracture spacing (S) is measured between all fractures. Fracture abundance is compared to the thickness (T) of the fractured layer in outcrops and the thicknesses (T_r) of the reservoir rock units that are divided based on lithofacies types. Measurements are simplified for the ratio between S and T , by which rock layers are expected to exhibit balanced saturation ($S = T$), over-saturation ($S < T$), or under-saturation ($S > T$) levels.

2 GEOLOGIC CONTEXT

“The geology of the peninsula of the Arabs is truly of the Arabian simplicity: Stack of plutonic rock, whereupon lie sandstones, and upon the sand-rocks, limestones.”

Doughty, 1880

2.1 INTRODUCTION

The Arabian Platform exhibits a lengthy and spatially variable tectonic history, from the stable western interior to the more active eastern margin. Fractures have been studied from several rock formations in many regions of the platform, from Central Arabia to the Zagros Mountains. The interior of the Arabian Plate in the regions of Central and Eastern Arabia must stand out in the specific geological context for fractures in gently deformed carbonates (Fig. 2.1). The results from these regions may yield important insights on the nature and abundance of carbonate fractures, not least for the modeling of the carbonate reservoirs in the Arabian Platform.

The platform is the Earth’s richest region in hydrocarbon resources (Fig. 2.1). The region holds nearly one-third of the world’s hydrocarbon reserves and is ranked fifth for production rate (EIA, 2016). The hydrocarbons dominantly exist in carbonate reservoirs, in contrast with regions outside the Arabian Platform where most hydrocarbons are hosted in siliciclastic reservoirs (e.g., Bjørlykke and Jahren, 2010).

2.2 THE ARABIAN PLATFORM GEOLOGY

The Arabian Plate is composed of two distinct geological provinces, the Arabian Shield and the Arabian Platform (Fig. 2.1). The provinces tectonically make up the Arabian Plate, which became among the earth's youngest lithospheric plates after it was separated from Africa by the Red Sea Rift around 25 million years ago (e.g., Laughton, 1966; Bosworth et al., 2005). The oldest rocks in Arabia exist in the Arabian Shield, which forms the Sarawat, Hejaz, and Midyan Mountains in Western Arabia. These rocks form part of the Precambrian basement underlying the Arabian Platform (e.g., Johnson, 1998). The Arabian Shield, together with the Nubian Shield in northeast Africa, is composed of crystalline rocks that were accreted in the Precambrian, from about 950 to 550 million years (Ma) ago (e.g., Stoesser and Camp, 1985). The Arabian Platform (also known as the Arabian Shelf) is a sequence of continental and marine rocks deposited in the last 525 million years from the Cambrian to Pliocene under controls of the basement architecture, the Tethys Ocean eustasy, and the Arabian Plate tectonics (e.g., Al-Husseini, 1997; Ziegler, 2001; Haq and Al-Qahtani, 2005).

The focus of this research is the Arabian Platform in Central and Eastern Arabia (Fig. 2.1). In this region, lithology, depositional environments, and tectono-stratigraphy of the platform sequences have been studied repetitively in the past seven decades, following the oil discovery in the Arab carbonates of the Dammam Dome in 1938 (Steineke et al., 1958). The subsurface geology is typically studied by geologists of Aramco in Saudi Arabia and other national oil companies in the Gulf States. Outcrops were studied by numerous geologists, from Aramco, the French Geological Survey (Bureau de Recherches Géologiques et Minières), the Saudi Geological Survey, and some universities.

In the region, the platform rocks dip gently and uniformly from Central Arabia eastward, toward the Arabian Gulf and Rub' Al-Khali basins (e.g., Powers et al., 1966; Sharland et al., 2013) (Fig. 2.2). The platform can be broadly divided into two stratigraphic megasequences: the Palaeozoic and the Late Permian to Holocene (e.g., Wender et al., 1998; Ziegler, 2001). Each of these was formed in a period of roughly 250 million years in the Tethys Ocean on the stable

passive margin of Gondwana. The Palaeozoic section, also known as pre-Khuff clastics, is a sequence of dominantly siliciclastic sediments produced by depositional cycles in terrestrial to shallow marine environments of the Paleo-Tethys Ocean (e.g., McGillivray and Hussein, 1992; Konert et al., 2001). The Late Permian to Holocene section is a carbonate-dominated sequence of sediments that were mostly deposited in the passive margin of the Neo-Tethys Ocean (e.e., Ziegler, 2001; Sharland et al., 2013) (Fig. 2.3 and Fig. 2.4). The section represents a major transgression event that initiated the deposition of an extensive carbonate sequence, including the platform of the Late Jurassic carbonates (Fig. 2.2). The sedimentary basin generally exhibits an obvious layer-cake style for the post-Permian rocks (e.g., Murriss, 1984). Nonetheless, not every rock formation is continuous in the entire Arabian Platform, because of the different rates of sediment deposition, hiatus, and erosion (e.g., Al-Husseini, 1997). Most rock formations exist in Eastern Arabia, where the platform thickness is probably near 10 km (e.g., Al-Amri, 2013).

2.3 THE LATE JURASSIC ARAB CARBONATES

The Late Jurassic sequences of the Arabian Platform are divided into five formations: Hanifa, Jubaila, Arab, Hith, and the lower part of Sulaiy (e.g., Powers et al., 1966), (Fig. 2.4). The sequences of these formations conformably extend from their escarpments in Central Arabia and dip gently toward the Arabian Gulf. These rock formations make up the Jurassic petroleum system, which includes some regional organic-rich source rocks (Hanifa), stacked reservoirs (Hanifa, Arab, Hith), multiple seals (Arab anhydrite and Hith), and several oil fields including the world's largest oil field, Ghawar (e.g., Al-Husseini, 1997). The Jurassic rocks of the platform constitute one of the most prolific petroleum systems in the world (e.g., Murriss, 1984; Pollastro, 2003).

Following the discovery of oil, the Arab carbonates have been systematically studied to characterize and extract hydrocarbons from the reservoirs. A wealth of information was obtained on the sequence stratigraphy and lithofacies of the Arab reservoirs in Eastern Arabia and the reservoir equivalent outcrops in Central Arabia (e.g., Steineke et al., 1958; Powers et al., 1966; Wilson, 1985; Alsharhan and Kendall, 1986; Mitchell et al., 1988; Al-Husseini, 1997; Davis et al.,

1997; Sahin and Saner, 2001; Ziegler, 2001; Cantrell et al., 2001; Handford et al., 2002; Voelker, 2004; Hughes, 2004; Lindsay et al., 2005; Al-Awwad and Collins, 2013; Sharland et al., 2013).

The Arab Formation was deposited in the Late Kimmeridgian in shallow marine to sabkha environments, with four distinct cycles (e.g., Powers et al., 1966; Al-Husseini, 2009). Each cycle produced a shallowing-upward marine carbonate sequence and overlying anhydrite. The carbonate members are A, B, C, and D, in descending stratigraphic order from younger to older (Fig. 2.4). Each member is capped by anhydrite rock in the Arab Formation, except the uppermost member Arab-A, which is capped by the Hith Formation. The Hith Anhydrite is the major seal system of the Jurassic hydrocarbon system in the Arabian Platform.

The equivalent of the upper Arab carbonate reservoirs (A and B) is absent in outcrops in Central Arabia, due to the weathering of their overlying and interbedded anhydrite (e.g., Powers et al., 1966). The equivalent of the Arab C reservoir is present in a few outcrops as brecciated and collapsed carbonates (e.g., Powers et al., 1966). The equivalent of the Arab-D reservoir is the Arab-D member and Upper Jubaila that are present in several locations in Central Arabia (e.g., Lindsay et al., 2005). The thickness of the Arab Formation ranges from tens of meters (of the remaining carbonate outcrops) in Central Arabia to about 128–150 m in the subsurface in Eastern Arabia (e.g., Sharland et al., 2013).

The Arab reservoirs are composed of varieties of limestone and dolomite lithofacies (e.g., Mitchell et al., 1988). The lithofacies exhibits a wide variety of matrix porosity, from micro and macro interparticle pores to macro intraparticle, moldic, and vugular pores. The reservoir rock layers alternate between tight (low-permeability) and super permeability (super-k) (e.g., Cantrell and Hagerty, 1999; Voelker, 2004; Al-Awwad and Collins, 2013).

The rock mechanical parameters of the Arab reservoirs are primarily functions of porosity and, to a lesser degree, of mineralogy and fabric (Ameen, et. al., 2009). In the Arab-D reservoir of Ghawar, the intact matrix is not sensitive to the dynamics of the reservoir confining stress under production conditions (Ameen, et. al., 2009). The mechanical properties of the Arab-D in outcrops showed moderate correlation to porosity and permeability of the rock lithofacies (Abdlmutalib et al., 2015).

2.4 THE CENOZOIC RUS CARBONATES

The outcrops in Eastern Arabia are comprised of the Cenozoic sequences of the Arabian Platform. The sequences include the rock formations of Umm er Radhuma (UER), Rus, Dammam, Hadrukh, Dam, and Hofuf (e.g., Powers et al., 1966) (Fig. 2.3). The deposits of the Cenozoic sequences were mostly carbonate-dominated in shallow marine setting, followed by terrestrial and shallow marine sediments in restricted basins until the closure of the Neo-Tethys Ocean around 10 million years ago (e.g., Ziegler, 2001; McQuarrie et al., 2003).

In Eastern Arabia, the outcrops of the Dammam Dome range in age from the Palaeocene-Early Eocene to Middle Miocene (e.g., Tleel, 1973). The Palaeocene to Early Eocene UER Formation is the lowermost formation, with two small localities over the dome. The regional stratigraphy above the UER Formation includes the Rus, Dammam, Hadrukh, and Dam Formations. These rock formations are present within the dome region except the Neogene clastic formation of Hadrukh, which borders the dome (e.g., Tleel, 1973). The absence of the Hadrukh Formation is related to the uplift of the dome region in the sedimentary basin of Eastern Arabia.

The focus of this research is the Rus Formation in the area of Dammam Dome (Fig. 2.5). The formation was dated to Eocene and named after its type section at Jabel Umm ar-Rus, near the dome central region. The type section was referred to as the “Chalky Zone” when it was first established in 1934 by Aramco exploration geologists S. B. Henry and J. W. Hoover. Later, R. A. Bramkamp (an Aramco geologist) applied the name “Rus Formation” in 1946 as a replacement for the term “Chalky Zone” for the interval between the UER and the Dammam Formation (Tleel, 1973). The formation is underlain and overlain by rocks of early Eocene age and, therefore, it was presumed to be entirely Early Eocene (Ypresian).

A summary of the different subdivisions of the Rus Formation from previous publications is presented in Tab. 2-1 and Fig. 2.5. This research adopts the divisions of Weijermars (1999): Lower, Middle, and Upper for the three units of the Rus Formation. The Middle Rus is the main subject of this research on fracture abundance from the dome outcrops. It is a competent layer of limestone sandwiched between the non-competent carbonates of the shale-rich Upper Rus and

marl-rich, cavernous Lower Rus (Tleel, 1973; Weijermars, 1999; Abdullatif, 2010; Al-Fahmi, 2012). The dome outcrop fractures, structures, and stratigraphy are described in several studies (e.g., Tleel, 1973; Abdullatif, 2010; Al-Fahmi, 2012; Al-Fahmi et al., 2014).

2.5 STRUCTURES IN CENTRAL AND EASTERN ARABIA

The Arabian Platform interior, in Central and Eastern Arabia, was tectonically stable during most of the duration of the platform formation (e.g., Powers et al., 1966) (Fig. 2.6). Powers et al. (1966) designated the region as ‘tectonically stable’ in the relative sense that it has been subjected mainly to ‘gentle warping and tilting’. Obviously, the region contrasts tectonically with the mobile margin of the platform in Taurus, Zagros, and Oman Mountains (e.g., Powers et al., 1966). These mountains were formed by the Late Cretaceous obduction of the Semail ophiolite and the Neogene Arabian-Eurasian collision (Mouthereau et al., 2012). The contractional tectonic elements are not, however, manifested directly in Eastern and Central Arabia. These regions have been relatively passive in the frame of tectonic megasequences. Most of the platform deformation (shortening) was accommodated to the east within the Zagros Folded Belt and underthrust Arabian margin (e.g., McQuarrie and Van Hinsbergen, 2013).

The existing deformation in Central and Eastern Arabia can be described as gentle folding in the otherwise nearly flat regions of the platform interior (Fig. 2.2 and Fig. 2.6). The structures in the region can be divided into four structural styles: anticlines, domes, regional arches, grabens, and a sprawling homocline. The platform structures were mainly shaped by salt tectonics and reactivation of the Precambrian basement faults during a mid-Carboniferous deformational event coinciding with the Hercynian orogeny (e.g., Konert et al., 2001). Subsequent tectonic events produced additional growth in the anticlines and domes during the Late Cretaceous and the Neogene, although their structural dips are very gentle, ranging from 2° to 6° on average (e.g., Faqira et al., 2009; Al-Fahmi et al., 2016).

2.5.1 The Anticlines and Domes

The structural styles of the hydrocarbon fields in Central and Eastern Arabia are either anticlines or domes. Their structures were developed by slow uplift, originating from the

reactivation of Precambrian basement faults and Hormuz salt movement (Fig. 2.2). The structural dips on the limbs of the anticlines and domes are very gentle, ranging from about 1.5° to 4°.

Most anticlines have a north–south (N–S) trending axis, but some have northwesterly and northeasterly trends (e.g., Powers et al., 1966; Al-Husseini, 2000) (Fig. 2.6). The N–S anticlines were the subject of many studies on the platform interior tectonics. Some authors argued that the N–S anticlines were not produced by the Arabian–Eurasian collision, because the anticlines are oblique to the Neogene Zagros-trend folds and older than them (e.g., Powers et al., 1966; Hancock et al., 1984). Some authors relate the N–S anticlines to the Amar collision (640–620 Ma) of the Rayn Plate with the Arabian-Nubian Shield, and the ensuing Najd Rift (570–530 Ma) (e.g., Al-Husseini, 2000) (Fig. 2.2). Notable examples of the N–S anticlines are the Summan Platform and En-Nala Anticline of Ghawar and Safaniya, the world’s largest onshore and offshore hydrocarbon fields, respectively (Fig. 2.6).

The domes are concentrated in the eastern regions of the platform, in the northern and southern basins of the Arabian Gulf (Fig. 2.2). The domes are of two types: extruded in the Zagros Mountains and buried below the platform sequence. The buried domes were interpreted to be salt domes based on the following: (i) oval shapes and coinciding negative anomalies in gravity survey maps (e.g., Powers et al., 1966); (ii) regional seismic interpretations (e.g., Dyer and Husseini, 1991; Stewart, 2017); and (iii) style of the deformation in the sedimentary cover above salt (e.g., Al-Fahmi et al., 2016). Furthermore, great areas of the eastern regions of the platform sequence are underlain by the Eocambrian Hormuz salt (e.g., Beydoun, 1991). Approximately 160 diapirs of the Hormuz salt have been extruded in the Zagros Mountains, and they uplifted about 20 of the islands in the southern basin of the Gulf (e.g., Edgell, 1996; Bahroudi and Koyi, 2003). The extent of the salt in the Zagros and Arabian Gulf regions is deduced from emergent diapirs, where the depositional salt thickness is large enough to develop salt ridges, pillows, and diapirs (Callot et al., 2007). Some of the dome structures continued to grow to uplift the Cenozoic strata, and hence influenced the topography of the regions. The regionally high topography attracted the geologists who explored for hydrocarbon resources in the 1920–’30s, and led to the first discovery of oil in the domes of Bahrain and Dammam (Fig. 2.2).

2.5.2 The Interior Homocline

The rock strata in the platform interior form a distinctive and laterally continuous structure called the interior homocline (e.g., Powers et al., 1966) (Fig. 2.2 and Fig. 2.6). This structure is referred as “the homocline” in the text. The western borders of the homocline are well defined by the splendid escarpments of the Paleozoic and Mesozoic rocks that are arranged in curved belts (about 400 km wide) in Central Arabia (Fig. 2.6). The eastern boundary is probably located to the west of the Ghawar Field, as the homocline terrace transitions into the flat setting of the platform (Fig. 2.2). The platform sequences dip gently and uniformly eastward and disappear under the sands of An-Nafud Desert. The continuity of the rock strata in subsurface was mapped from boreholes and 2-D seismic reflection surveys. The dips of the platform strata in the homocline are too small to be noticeable from outcrops. The dips are around $0^{\circ} 30'$, and slightly more than $1^{\circ} 00'$ in older units (e.g., Powers et al., 1966).

The term “homocline” was used in reference to the general eastward dip of the platform strata. However, the changes in the strata strikes make the homocline of north-dipping and south-dipping hinges separated by the E-W trending arch of Central Arabia (e.g., Powers et al., 1966). The homocline is, therefore, an anticline.

The origin of the homocline is not well constrained. The variations in thicknesses and lithofacies in the platform strata in Central Arabia were attributed to eustasy and stable tectonics (e.g., Le Nindre et al., 2003; Al-Mojel, 2017). Some reports, however, suggest that the strikes of the Paleozoic strata were caused by gentle flexing of the underlying basement (e.g., Powers et al., 1966). The role of the basement is envisaged in the uplift of Central Arabia by reactivation of deep-seated basement faults during the Devonian to early Triassic Hercynian Orogeny (e.g., Bamousa et al., 2016). The uplift continued in the Mesozoic and Cenozoic periods, leading to the development of extensional structures (i.e., arches, grabens) near the homocline crestal regions and maximum curvature.

2.5.3 The Arabian Arches and Grabens

Arches are among subtle structures in the Arabian Platform in Eastern and Central Arabia.

The two notable arches are the Qatar Arch and the Central Arabian Arch (CAA) (e.g., Powers et al., 1966), (Fig. 2.7). The Qatar Arch probably formed during the Amar collision, because it is similar to the N–S regularly spaced structures of the Summan Platform, Khurais-Burgan Anticline, and En Nala (Ghawar) Anticline (Al-Husseini, 2000), (Fig. 2.7). The Hormuz Salt is believed to be absent along the Qatar Arch and the N-S anticlines in the region (e.g., Konert et al., 2001).

The CAA is one of the subtle structural features of the homocline. It is a ridge extending eastward from the Arabian Shield toward the Qatar Peninsula and separates the homocline into northern and southern regions (e.g., Hancock and Kadhi, 1978). The origin of the CAA is debated, due to its unresolved history (e.g., Powers et al., 1966; Hancock and Kadhi, 1978). Although the CAA has very gentle dips, it marks the area of maximum curvature of the homocline (Fig. 2.7). The CAA was slightly positive during Early Paleozoic, because pre-Permian strata pinch out against it (e.g., Powers et al., 1966). The CAA may have influenced the Phanerozoic sedimentation and the south plunge on hydrocarbon-bearing anticlinal closures to the northeast (Ayres et al., 1982). The amplification of the CAA during Late Cretaceous to Eocene is believed to be responsible for the development of the Central Arabian Graben (CAG).

The CAG is a 560-km en echelon graben that cuts about 1800 m of the Mesozoic-Cenozoic sequence of the platform in Central Arabia (e.g., Powers et al., 1966; Hancock et al., 1984) (Fig. 2.7). Away from the CAG, folds are uncommon, except southeast of Riyadh (capital of Saudi Arabia), where there are some low-amplitude NW trending folds (Hancock et al., 1984; Al-Mahmoud et al., 2009). The CAG is bounded by high-angle normal faults, subsidiary antithetic faults, and multiple folds. Similar to the CAA, the CAG began to form in the Cretaceous and continued to evolve into the Eocene (e.g., Powers et al., 1966). The proposed mechanisms that may have led to the development of the CAG include (i) regional tension over the crest of the CAA (Powers et al., 1966), (ii) left-lateral shear along a buried fault zone in the crystalline basement (Brown, 1972), and (iii) northward stretching and separation above an arcuate basement fault of an East Arabian block (Al Kadhi and Hancock, 1980; Hancock et al., 1984).

2.5.4 Fractures and Present-Day S_{Hmax}

2.5.4.1 *Reservoir Fractures in the Platform Interior*

Over most of the past seven decades, the Arab, Hanifa, and Khuff carbonate reservoirs were viewed as unfractured. This view was held by the oil industry in the Arabian Gulf region for some obvious reasons. Fractures were either missed or unobserved in the extensively acquired vertical cores of the reservoir rocks in Ghawar, Abqaiq, Qatif, Khurais, and many other fields in Eastern Arabia. According to Swart et al. (2005), the “physical evidence for the presence of fractures is largely absent in the cores”. The datasets of fluid pressure indicate the presence and impact of fractures (e.g., Al-Thawad et al., 2001; Al-Dhafeeri and Nasr-El-Din, 2007), but the pressure datasets are uncertain for such reservoirs that are highly porous and permeable for the prolific oil production. Most Arab reservoir rocks are of high porosity (19–30%) and include permeable zones of over 1000 millidarcies (mD), which were coined “super-k zones” by Aramco in the 1970s (e.g., Voelker, 2004; Al-Dhafeeri and Nasr-El-Din, 2007). The porosity of the Arab reservoirs is much higher than the porosity (2–8%) of the deeper Permian Khuff gas reservoirs (e.g., Ehrenberg et al., 2007). Additionally, the structural setting of the Arab and other carbonate reservoirs in the platform interior are anticlines and domes of very gentle dips that contrast the intensely folded and faulted carbonates at the platform margins. According to Alsharhan and Kendall (1986), “these structures are characterized by gentle dips, which make them less susceptible to fracturing”, and such views continue to permeate in the recent literature on the Arab reservoirs (e.g., Al-Awwad and Pomar, 2015).

The general view that the aforementioned reservoirs are unfractured has, however, slowly changed with the advancement of directional drilling and borehole imaging since the mid-1990s. Luthy and Grover (1995) described fractures using borehole images of two deviated boreholes in the Hanifa reservoir in the Abqaiq field, which is a dome structure described in some publications (e.g., Malinowski, 1961) (Fig. 2.2). Fractures were assumed in the early 1990s to be responsible for the high oil production of the Hanifa reservoir, which is a tight rock formation (Grover, 1993). In the following years, reservoir fractures were predicted using indirect methods, such as 3-D seismic

attributes and reservoir pressure datasets from well transient tests, flowmeter tests, and historical production rates (e.g., Lawrence, 1998; Mohamed et al., 1999; Al-Qahtani and Zillur, 2001; Al-Thawad et al., 2001; Al-Qassab et al., 2002; Azeemuddin et al., 2002; Akresh et al., 2004). Some of these studies suggest that fractures influence hydrocarbon production and water injection. Water injection was also suggested to initiate and propagate hydraulic fractures that connect to reservoir fractures, high-permeability intervals, or both (e.g., Azeemuddin et al., 2002).

Most of the tangible observations on the reservoir fractures were collected using borehole imaging of directional boreholes. Recently, two studies have compiled fracture measurements on a regional scale from the Khuff reservoirs (Ameen et al., 2010; Ameen, 2014). To date, the information about fractures in the Arab reservoirs is limited to two conference abstracts on the Qatif (MacPherson and Ameen, 2014) and Khurais fields (Alghamdi et al., 2016), as well as a method-based paper on the Khurais and Khursaniyah fields (Thagafy et al., 2017) (Fig. 2.2).

2.5.4.2 Fractures and Stress Fields in Carbonate Reservoirs

Fractures in the above-mentioned reservoirs were identified from borehole images in two systems, a dominant system of open-barren fractures and a minority system of mineralized fractures, which often were interpreted as calcite veins (e.g., Ameen et al., 2010; Ameen, 2014; MacPherson and Ameen, 2014; Alghamdi et al., 2016; Thagafy et al., 2017, and unpublished Aramco reports). The open-barren fractures were categorized based on their strike azimuths into NE–SW, E–W, and NW–SE regional systems from major hydrocarbon fields such as Ghawar, Khurais, and Abqaiq (Aramco internal reports).

The majority of the interpreted fractures exhibit NE–SW orientations, which is unexpected given that most directional boreholes, especially in the Khuff and Hanifa reservoirs, were drilled in a range of angles that were close to the NE–SW azimuth. The NE–SW orientation has long been treated as the safer trajectory for drilling horizontal boreholes in the deep reservoirs in Eastern Arabia (Fig. 2.6 and Fig. 2.7). This trajectory minimizes potential instability of directional boreholes under the effects of the S_{Hmax} , especially for the reservoirs deeper than the Arab-D such as Hanifa and Khuff reservoirs (Aramco unpublished reports).

Measurements of breakouts and wall-tensile fractures have been used to estimate the

orientation of the present-day stress in Eastern Arabia (Lauten et al., 2001; Al-Ruwaili and Chardac, 2003; Ameen, 2014) (Fig. 2.6). These studies indicate that the present-day S_{Hmax} in the region is higher than the vertical sediment load and is oriented northeast–southwest (Ameen et al., 2010). The present-day S_{Hmax} is linked to the compressional regime of the Zagros fold and fault belt, induced by the collision of the Arabian and Eurasian Plates (e.g., Mouthereau et al., 2012).

The abundance of the NE–SW and NW–SE fractures was assumed to be related to regional systems, because these fractures do not correlate with the fold-fracture models that were applied on the reservoir anticlines (see, for example, Ameen et al., 2010). For example, the dominant NE–SW system is present and consistent in the Ghawar and Khurais anticlines, as well as in the Abqaiq Dome; these structures vary in shapes and axis trends. According to Ameen et al. (2010), the evolution of the fractures in the Khuff reservoir was controlled by the extensional and consequent compressional plate tectonics instead of local structures.

The abundant NE–SW system is parallel, and hence assumed to be linked, to the far-field compressive stress field that was ensued by the Neogene Arabian–Eurasian collision. Nonetheless, control of local structures in the fracture development is documented in Eastern Arabia. Fractures in the Arab reservoirs in Khurais and Khursaniyah were influenced by the stress superposition of the flexural growth of these anticlines (Thagafy et al., 2017).

2.5.4.3 Fractures in the Platform Interior Outcrops

The platform interior is mostly covered by the sand of the Al-Nafud Desert, between the Dammam Dome in Eastern Arabia and the CAG in Central Arabia. Some outcrops in the platform interior were studied using field maps and satellite images for lineaments of possible fractures and faults in the Neogene sediments, Wadi Al-Batin, and the Ghawar Anticline (e.g., Hancock and Bevan, 1987; Saner et al., 2005; Bamousa et al., 2016).

In the notable Dhruma-Nisah (150 km) segment of the CAG system, fractures were divided into 10 sets of vertical joints, veins, and small faults that are arranged symmetrically about the en echelon graben. More than 90% of the fractures are joints, and the remainder are either calcite veins or, more rarely, faults that mainly occur in the graben domain (Hancock et al., 1984). Recently, Abdmutalib and Abdullatif (2017) studied fractures and rock lithological properties from

Wadi Nisah and identified several sets of fractures and faults (with small displacements) in the Arab-D and Upper Jubaila.

The fractures in the platform interior outcrops were considered neotectonic regional joints formed within a region subject to uplift and erosion (Hancock et al., 1984; Hancock and Engelder, 1989). In the CAG region, fracture evolution was linked to the graben tectonics (Al Kadhi and Hancock, 1980; Abdilmatalib and Abdullatif, 2017). The CAG is a shear zone without much obvious structural analogy to the hydrocarbon anticlinal structures in Eastern Arabia, except from the viewpoint that the CAG region is gently deformed. The NE–SW trending lineaments, such as Wadi Al-Batin, were interpreted as foreland response to the Neogene collision of the platform's eastern boundary at Zagros (Hancock et al., 1984).

2.6 STUDY AREAS

The study areas can be divided structurally into two regions: the homocline in Central Arabia and the dome in Eastern Arabia. The two structures are compared in Tab. 2.2. according to their origin, size, shape, and predicted fracture orientations from the geometry of a spatially homogenous folded layer (i.e., without pre-existing fractures) (Ch. 1).

2.6.1 The Homocline

Some descriptions on the origin and geographic extent of the homocline are presented in Ch. 2.5.2.

In this research, fractures in the homocline were studied from the Arab-D outcrops from four sites (Fig. 2.8). Site 1 (N 25° 09' 14" N, 46° 12' 28" E) and Site 2 (25° 09' 50" N, 46° 13' 50" E) are located in Wadi Malham, which is about 80 km north of Riyadh City. Site 3 and Site 4 (23° 28' 19" N, 46° 52' 11" E) are located at Howtat Bani Tamim, 150 km south of Riyadh. The sites are located on the northern and southern limbs of the homocline. The sites were recommended by A. S. Al-Mojel (Aramco carbonate sedimentologist and stratigrapher) as typical locations for the carbonates of the Arab and Upper Jubailah Formations (the equivalent of the Arab-D reservoir in subsurface). An investigation of the lithology and high-resolution stratigraphy of the four-site outcrops was performed by A.S. Al-Mojel for his PhD project. This project followed regional

studies by the BRGM and SGS on the geology of the Paleozoic-Mesozoic-Cenozoic sequences of the platform in Central Arabia (e.g., Le Nindre et al., 2003; Vaslet et al., 2005) (Fig. 2.8). The four sites have complete sections for the Arab D and Jubaila carbonates. Other Arab members (A and B) are not present in these outcrops. A few areas have lower sections of the Arab-C, but they are mostly as breccia of weathered, karstified, and collapsed outcrops.

Fractures in these regions have not been previously described. Previous fracture studies were focused on the trough and graben systems of Central Arabia (Hancock and Kadhi, 1978; Abdilmatalib and Abdullatif, 2017). The Arab-D and Jubaila in the four sites form a continuous stack of horizontal layers that are not interrupted by faults, folds, or karstified slumps. The sites are, therefore, ideal for studying fractures in the carbonate layers of very gentle folds in the Arabian Platform. The areas represent the gentlest parts of the homocline, from sites located to the north and south of the Central Arabian Arch.

2.6.2 The Dome

The dome outcrops and subsurface were studied continuously in the past decades, since the oil exploration and discovery in the dome in the late 1930s. The dome outcrops were the subject of numerous studies on topography, stratigraphy, lithology, structure, fractures, and geochemical and geomechanical properties (e.g., Powers et al., 1966; Chapman, 1971; Tleel, 1973; Fryberger et al., 1983; Jado and Johnson, 1983; Çağatay, 1990; Weijermars, 1999; Al-Shuhail, M. M. Hariri, et al., 2004; Hariri and Abdullatif, 2005; Abdullatif, 2010; Al-Fahmi, 2012) (Fig. 2.5 and Fig. 2.9).

The structural growth of the dome was attributed to deep-seated salt diapirism belonging to the infra-Cambrian Hormuz Salt (e.g., Weijermars, 1999; Al-Fahmi, et al., 2016). The salt intrusion below the dome was first interpreted on the basis of structural geometry of a semicircular folding and a strong negative gravity anomaly (Powers et al., 1966). According to Tleel (1973), the dome major axis, from outcrops, trends between north 30 and 40° west, and extends for about 14 km (Fig. 2.9). The average dips on the northeast and southwest flanks are 1°30' and 1°10' respectively. The plunge on the southeast is about 1°12' and on the northwest slightly less than 1°. Minimum structural relief between the boundary and the crest is estimated at 100 m at the top of the Rus Formation (Fig. 2.9).

Fractures were studied from the Cenozoic Rus carbonates of the dome (e.g., Al-Shuhail, M.M. Hariri, et al., 2004; Al-Fahmi, 2012). The outcrops are fractured by two dominant systems: NE–SW and NW–SE (Al-Fahmi, et al., 2014), (Fig. 2.10). The NW–SE system is found to be the earlier system based on abutting relationships. Some of the NW–SE fractures are visible on satellite images because of their long traces and the vegetation hosted in the fractures in an arid region (Fig. 2.10). The fractures are mostly confined and vertical to the Middle and Lower Rus units. The fractures are mostly barren (in excess of >95%), and only a few are filled by gypsum and calcite.

The systematic fractures in the outcrops were attributed to the growth of the dome (bending) (e.g., Hariri, et al., 2004; Al-Fahmi, 2012). The theory on fracture origin is supported by observations from outcrops and geomechanical modeling such as (i) fracture systematic orientations, (ii) mechanics of rock layers in relation to the degree of bending, and (iii) records of elevations, sedimentation, and hiatus that indicate an episode of layer doming (uplift) in the Oligocene (Al-Fahmi, et al., 2014). The episodic growth during most of the Cenozoic was estimated at rates of 7 to 7.5 m/M.a. from the unit thickness and unconformity time gap at the apex of the dome at Jebel Umm-ar-Rus (Weijermars, 1999).

Previous work on the subsurface of the dome includes 2-D and 3-D geological mapping based on information from core, borehole logs, and seismic reflection surveys. Recent work includes a 3-D numeric model of the dome subsurface structures, (Al-Fahmi et al., 2016), before the recent drilling of the directional boreholes, which provided the datasets used in this research. The 3-D numeric model of the dome was based on datasets from vertical borehole logs and a 3-D seismic reflection survey acquired in 2006. The model was aligned with the application of new structural restoration methods (Al-Fahmi et al., 2014; 2016) (Fig. 2.9 and Fig. 2.11). The restoration methods allowed to obtain a timeframe for the dome evolution and compute the 3-D rock dilation and distortions (first and second invariants of the strain tensor, respectively) for all stages of restoration steps on the top surface of the Arab-C (Fig. 2.11).

From the subsurface, the geometry of horizons (e.g., Arab-C) appears to be less elliptical than the outcrops with semicircular shape of a ca. N8°W elongation (Al-Fahmi et al., 2014) (Fig.

2.11). The initial stage of the dome growth is uncertain for those sequences that are older than Permian (Al-Fahmi et al., 2014). For younger sequences, the dome was formed by slow episodes of deeply seated and rising salt that deformed the overlain sequences (Al-Fahmi et al., 2016). The periodic growth episodes resulted in the bending of the Arab reservoirs, mostly during the Late Cretaceous, coinciding with the amplification of many anticlines in Eastern Arabia (Fig. 2.9). Subsequent episodes during the Oligocene flexed (or rather domed) the Rus carbonates. The strain patterns are elongated along a northwest–southeast-trending axis, which is normal to the northeast–southwest-trending maximum compressional stress orientation associated with the Arabia–Eurasia collision. The dilation is around 2% in the dome crest, and drops below 1% in the dome flank. The distortion is very small, although it shows similar distribution to that of the dilation (Fig. 2.11). The dome at the level of the Arab reservoirs is very gentle (with about 5° of structural dip on the limbs). The dome structural arch and dips are relatively higher than those of the anticlines such as Ghawar, Khurais, and Qatif (for comparison, see Faqira et al., 2009; Al-Fahmi et al., 2016).

The Cenozoic strata are lower in curvature and structural height than the Arab reservoirs (Fig. 2.9). By comparison, the dome curvature at the Arab reservoir level is relatively sharper than the curvature of other anticlines in Eastern Arabia including Ghawar and Khurais, whose structural dips are between 1.5° and 3°. The dome is slightly elongated with a NW–SE trending axis, which may be associated with the Zagros-fold trends (Ileel, 1973; Al-Fahmi et al., 2016). The dome growth is dominated by vertical rather than lateral displacement (Weijermars, 1999).

In this research, fractures in the dome were studied from the Arab reservoirs (A, B, C, and D) and the Middle Rus outcrops (Fig. 2.12 and Fig. 2.13). The study of the Arab reservoir fractures is based on datasets of core and electrical borehole images obtained from directional drilling done between 2012 and 2014. The outcrop measurements of fracture spacing and layer thicknesses were collected from the Middle, Lower and Lower Rus carbonates from 11 different sites in the central and northwestern flanks of the dome (Fig. 2.13:).

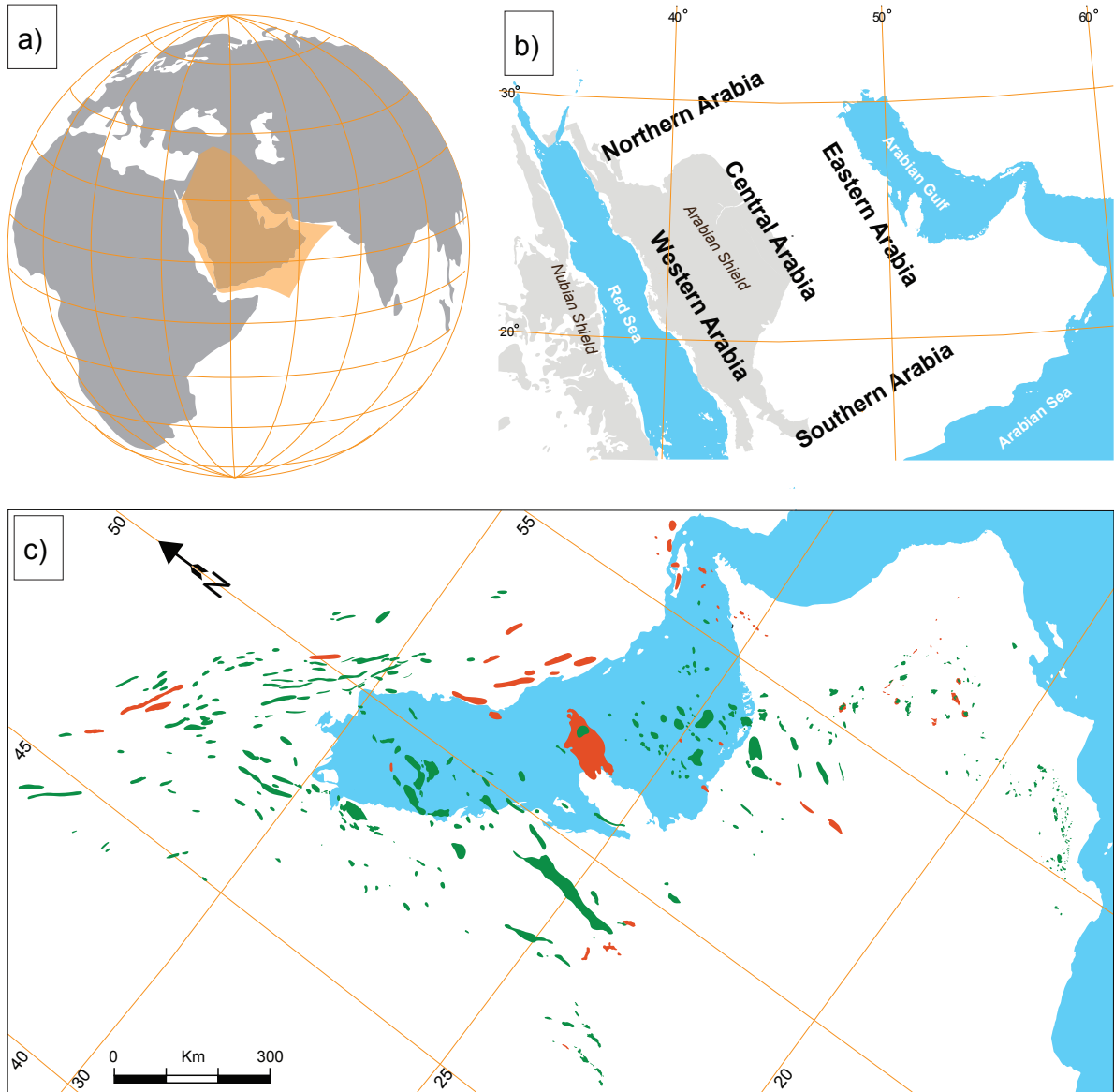


Fig. 2.1: a) Map of the Arabian Plate, which is tectonically defined from its borders with the African and Eurasian Plates; b) map of Arabia (also known as the Arabian Peninsula); c) map of the hydrocarbon fields in the Arabian Plate region (green color for oil-dominated fields, and red color for gas-dominated fields). The hydrocarbon production and reserves of these fields are often reported as under the Middle Eastern region in the energy and policy reports (see, for example, EIA, 2014).

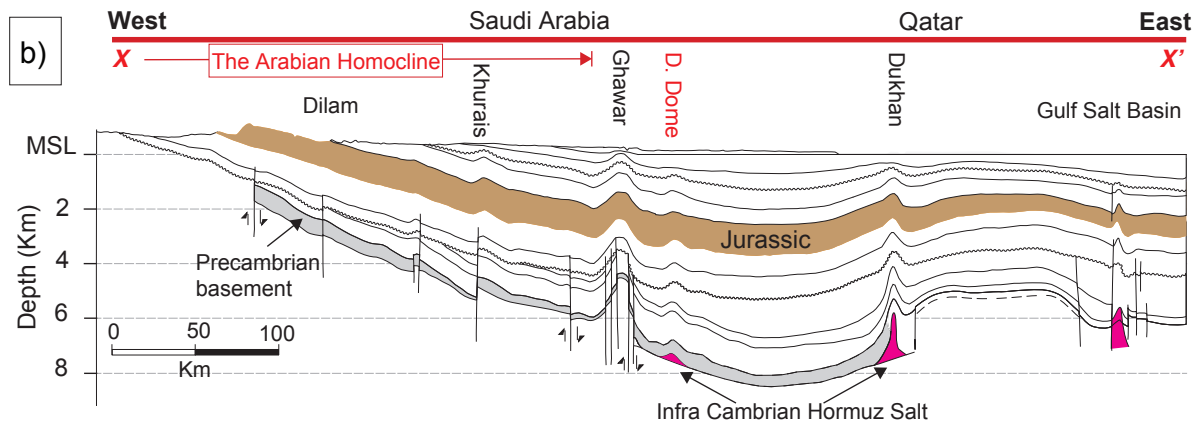
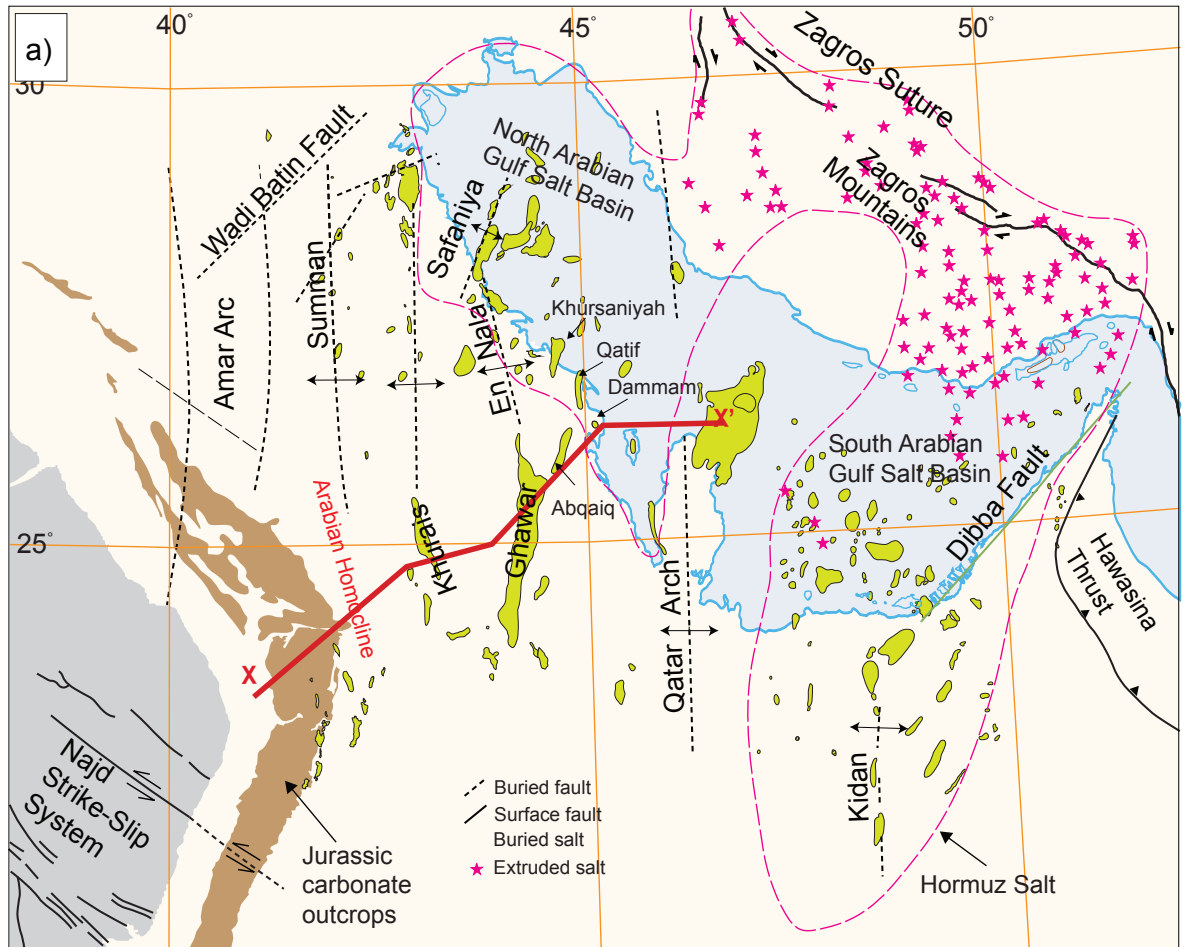


Fig. 2.2: Map and cross section of the Arabian Platform interior.

a) Map displaying locations of the Jurassic oil fields and major structural elements in Eastern Arabia; b) a regional cross section (X-X') on the map in (a), from Central to Eastern Arabia, demonstrating the structural and stratigraphic framework of the Arabian platform.

The Jurassic carbonate platform is highlighted (in brown color) in the cross section. The map is designed based on different publications including Al-Husseini (1997), Al-Husseini (2000), and Bahroudi and Koyi (2003). The cross section is modified from Konert et al. (2001). Note: The figures from GeoArabia publications are modified and published here with the courtesy of Dr. M. I. Al-Husseini, editor and owner of GeoArabia.

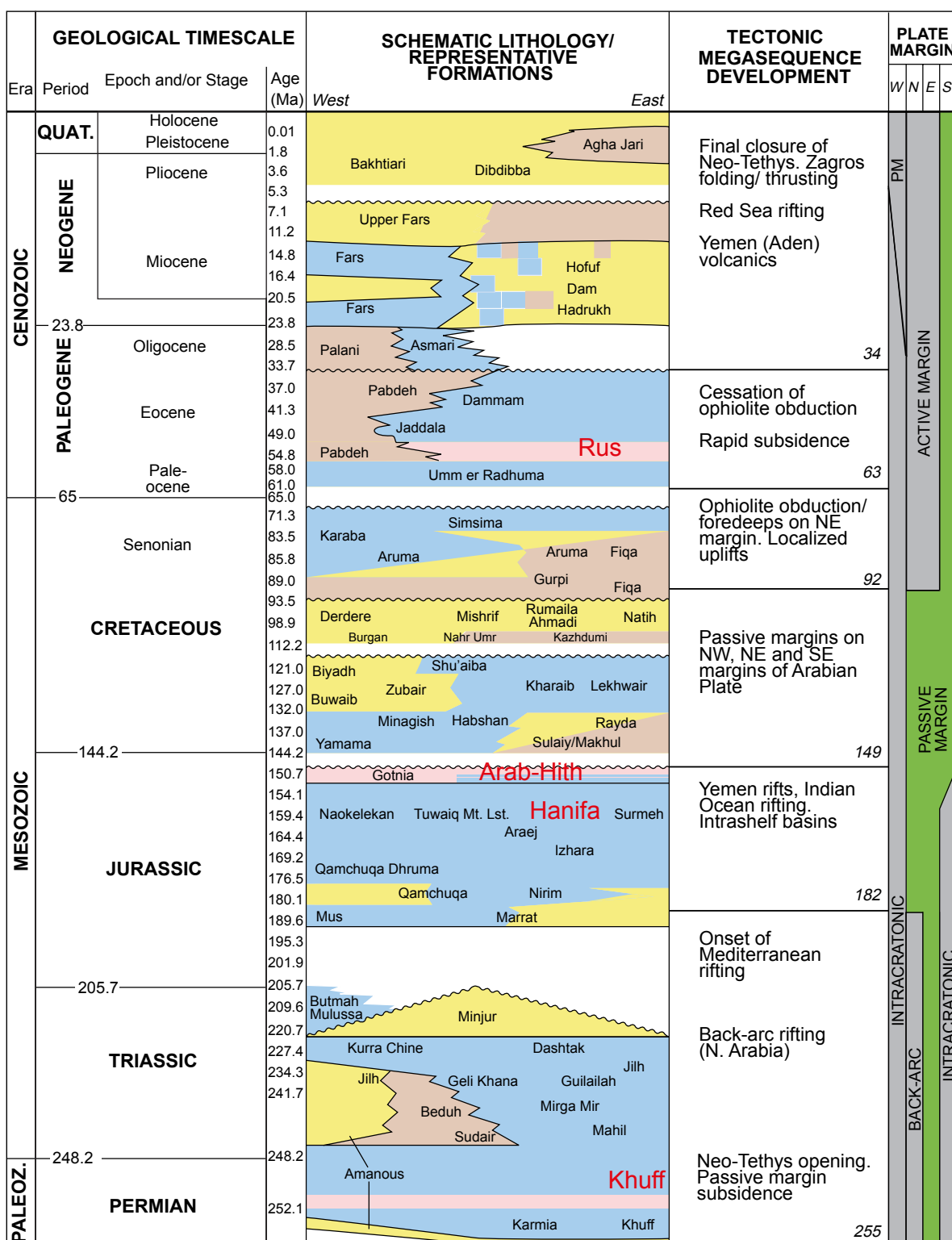


Fig. 2.3: a) Timescale, rock formations, and tectonic megasequence of the Arabian platform from Late Permian to Holocene, modified after Ziegler (2001), courtesy of GeoArabia.

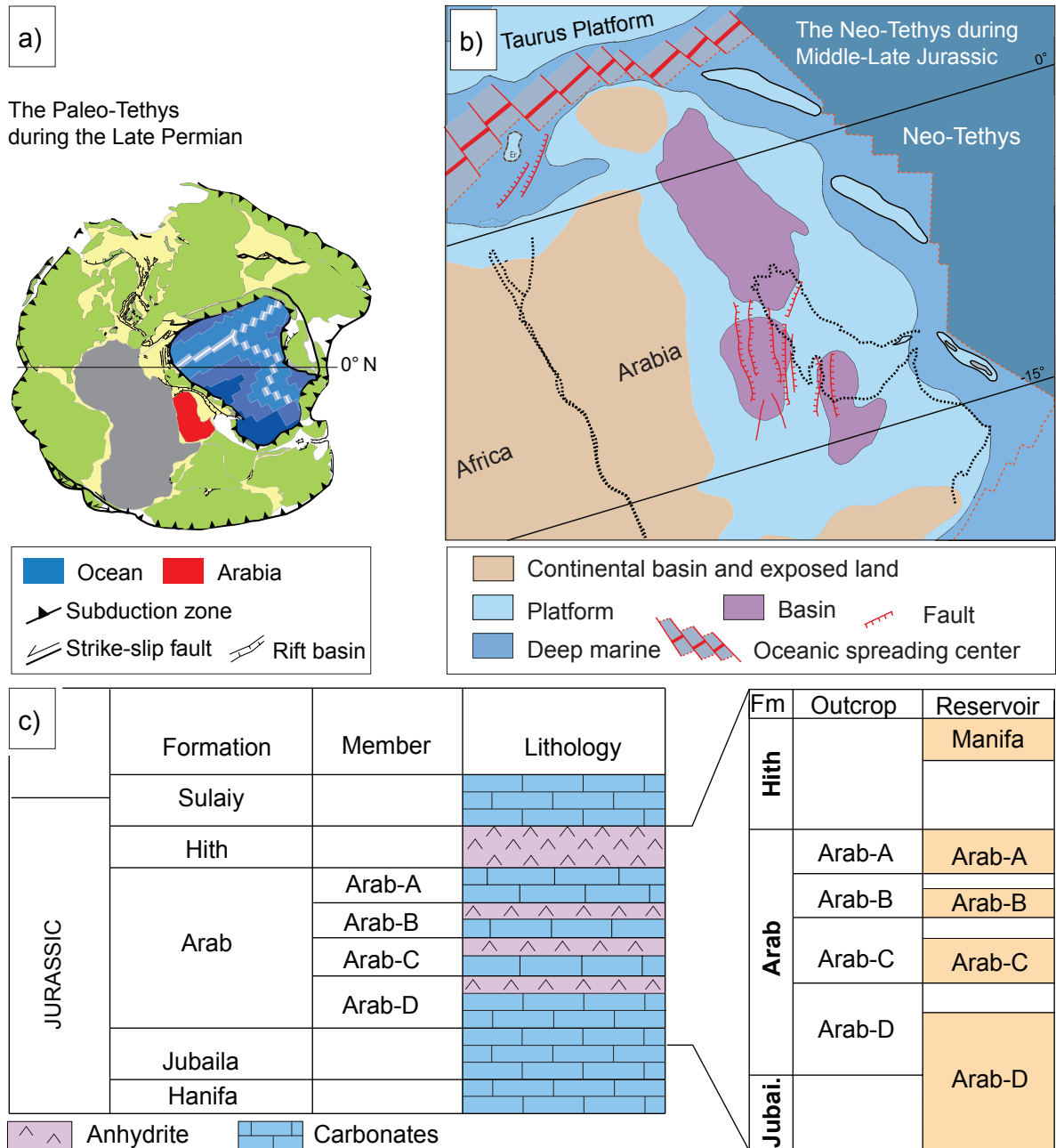


Fig. 2.4: Maps displaying the location of the Arabian Plate, and a) extents of the Paleo-Tethys during Late Permian, modified from Şengör and Atayman (2009); b) the Neo-Tethys during Middle Jurassic, modified from Frizon de Lamotte et al. (2011); and c) a generalized stratigraphic section of the Jurassic rock formations in Central and Eastern Arabia, modified from Cantrell and Hagerty (1999).

Weijermars (1999)		Tleel (1973)		Powers et al. (1996)	Bremkamp (1946)	Henry & Hoover (1934)
Upper Rus	Chalky Zone (25m)	Upper Rus	Chalky Zone (25m)	Unit 3 Chalky Zone (3.6m)	Rus Formation	Chalky Zone
Middle Rus	Jointed Limestone (10m)	Lower Rus	Zone of Calcite Geodes (10m)	Unit 2 (31.8m)		
Lower Rus	Marls (21m)		Zone of Quartz Geodes (21m)	Unit 1 (21m)		

Tab. 2-1: Subdivisions of the Rus Formation from different authors, from Weijermars (1999).

	The homocline	The dome
Size	About 150,000 km ²	About 150 km ²
Shape	East plunging anticline	Oval, with an elongation of the N-NW axis
Structural dips	0°-1°	0°-5°
Folded rocks	Paleozoic, Mesozoic, and Cenozoic	Paleozoic, Mesozoic, and Cenozoic
Burial level of the Arab carbonates	Poorly constrained, but shallower than the 1.6 km burial in Eastern Arabia.	Around 1.6 km
Origin	Reactivation of deep-seated basement faults	Rising of deep-seated salt pillow
Expected fracture orientations according to fold shape	Anticline-related fractures that their orientations reflect the symmetry of an anticline (e.g., Price and Cosgrove, 1990), see (Ch. 1.5.2) and (Fig. 1.7).	Dome-related fractures of radial orientations that reflect the directions of maximum stretching, which corresponds to the vectors of the maximum curvature (e.g., Al-Fahmi et al. 2014).

Tab. 2-2: Comparison of the homocline and the dome.

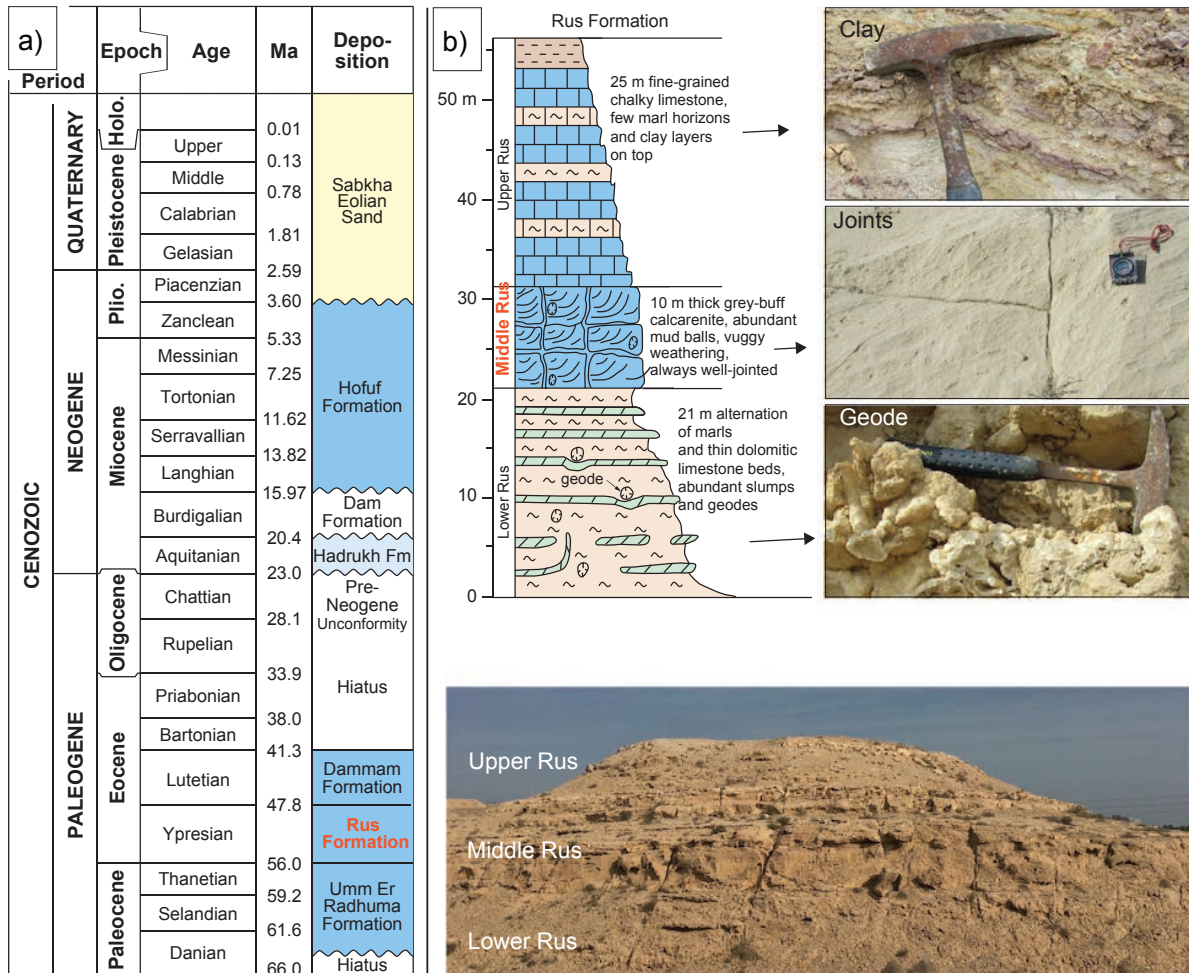


Fig. 2.5: a) The Cenozoic stratigraphic column of the Arabian sedimentary basin in Eastern Arabia; b) stratigraphic column of the Damman Dome outcrops, modified from Weijermars (1999). Outcrop pictures are from Al-Fahmi (2012). Geologic ages are adopted from Geological Time Scale GTS 2012 (Gradstein et al., 2012).

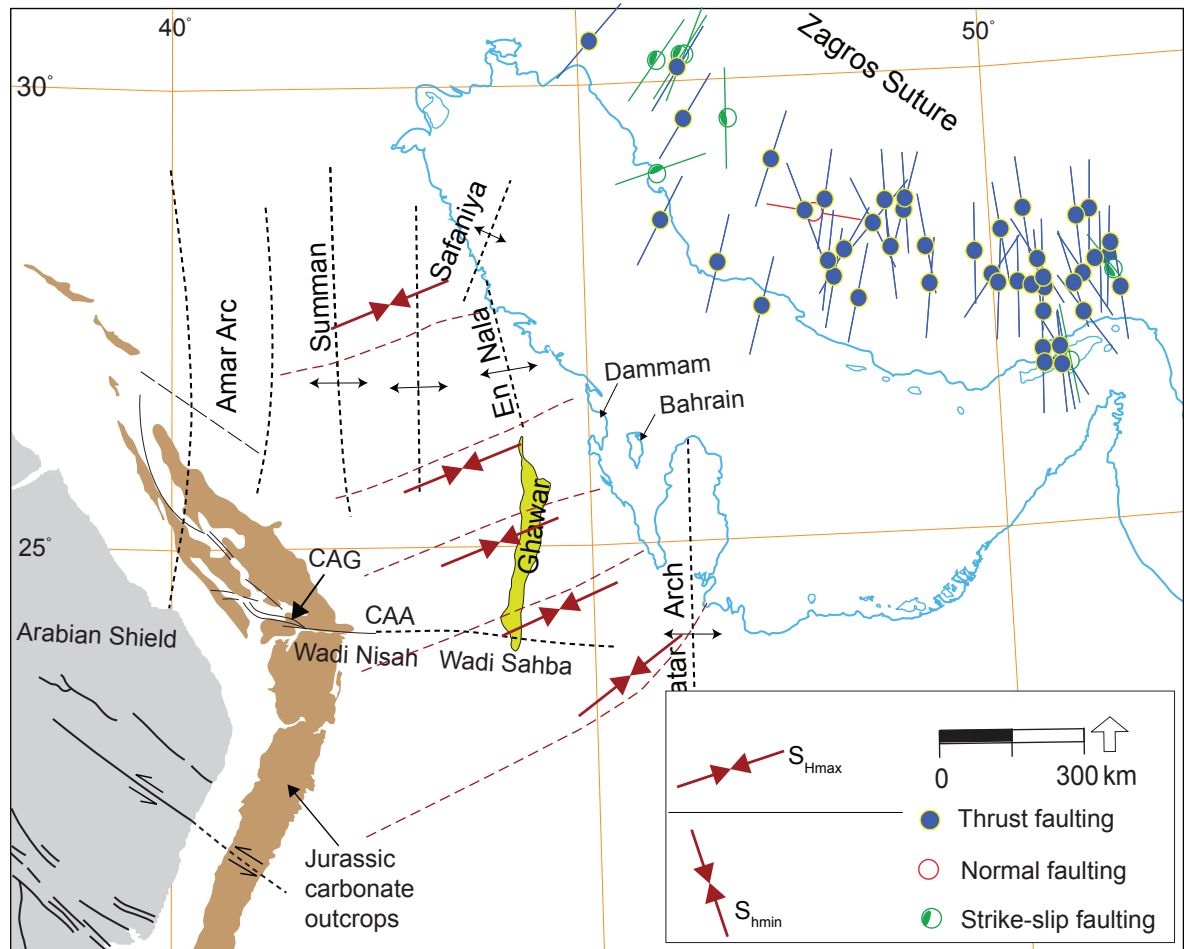


Fig. 2.6: Map demonstrates major structural elements in the Arabian Platform interior in Central and Eastern Arabia, modified from Al-Husseini (1997).

The map also shows the tectonic regimes of thrust, normal, and strike-slip faulting in the eastern part of the Arabian Plate in the Zagros region, modified from World Stress Map (Heidbach et al., 2010), as well as the trends (dashed line) of the present-day S_{Hmax} in Eastern Arabia, modified from Ameen et al. (2010).

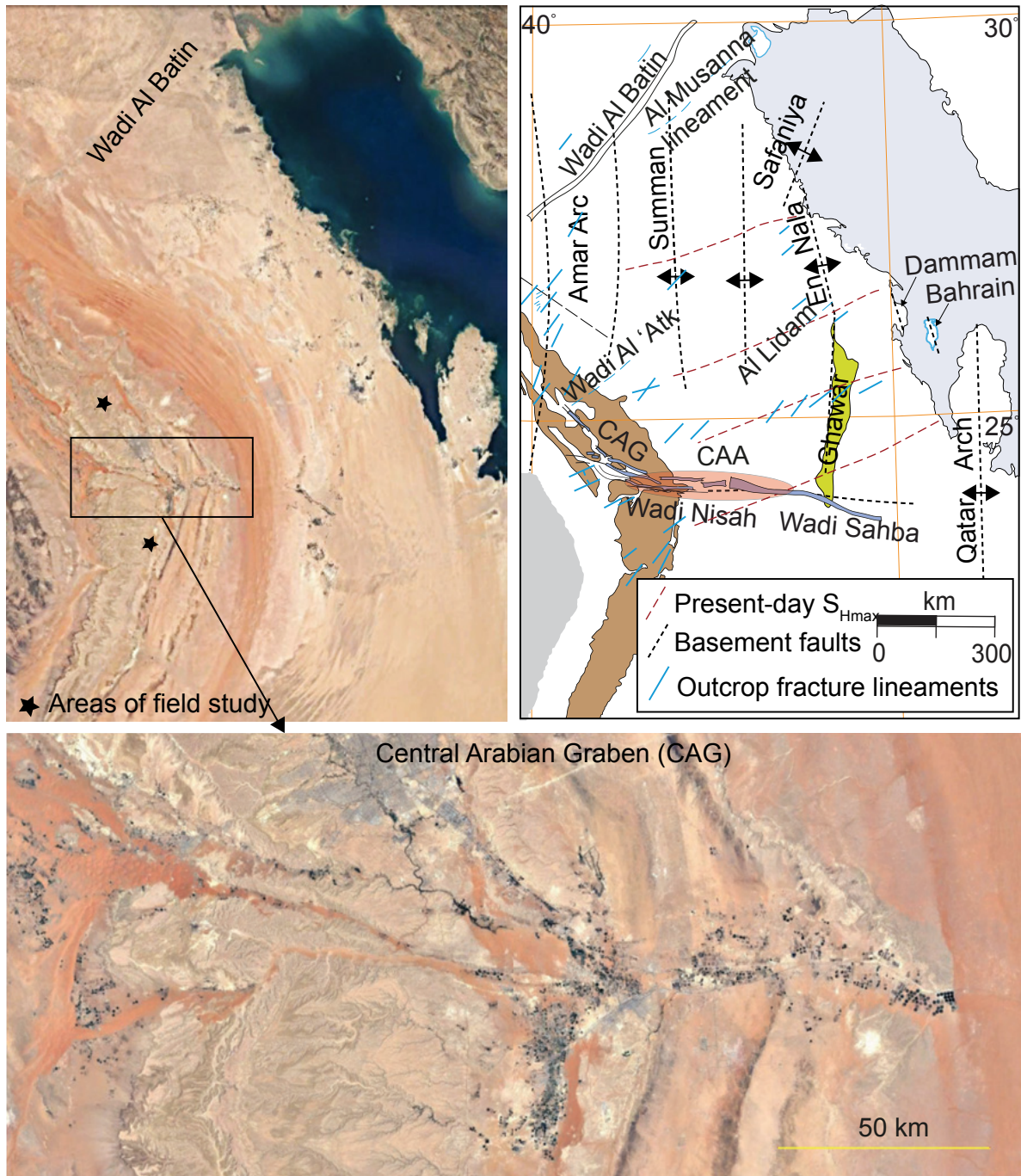


Fig. 2.7: Satellite images of Central Arabia show the study areas, the CAG, and the homocline, from the curved belt of the Mesozoic rocks of the Arabian platform.

Above right, a simplified geologic map of the structural lineaments and joint trends in the outcrops in the platform interior, compiled from Hancock et al. (1984), Ameen et al. (2010), and McGillivray and Hussein (1992).

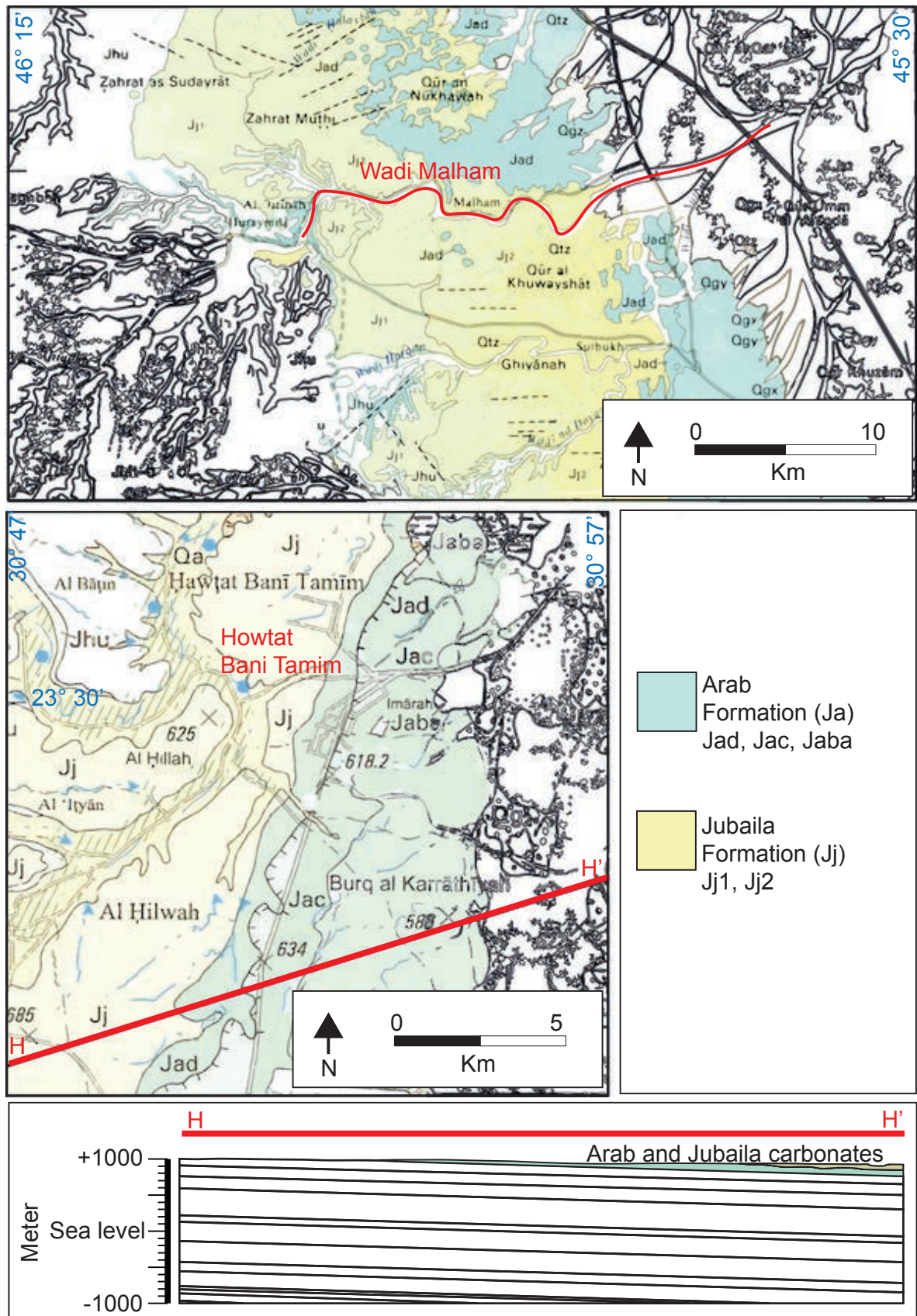


Fig. 2.8: Generalized geologic maps and a cross section of the study areas around Wadi Malham and Howtat Bani Tamim, also spelled Hawtat Bani Tamim, modified from geologic reports of the Saudi Geological Survey.

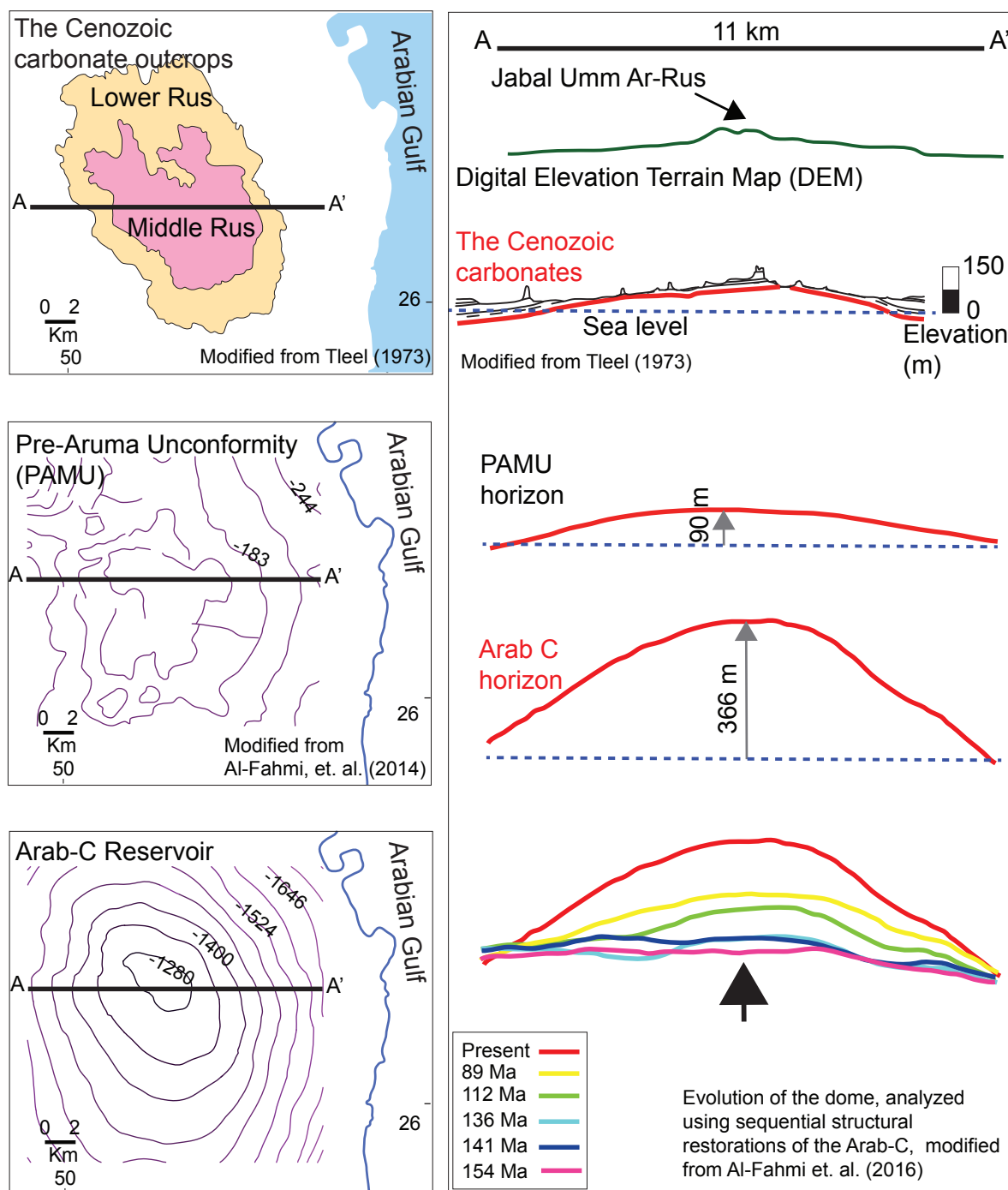


Fig. 2.9: Maps and cross sections of the dome show gentle but varying degrees of curvature between the Cenozoic Rus carbonates in outcrops and the buried Arab carbonate reservoirs (resembled by Arab-C). The Arab reservoirs experienced multiple events of vertical structural growth since the rock formation in the Late Jurassic.

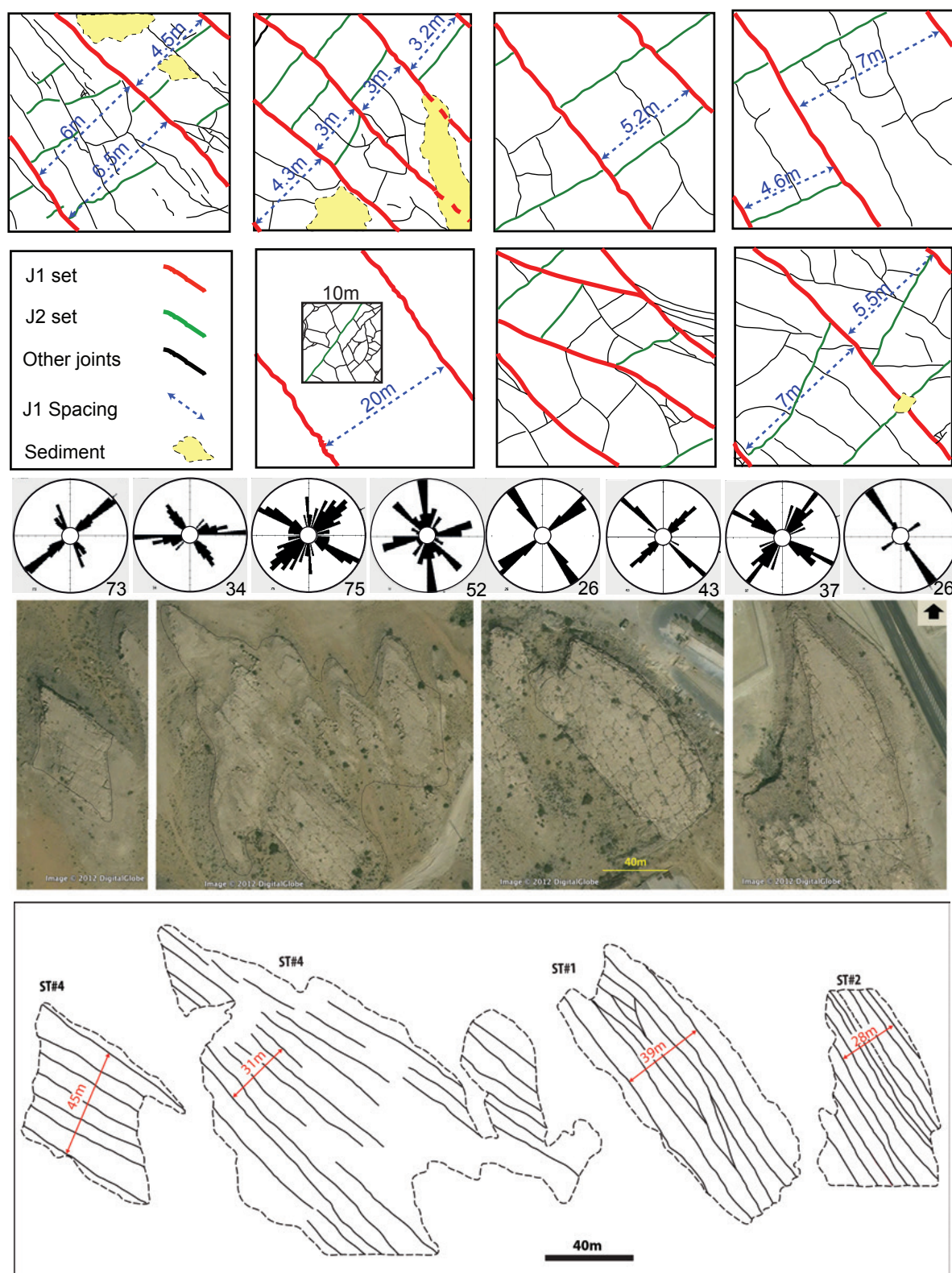


Fig. 2.10: Field maps, rose diagrams, and satellite images demonstrate patterns of fractures (joints) in the Middle Rus carbonates in the Dammam Dome, adapted from Al-Fahmi (2012).

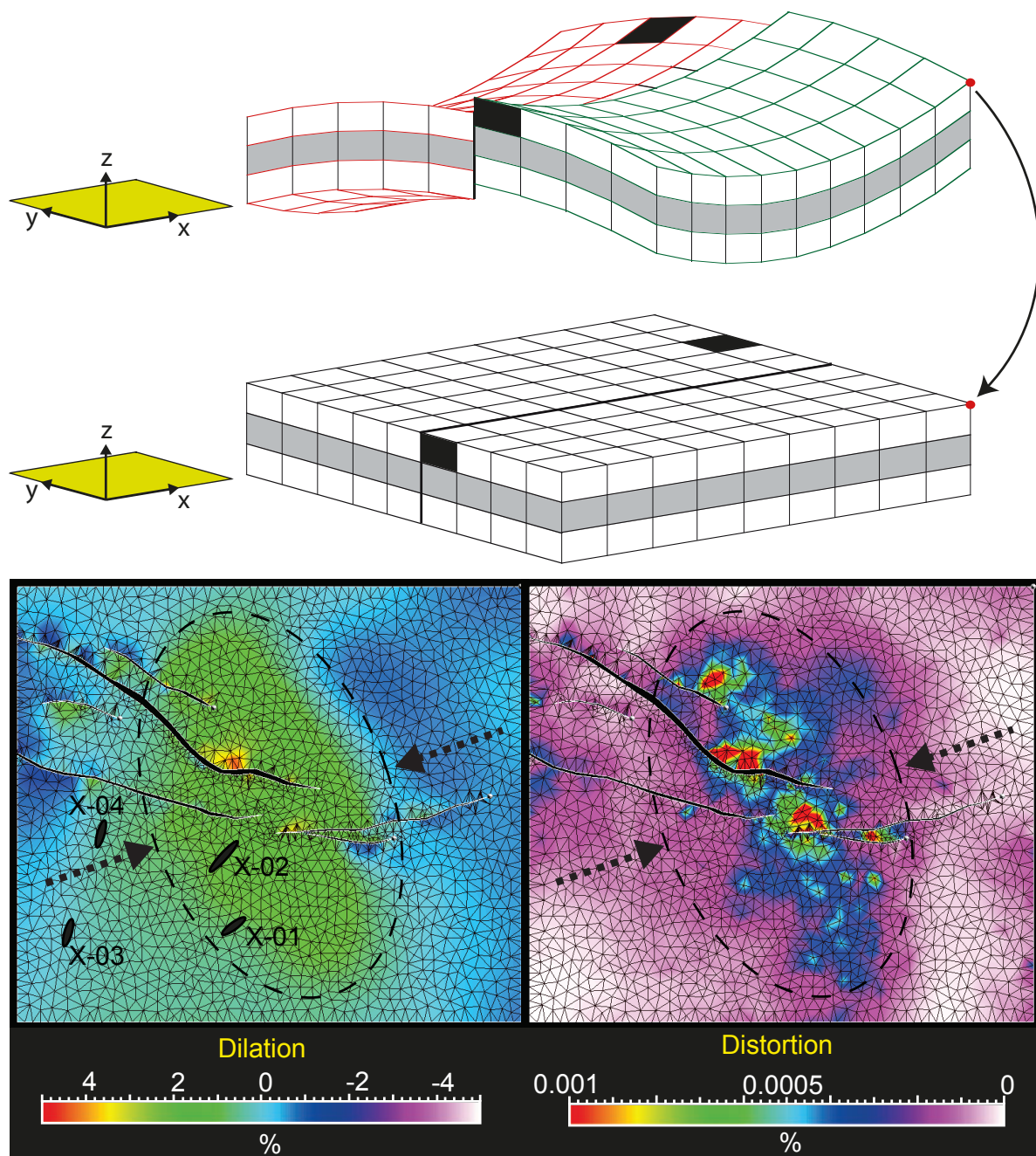


Fig. 2.11: Above, a diagram illustrates concept of the 3-D structural restoration applied on the study area; below are two strain pattern maps, computed from applying the structural restoration techniques. The figures are modified from Al-Fahmi et al. (2016).

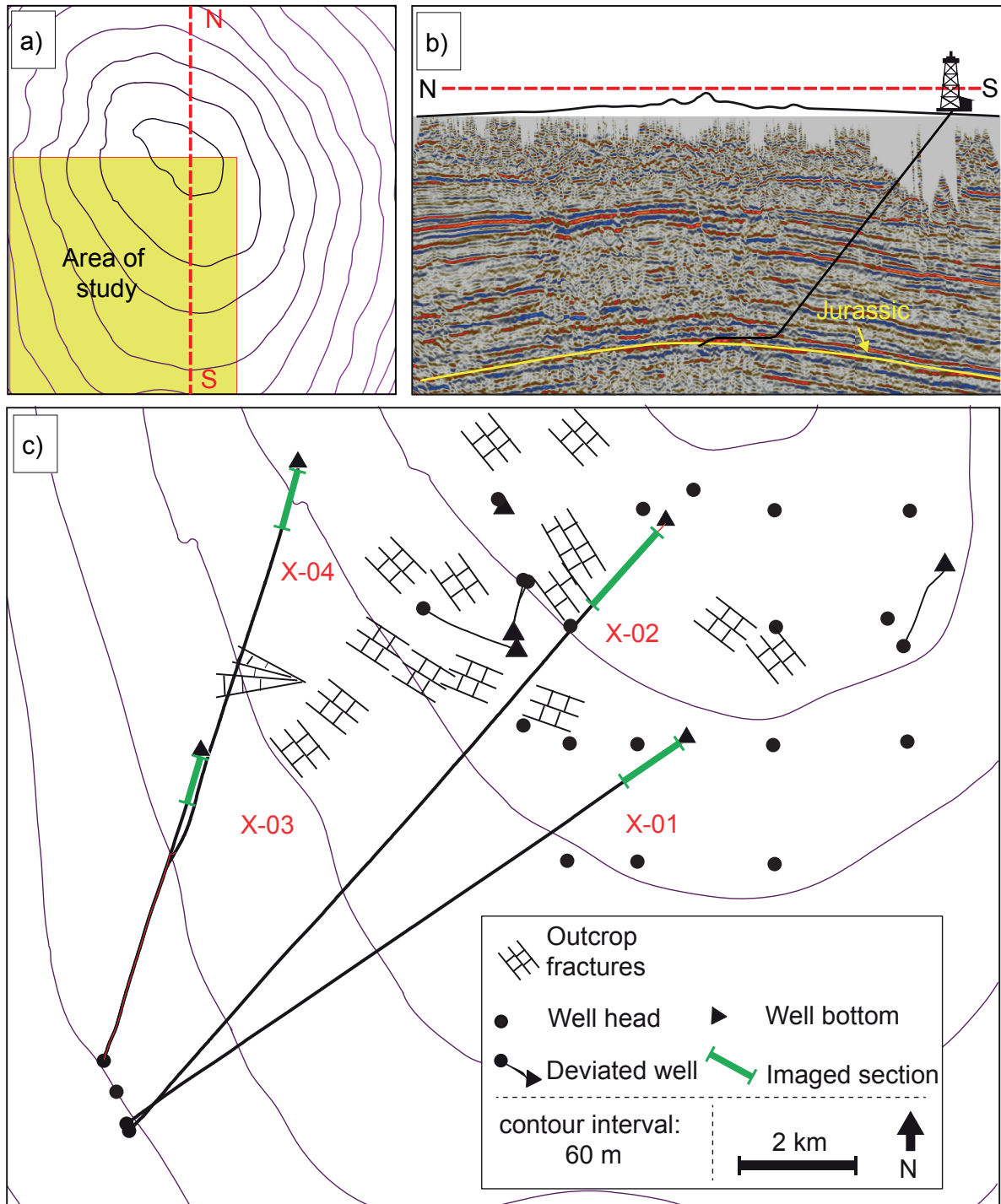


Fig. 2.12: Contour map of the dome, mapped from the top of the Arab C member; b) N-S seismic reflection section of the dome in (a); c) map of the study area of the dome in (a), demonstrating the locations of boreholes and patterns of outcrop fractures, modified from Al-Fahmi (2012).



Fig. 2.13: Satellite images of the Cenozoic Rus carbonates in the dome, from Google Earth. Outcrop widths are in the range of 50 to 150 m.

3 METHODS AND DATASETS

3.1 INTRODUCTION

This chapter is devoted to introducing the methods and datasets of this research. The contents are organized under two sections.

The first section provides an overview of fracture properties and methods of descriptions. Fracture properties are broadly divided into geometry and mineralization. The information on fracture geometry is diverse. Fracture sizes, dips, strikes, roughness, wall matching, displacement mode, and abundance of fractures were considered for descriptions, whenever possible, from the datasets. Other fracture geometrical and topological information, such as linearity, spatial patterns, branching, abutting relations and connectivity, was not considered. The information on fracture mineralization is considered for type and grade of fracture-filling minerals or lack thereof.

The first section introduces, under six sub-sections, the fracture properties and their potential relations to the fracture hydromechanical properties. Each subsection is written in a style to orderly address the following questions:

- 1) What defines the fracture property?
- 2) Why is the fracture property relevant to the hydromechanics of reservoir fractures?
- 3) How is the fracture property measured or described from outcrop and subsurface rocks?
- 4) How are fractures classified according to the fracture property?

The second section is dedicated to introducing the methods and datasets of the research. Fracture mineralization and geometry were described for individual fractures using some conventional techniques in the disciplines of rock mechanics and structural geology. Some new

methods were also developed or advanced for descriptions of some fracture properties. The methods allowed to identify if fractures exhibit similar properties to classify fractures into systems in the study areas and then correlate the systems across the carbonate platform (i.e., between outcrop and subsurface reservoir rocks).

3.2 FRACTURE PROPERTIES

3.2.1 Mineral Fills

A fracture in a rock mass is mineralized if its two walls are bonded or bridged with minerals, or separated but coated by mineral crystals that are distinguishable from the crystals of host rock minerals. Otherwise, the fracture is barren (barren) of mineralization (Fig. 3.1).

The presence or absence of fracture-filling minerals is imperative information in the analyses of reservoir rock fractures. Porosity and permeability of reservoir fractures depend on the size of fracture apertures. Mineralization may choke or reduce fracture apertures, depending on grade (whether complete or partial) and permeability of the mineral fill. The presence of mineralization is useful for geological analyses. The mineral fills in fractures are viewed as archives of historical information about fluid influxes, diagenesis, and deformation in rock formations (Bons et al., 2012). Some studies have attempted to describe fracture kinematics from textures and chemistry of filling minerals to relate them to the mechanisms of fracture formation (e.g., Hooker et al., 2012). Nevertheless, the use of mineral fills for relating fracture genesis is debatable. For example, some types of veins in sedimentary rocks have long been debated if they were formed and subsequently filled by minerals, or formed and synchronously propagated under forces of fluid explosion and mineral crystallization (Cobbold et al., 2013; Al Duhailan et al., 2015; Meng et al., 2017).

The presence or lack of mineral fill can be visually described from outcrops, drill cores, and high-resolution borehole images. The petrography of filling minerals in fractures can be described from thin sections and scanning electron microscope based cathodoluminescence (SEM-CL) imaging (Hooker et al., 2012). Furthermore, mineral fills can be sampled for chemical and isotopic analyses to relate sources of paleo-fluid systems and deformation in rock formations (Baatartsogt et al., 2007). The geological methods of describing barren and filled fractures are generally similar

for outcrop and subsurface rocks. However, fracture descriptions are generally challenging from subsurface rocks (core and borehole images). A core is typically considered “the ground truth” and “the direct sampling method” for subsurface rock information, but barren fractures can be confused with the core breaks produced by either coring or handling processes (Kulander et al., 1990; Lorenz and Cooper, 2017). Most puzzling questions that surround barren fractures in cores can be summarized by three viewpoints:

- 1) It is difficult to distinguish fractures from drilling-induced fractures (DIFs).
- 2) Fractures in subsurface rocks must be filled or bridged by minerals; they cannot be mechanically void.
- 3) Mineral fills can be partially lost or broken due to the mechanical or chemical operations during drilling and preparation of core and thin sections in laboratory.

It is not unusual to find that some publications supported the interpretation of naturally occurring fractures in cores by reporting the presence of mineralization. Relying on the presence of mineralization as a basis for reporting fractures from cores may have led to biases in past reports of fractures in subsurface rocks.

Classifying rock fractures on the basis of degree and type of fracture mineralization is an established practice in geotechnical and reservoir studies. Outcrop fractures have long been noted for almost two centuries as rock joints and veins, a division that is primarily based on the presence or absence of mineralization (Price and Cosgrove, 1990). Classifying fractures in subsurface rocks follows the outcrop methods, although it happened much later in the 20th century. For example, Waldschmidt et al. (1956) presented the following four classes of reservoir rock fractures based on descriptions of core samples from several sites in the United States:

- 1) Open fractures: Separation of fracture walls is visible.
- 2) Partly filled fractures: Walls are coated or bridged with crystals.
- 3) Filled fractures: The fractures are completely filled with crystals.
- 4) Closed fractures: Separation of fracture walls is invisible.

The later class that Waldschmidt et al. (1956) termed “closed fractures” is ambiguous, because the term fracture describes a visible mechanical discontinuity in the rock mass. Moreover,

closed fracture is a term that has been used in some publications to denote the fractures filled with an impermeable mineral to indicate that they are sealed paths to the fluid flow in reservoir rocks (e.g., Golf-Racht, 1982). Some studies divide reservoir fractures into two classes: (i) mineralized fractures and (iii) barren fractures (e.g., Ameen, 2014).

3.2.2 Orientations (Dips and Strikes)

Fracture orientations in the 3-D space of a rock mass are defined by the fracture dips and strikes (Fig. 3.2). Strikes of fractures are treated as potential trends for fluid flow anisotropy in reservoir rocks (e.g., Heffer and Dowokpor, 1990), and trajectories of the past stress fields, according to the models relating fractures to fold structures and regional tectonics (e.g., Engelder and Geiser, 1980; Cosgrove and Ameen, 2000). In addition, fracture orientations determine fracture intersections.

Fractures of a systematic (nearly parallel) trend have limited intersections, whereas randomly oriented fractures (i.e., with high angles to each other) increase the probability of fracture intersections and connectivity. The relations between fracture orientations and stress fields are fundamental for defining and predicting fracture systems (Price and Cosgrove, 1990). Orientation of a fracture reflects the mechanism that generated the fracture, although the orientation can also be directed by the rock mechanical properties.

Fracture dips, in particular, define the driving stress field of the fractures: tensile or shear. Measurements of fracture dips have been used to identify fracture types when displacement modes were not distinguishable. Fractures are notable as sub-vertical, while faults as inclined planes to the planes of layered rocks. This general view is supported by the ubiquity of normal-bedding joints in sedimentary layered rocks. According to Price and Cosgrove (1990), the majority of joints (>95%) that form in sedimentary rocks are oriented within 10 degrees of normal to the bedding plane. Relating fracture orientations to the stress field is fundamental in theoretical modeling and laboratory experiments, especially under uniaxial compressive stress tests (e.g., Peng and Johnson, 1972).

Fracture dips are dependent on the remote driving stress field and independent of the rock heterogeneity (Hancock and Engelder, 1989; Olson and Pollard, 1989). According to the

theories of fracture genesis, fractures propagate in the $\sigma_1 - \sigma_2$ plane, in a direction perpendicular (normal) to σ_3 (Pollard and Aydin, 1988). Fractures are vertical and parallel to σ_2 for an extensional stress regime that typically has $\sigma_1 = \sigma_v$, $\sigma_2 = \sigma_H$, $\sigma_3 = \sigma_h$ (the subscripts v , H , and h are for vertical, maximum horizontal, and minimum horizontal stresses, respectively). In compressive stress regimes, vertical fractures can form with orientations parallel to the maximum direction of compression ($\sigma_H = \sigma_1$) and perpendicular to the minimum horizontal stress ($\sigma_h = \sigma_3$) (e.g., Engelder and Geiser, 1980).

Fracture dip is the angle between the fracture and the horizontal plane, and can range between 0° and 90° . The dip is typically measured for the true dip, which is the steepest angle of an inclined plane in the direction normal (90°) to the plane strike. Fracture strike is measured for the line created by the intersection of the fracture plane and a horizontal plane in azimuth degrees, from 0° to 360° . Fracture strike can be approximated to a compass cardinal and intercardinal point. Fracture dips and strikes can be measured from outcrops using a geological compass. Measurements can be made if one of the fracture walls are apparent from the top or side (cross section) of the sedimentary layer in outcrops. Borehole images and oriented core are typically used to measure fracture dips and strikes in subsurface rocks. Orientation measurements from borehole images are performed numerically for the dip angle of the intersected fracture using a sinusoid-fitting technique (Zemanek et al., 1970) and the following formula:

$$\text{Dip angle} = \tan^{-1} (b/d),$$

where b is the amplitude of the sinusoid, and d is the borehole diameter. The direction of dip is computed from the position of the maximum and minimum of the sinusoid. Measurements of dips and strikes ($\pm 90^\circ$ from dip direction) can be computed for any planar feature crossing the boreholes from the sinusoidal trace within the unwrapped image display (Fig. 3.3). A planar surface can also appear as a straight line if the angle between the surface and the borehole trajectory is 90° . Orientation measurements and statistical distributions can be plotted using stereographic projections such as stereonet or rose diagrams. Measurements of fracture orientations depend on fracture linearity, size, and spatial patterns. In general, it is much easier to measure large and long fractures in a few systematic sets with a linear attitude than it is to measure

small fractures with curvilinear and polygonal (mud-crack style) patterns. Because fractures are often simplified from planar features to linear features, a fracture trace with a north strike is equally with a south strike. Thus, it is sufficient to report the strike measurements as either north–south (N–S), or simply north if using only the upper half of the stereonet plot.

Dips and strikes are the most commonly reported properties of outcrop fractures in geological publications. The plethora of measurements are driven by the relations between fracture orientations and stress fields that were noted since the late 19th century. Fractures, particularly joints, tend to be perpendicular to the planes of their host carbonate layers. Carbonate layers are deposited horizontally (flat) in the sea, but can be later tilted and overturned under tectonic processes. In flat and nearly flat carbonates, fractures are normally vertical or subvertical ($>70^\circ$). Measurements of fracture dips and strikes from subsurface are less common. Measurements are mostly limited by the (i) availability of core, (ii) quality of core recovery from fractured intervals, and (iii) geometry of core if from vertical or slanted (deviated) boreholes. The nature of fracture dips as vertical or near vertical in nearly horizontal layers of sedimentary basins means that their intersection is very limited to non-existing in vertical boreholes. These limitations are additional to the difficulty of acquiring oriented cores from deviated boreholes, and identifying barren fractures from DIFs.

The main source of fracture orientation measurements seems to be from borehole images. Borehole imaging tools were introduced in the petroleum industry as “dipmeters”, and the term is still in use nowadays (e.g., Pöppelreiter et al., 2010). Similar to measuring fracture orientation using cores, measuring fracture orientations using borehole images depends on the ideal geometry of boreholes and quality of borehole imaging acquisition. In addition, the borehole imaging measurements can have ranges of errors and cannot be treated as exact values for fracture orientations in subsurface (e.g., Genter et al., 1997).

Fractures are classified based on their dips into vertical, inclined, and horizontal. Fracture dips are often referenced to the setting of layers, and therefore the fractures are often reported as layer-normal or layer-parallel fractures. Based on strikes, fractures are typically classified into different sets based on subparallel strikes that are defined by the azimuth degrees, or the compass

cardinal and intercardinal points. There are no specific rules on what can be expressed as a “set of fractures” based on strikes. Wide ranges of about 40° azimuth around a mean value may be used to define a set of fractures. This is normally done because of the expected dispersions of fracture strikes and the “tolerance” toward measurement errors. Fracture patterns from tops or sections of rock layers are a product of fracture spatial distribution (orientation, size, location, abutting relation, and spacing). Fracture patterns are often classified as systematic, non-systematic, ladder-like, polygonal, orthogonal, and conjugate systems.

3.2.3 Size (Length, Height, and Width)

The size of a fracture is a 3-D geometrical property that generally requires descriptions for length, height, and width (Fig. 3.4). Fracture width is a measure for the separation (or the shortest normal distance) between fracture walls. Other terms that are applied for fracture widths include thickness and aperture. Fracture aperture is the physical opening between fracture walls. Individual fractures in layered rocks can be idealized as rectangular plates, which exhibit lengths that are much greater than heights, and heights much greater than widths.

The hydromechanical properties of fractures depend greatly on the size of fractures (e.g., Bazant and Planas, 1997). Fracture aperture is the building block of theoretical estimations of fluid flow through reservoir rock fractures. Fracture apertures are often viewed from both mechanical and hydraulic perspectives (e.g., Renshaw, 1995). The mechanical aperture of a fracture is basically the physical width of fracture opening, which is often estimated from assuming parallel walls of fractures. The hydraulic aperture is described theoretically and experimentally with relationships to the physical aperture, roughness of fracture walls, and pressure gradients of fluid flow (e.g., Barton et al., 1985; Jaeger et al., 2007).

The hydraulics and mechanics of fractures are also related to the sizes of other fracture dimensions, height and length. Furthermore, fracture sizes are key for obtaining information on fracture initiation, propagation, and arrest. The sizes of fractures preserve some information about fracture mechanics and kinematics in rock formations. For example, mineral fills preserve fracture width and record changes in fracture opening behavior. Fracture width is also related in some studies to fracture length by statistical relations, especially for mineral-filled fractures. Fracture size

can be dynamic, which means that it can change over time under dilating, compressing, or shearing stresses and controls of rock mechanics. Fracture size, therefore, determines other spatial properties of fractures in rock formations. For example, fracture size is related to fracture spacing and connectivity, because fracture size determines the probability of fracture intersections. In theory, collections of short and micro-fractures are less well connected than collections of long and macro-fractures for the same abundance and orientation distribution (e.g., Balberg and Binenbaum, 1983). Furthermore, fracture height and length are important properties of fractures in layered rocks. Fracture height is often related to the thickness, lithology, and mechanics of host rock layers. Notably, fracture height is used to define fracture stratigraphy.

The size of outcrop fractures can be measured using a tape measure or scaled high-resolution photography. Measuring the size of subsurface fractures is typically limited to fracture width in core and borehole images, because fracture height and length typically extend beyond the borehole. Apertures of subsurface fractures are measured using electrical borehole images as a function of several parameters including the physical aperture and the resistivity of mud filtrate (e.g., Luthi and Souhailé, 1990).

Measurements of fracture size are generally the most challenging aspect of fracture geometrical characterization, whether from outcrops or subsurface rocks. Measurements of fracture size are typically limited to one or two dimensions of height and width. Fracture length (i.e., the distance between end points) of an individual fracture is difficult to measure even from outcrops. Fracture height is commonly measured for layered rocks from measurements of layer thickness. Fracture width is commonly measured for mineralized fractures in outcrops. Unlike height and length, the width of a fracture is not an absolute value, but rather an average of several measurements for the distance between fracture walls across traces of fracture length or height.

Fractures are generally classified according to their size into micro- and macro-fractures. Some classifications are based on the size of the fracture system, rather than the individual fractures, as in the publications proposing scaling relationships (e.g., Bonnet et al., 2001). But, in general, width, height, and length of fractures can also be described by relative terms such as narrow, wide, large, small, short, long, and many other terms. Other classes are related to the

setting created by sizes of fractures in relation to the host rock. Fracture height is used to divide fractures in layered rocks into layer-bound and thoroughgoing fractures. Fracture aperture is used to describe if a fracture is mechanically open (with obvious separation) or closed (when the walls are in complete contact).

3.2.4 Roughness and Wall Matedness

Roughness is the undulations of rock fracture walls. Wall matedness (or matching) refers to the degree of perfectly interlocking (mating) walls. The deviations of fracture walls from interlocking walls are recognized as non-matedness or mismatching of fracture walls (Fig. 3.5).

Roughness and mismatch of fracture walls are key hydromechanical parameters of shear strength and hydraulic conductivity (permeability) of rock masses (Barton, Bandis, et al., 1985; Olsson and Barton, 2001). Fracture roughness is central in some competing theories relating fractures and faults to anisotropic permeability in subsurface rocks. For example, Barton et al. (1995) have used temperature logs of three boreholes that can indicate localized fluid flow in fractured and faulted crystalline rocks. The results indicate that fracture permeability is much higher in the fractures optimally aligned with the S_{Hmax} (e.g., Barton et al., 1995). The correlation was interpreted by citing the empirical studies that demonstrate the effects of roughness and shear dilation of fracture walls on the fluid flow potential (e.g., Barton et al., 1995; Rogers, 2003).

The fracture displacement can mechanically produce wall mismatching and hence apertures between walls of fractures (e.g., Brown, 1987; Zhao, 1997). These assumptions embed that walls of fractures were both perfectly matching and rough before experiencing slips under present-day tectonic stresses. Such fractures are called critically stressed fractures (CSF), whose ratios of shear to normal stresses exceed their frictional strengths (Barton et al., 1995). The hypothesis of CSF has been advanced to applications of reservoir geomechanics (e.g., Longuemare et al., 2002; Rogers, 2003; Verma et al., 2007; Zoback, 2010; Hennings et al., 2012; Sathar et al., 2012). Nonetheless, the same correlation between optimally oriented fractures and the S_{Hmax} can be otherwise interpreted as a result of the least resistance of the fractures to closure and hence most dilated for fluid flow (e.g., Heffer and Lean, 1993). The two theories lack any supporting measurements on fracture roughness and wall mismatch, and so it is uncertain how to specifically

relate permeability to fracture roughness and fracture displacement in subsurface rocks.

Roughness measurements have been almost exclusively reported from numerical simulations and laboratory experiments on artificial fractures and fractures in outcrop and near-surface rocks. Roughness measurements on fractures in deep subsurface rocks are rare to non-existing, with only one mention of measurements by Barton et al. (1985) for fractures in core samples from the Ekofisk reservoir in the North Sea. No measurements have been found on wall mismatch of fractures in reservoir rocks. Roughness seems to be the most obscure property of subsurface fractures. In the laboratory, roughness has long been described using various empirical, statistical, and fractal methods (Barton and Choubey, 1977; Tatone and Grasselli, 2010). Roughness can be measured for 2-D profiles and 3-D surfaces. Rock surfaces from outcrops display roughness at various sizes that can be roughly divided into large-scale (waviness) and small-scale (unevenness) components (e.g., Tatone, 2009). Roughness measurements are mostly conducted on small surfaces of fractures ($<1 \text{ m}^2$). In addition, roughness is typically measured for barren fractures (rock joints), because surfaces of mineral-filled fractures are not accessible.

Fractures, particularly joints, are classified according to their roughness based on the well-known joint roughness coefficient (JRC) scale of Barton (Barton and Choubey, 1977) (Fig. 3.5). The JRC scale is comprised of 10 typical profiles with values ranging from 0 (for smooth surfaces of fractures) to 20 (for very rough surfaces of fractures). Fractures can be classified based on the degree of wall “matedness” into mated (wall-matching) fractures and non-mated (wall-mismatching) fractures.

3.2.5 Displacement Mode

Mode of fracture displacement defines how a rock has lost cohesion along a plane of fracture, and how the fractured blocks moved (slipped) along the formed fracture plane. The displacement mode is defined in a 2-D and 3-D framework from a local reference for directions on the fracture planes (walls) (Fig. 3.6).

The relations between fracture mode of displacement and hydromechanical effects are not straightforward. The displacement mode is basically used to explain the stress fields that generate fractures and faults, and may yield useful information to develop the hydromechanical relations for

fractured or faulted rocks. For faults, the relations depend on the nature and size of fault zones, with several parameters related to fluid pressure and host rock properties that eventually make faults as either sealing or conducting zones in subsurface rocks (e.g., Marco Antonellini, 1995; Cartwright et al., 2007). The geological models of fractures are generally concerned with fracture aperture, with consideration to mineral fills and wall roughness. The displacement mode of fractures is initially tensile, but may evolve to shear displacement with subsequent rock deformation. Fracture displacement can be studied from the growth of mineral crystals in veins, because they preserve information on the kinematic and hydraulic history of fracture displacement (e.g., Cobbold et al., 2013; Meng et al., 2017).

Displacement modes are described from the separation of fracture walls (width and aperture), as well as the displacement of rock features (marker) such as bedding planes. In addition, displacement mode can be related from wall structures (morphology) such as plumose structures of joints and slickensides of faults. Displacement can be described and measured for fractures in outcrops, cores, and borehole images, if the fracture separated an obvious marker in rocks. The magnitude of displacement is equivalent to the size of fracture width.

Fractures are classified based on the basic crack mode of displacement into Mode I (fractures), Mode II (compaction structures), and Mode III (faults).

3.2.6 Abundance

Abundance is a measure of the amount of fractures in rock formations. Abundance is one of the properties that are measured to describe the fracture spatial distribution in rocks (Mauldon and Dershowitz, 2000). The term abundance is synonym in the geotechnical literature to other quantitative and qualitative terms such as intensity, density, frequency, persistence, and spacing (Mauldon and Dershowitz, 2000).

Fracture abundance is one of the most important, and probably least characterized (Dershowitz and Herda, 1992), properties of fracture spatial distribution such as orientation, size, shape, and spatial location (Dershowitz and Einstein, 1988; Dershowitz and Herda, 1992). Measuring fracture abundance is important to characterize the hydraulic and mechanical properties of rocks at surface and subsurface. The most common model for relating fracture abundance is

the linear relation between fracture spacing and layer thickness in sedimentary layered rocks (see Ch. 1.5.1).

The measuring methods of fracture abundance are varied. Fracture spacing is the mostly used method to estimate fracture abundance in layered rocks. It is a measure of the distance between fractures intersected by scanlines or boreholes (Fig. 3.7). In structural geology, fracture spacing is measured along a line perpendicular to the average orientation of parallel or semi-parallel fractures from top or cross sections of layers. In rock mechanics, the spacing of fractures is measured for all encountered structural discontinuities regardless of their orientations and types (opening-mode, shear, filled, barren) (Priest and Hudson, 1976).

The models for fracture abundance are numerous in the geological literature. The models are mostly based on outcrop observations. Measuring and modeling fracture abundance in subsurface rocks are very limited because of the shortages of direct datasets on fractures. Cores have been used in a few studies, (e.g., Narr and Burruss, 1984; Narr, 1991; Sagi et al., 2014), to measure fracture abundance in carbonate reservoirs. The main source of many measurements is borehole imaging. Other geophysical methods of borehole logging and seismic imaging were not apparently used, but they are unlikely to exhibit fractures for abundance measurements.

Fractures are classified according to their spacing in layered rocks into regularly spaced and non-regularly spaced. The geological literature includes general terms for fracture abundance such as high, low, increased and decreased, and over-saturation and under-saturation, within specific contexts of study areas.

3.3 DATASETS AND METHODS

The datasets of this research are divided into two types: reservoir datasets and outcrop datasets. This division is appropriate to realize the difference in the methods of data acquisition and analysis for outcrop and subsurface fractures. The outcrop and reservoir datasets can also be divided based on the nature of descriptions into two types: fracture descriptions (of mineralization and geometry) and lithology descriptions. The descriptions of fractures were done by the author of this research. The descriptions of rock lithology were based on previous work, with some modifications by the author to ensure uniformity of the reported descriptions.

3.3.1 Outcrop Datasets and Methods

The outcrop datasets were collected from two regions in the homocline in Central Arabia in addition to the dome outcrops in Eastern Arabia.

The datasets from the homocline include measurements of fractures and descriptions of carbonate lithology of the Arab and Jubaila outcrops from four sites at Wadi Malham and Howtat Bani Tamim (Fig. 3.8). Fractures were described and measured for their spacing using a measuring tape that was horizontally placed along the flat beds of the outcrops. The scanned fractures are described at each site for mineralization (mineralized and barren), dips, strikes, heights, and displacement modes. The descriptions include measurements of layer thickness and identification of lithologic type of the fractured rock units. The rock units were selected to study fractures and provide measurements from different lithofacies, thicknesses, and positions (i.e., from lower, middle, and upper parts of the stacked layers in the outcrop). No measurements were collected for the width and length of the outcrop fractures. The outcrops have limited exposure for measuring fracture length, and measuring fracture aperture was unfeasible for weathered surface rocks. The detailed lithological descriptions are provided by A. Al-Mojel, who studied the stratigraphy of the sites for his PhD project at the University of Bordeaux, in France.

From the dome outcrops, fracture spacing is measured for the carbonates of the Middle Rus Formation, which dominates the dome surface area. The measurements are new and add to the wealth of information available on the fractures, structures, lithology, mechanical properties, and modeling of the Rus Formation at the dome outcrops (Tleel, 1973; Weijermars, 1999; Abdullatif, 2010; Al-Fahmi, 2012; Al-Fahmi et al., 2014).

3.3.2 Reservoir Datasets and Interpretation

The reservoir datasets include whole cores and electrical borehole images. The datasets were acquired by Aramco between 2012 and 2014 from the Arab reservoirs (A, B, C, and D) in the dome area (Fig. 3.9). The core and borehole images were acquired from extended-reach drilling of four boreholes in the southwestern region of the dome. The datasets are accompanied by a full suite of borehole logs such as gamma ray, density, neutron porosity, sonic, as well as pressure tests

for reservoir fluids. The 21.6 cm-diameter boreholes were drilled in the Arab Formation with different degrees of azimuth and inclination from a drilling site located on the southwestern periphery of the dome (see Fig. 3.9 and Tab. 3-1). The drilling program started with X-02, followed by X-01, X-03, and X-04, which is a sidetrack borehole from X-03. The given well names (X-01, X-02, X-03, and X-04) are for references in this research; they do not match the official well names that are used by Aramco.

Oil production and water injection was shut in this field for about 30 years. The data of the reservoir fluid pressure was insufficient for designing a balanced mud weight to drill the first directional borehole (X-02). The borehole was drilled in the reservoir section with a relatively high mud weight (over-balance) as a preventive measure to prevent the reservoir fluid from flowing into the borehole. The reservoir fluid is believed to contain some hydrogen sulfide (H_2S) gas, which is poisonous, corrosive, and flammable and must be contained during drilling operations. The drilling of X-02 resulted in some mud loss in the reservoir intervals while borehole imaging. As will be shown later, this has an effect on the borehole imaging of reservoir fractures. The other directional boreholes (X-01, X-03, and X-04) were drilled with a balanced mud pressure, based on the pressure measurements obtained from X-02.

The core was cut continuously along the reservoir sections using a coring technology that includes a polycrystalline diamond compact (PDC) bit with a coring barrel and a core catcher. The PDC coring bit is different from the usual drilling PDC bit by its central hole, which makes it possible to cut cylindrical rock (core) samples while moving downward on the drilling path designed for the borehole. The reservoir core is cut and moved into the core barrel (chamber), and the catcher prevents the core from falling into the borehole.

The core was cut from the Arab carbonate reservoirs as follows: 91.4 m with 6 cm diameter from X-01, and 189 m with 8 cm diameter from X-03. About 98% of the reservoir cored intervals were recovered as high-quality cylindrical core. The core from the X-03 borehole includes a section below the present-day oil-water contact, in the flank of the dome. The core of the X-01 borehole was totally in oil section at the dome crest (i.e., filled with oil). The core was mostly in its solid, whole cylindrical shape (Fig. 3.10). No more than 4.57 m of core were fragmented from the

283.5 m of the cored intervals. The limited damage of the core was in the vuggy intervals, where the rock cohesion is generally softer than in other reservoir intervals. Spectral gamma ray measurements of the core were routinely acquired in order to tie core depths to those of the standard well logs. The close-fitting core was scanned using an industrial scanner, which produced 360° optical images of core circumference in true color with a resolution of up to 10 pixel/mm and detail up to 40 pixel/mm.

The borehole images were acquired from the four boreholes using FMI HD and FMI MicroScope HD. The imagers are new generations of electrical (microresistivity-based) measuring tools (Brown et al., 2013) (Fig. 3.11). The FMI HD is typically positioned on a wireline and lowered to the borehole bottom, then dragged upward to the surface while the tool is scanning rocks of the borehole wall. The FMI MicroScope HD is one type of the electrical tools that can be used while drilling—called logging while drilling (LWD) tools in the petroleum industry. The FMI tools typically measure rock properties in a borehole filled with water-based mud. There are, however, versions of these electrical tools that can scan boreholes drilled and filled with oil-based mud, but they generally provide poorer-quality imaging, because of the low electrical conductivity of oil as opposed to water (e.g., Tehrani et al., 2002).

The four boreholes were drilled with water-based mud, with chemical and physical properties that are standard to the geophysical logging tools managed by Aramco for the Arab carbonate reservoirs. Electrical borehole images were acquired by the same operator and the same service company from the four boreholes along a total of 1805.6 m of the borehole intervals. In total, 1298.5 m of the imaged sections are in carbonates, and 507.2 m are in anhydrites. The wireline images of wells X-01 and X-03 were FMI HD that were acquired under similar borehole conditions. The images of wells X-02 and X-04 were acquired while drilling, using FMI MicroScope HD, which is a new electrical borehole imager that is positioned on the drill string behind the drilling bit (e.g., Amer et al., 2013).

Raw data from the borehole imaging tools are processed by using commercial software (e.g., Techlog) in the oil industry to produce oriented-electrical images of the borehole walls. Image processing includes signal conditioning, image enhancement, and image layout preparation (e.g.,

Zemanek et al., 1970; Prensky, 1999). Image processing also includes defining borehole orientations and shapes from the measurements of the imaging tool azimuth, inclination, and calipers. The images are presented in the format of 360° unwrapped-borehole layouts. Lithological fabrics can be distinguished from the images of up to 5 mm of the vertical and horizontal surface dimensions, and about 10-cm depth in the borehole wall (e.g., Laronga et al., 2011).

The processed wireline images of the X-01 and X-03 boreholes provided coverage of more than 80% of the borehole wall, leaving only narrow gaps between the tool measuring pads. The LWD imager, used in X-02 and X-04, provided full coverage of the borehole wall. The quality of the processed wireline images is excellent throughout the targeted intervals. The caliper data demonstrate the boreholes are cylindrical smooth holes, which are ideal for obtaining good-quality images, because the tool pads are contacting the wall.

Many calcite-filled fractures with widths below 2 mm were identified in some sections of the borehole images. Calcite-filled fractures can be used to test the imaging resolution, as they have finite widths. The quality of the borehole images of X-02 and X-04 was also excellent for these newly deployed LWD imagers. But the images appear pixelated and occasionally blurry when compared to the wireline image logs; hence, they are expected to provide fewer details about rock fabrics and fractures.

3.3.2.1 Fracture Interpretation from Core

Core descriptions were focused on the identification of fractures, DIFs, bedding planes, and stylolite planes. The core was described from the whole core samples, and then from the slabbed core, at the Core Lab of Saudi Aramco. The core was also described from the high-resolution optical scans. Information on core geometry (Fig. 3.12) and interpretation of the corresponding borehole images facilitated core interpretation.

The following criteria were developed during this research to identify barren fractures in the core and exclude the fractures that were induced by drilling or core handling (DIFs). The reservoir fractures from core are identified as follows: 1) they match fractures in the borehole images, 2) they have the same orientation at the same core interval (parallel sets), and 3) they differ in their basic geometry from the DIFs (Fig. 3.12 and Fig. 3.13).

The DIFs can be differentiated from barren fractures in core on the basis of distinct geometrical relationships between the core parameters and the surface morphology, trace shape, and frequency of barren fractures (e.g., Kulander et al., 1990; Lorenz et al., 1990; Lorenz and Cooper, 2017). The DIFs occur in core and in borehole walls during drilling and under the influence of high in situ stress (Li and Schmitt, 1998).

Various shapes of the DIFs have been used to indicate the principal stresses based on experimental and numerical modeling (Aadnoy and Bell, 1998; Haimson and Cornet, 2003). Core diskings and petal fractures are notable examples of DIFs. Core diskings typically grow at the base of vertical wells as planes normal to the axis of the borehole when the maximum and intermediate principal stresses are nearly perpendicular to the core axis (Li and Schmitt, 1998). Petal core fractures extend toward the axis of the core convex down to the bottom of the hole, and with an inclination in the direction of the least horizontal stress (Schmitt et al., 2012). Core diskings can also develop at flaws in the rock, such as pre-existing fractures (Flottmann et al., 2004).

3.3.2.2 Fracture Interpretation from Borehole Images

Borehole images were described for fractures, DIFs, bedding planes, and stylolites. The color schemes of images followed standard processing, in which dark tones are equated with conductive lithology, and light tones, with resistive lithology. Hence, open fractures and rock pores appear dark, and calcite-filled fractures and low-porosity (tight) intervals appear light in borehole images (Rider, 1999). Similar to fracture interpretation from core, fractures were differentiated from the DIFs on geometrical grounds, although the differentiation is generally easier from borehole images, because the DIFs in boreholes develop in a cylindrical wall due to the hoop stress and do not meet the geometry of a rock fracture intersected by the borehole. Fractures can be observed as complete traces, partial traces, and abrupt planar changes cutting imaged rock fabrics of the borehole. The DIFs can be observed in the form of breakouts and tensile wall-fractures (TWFs) (Schmitt et al., 2012).

Breakouts and TWFs appear in borehole images as conductive fractures nearly parallel the borehole axis (Fig. 3.12) Breakouts are zones of compressive shear fractures and spalling that develop due to the elongation of the borehole diameter (Bell and Gough, 1979). Borehole

elongation occurs in the direction of the minimum principal stress of compression that is acting orthogonal to the borehole axis. Therefore, borehole breakouts are often interpreted from caliper and borehole image datasets to reveal the present-day S_{Hmax} (e.g., Zheng et al., 1989).

The TWFs typically appear in borehole images in pairs that are nearly parallel to a vertical borehole axis and along the opposed sides of the borehole at 90° to the orientation of the breakouts if both are present (e.g., Brudy and Zoback, 1999). In deviated boreholes, experimental and field observations suggest that the TWFs are unaligned with respect to the borehole axis, as they develop in an en echelon pattern and first propagate in the direction of the borehole axis, then reorient to be perpendicular to the minimum principal stress (e.g., Jia et al., 2013).

3.3.3 Methods of Describing Reservoir Fracture Properties

The reservoir datasets are exceptional, because they contain long core sections coupled with high-quality borehole images from directional boreholes. The borehole orientations were optimal to intersect subvertical fractures in the gently dipping strata of the Arab reservoirs in the dome. The identification of barren fractures on core was facilitated by the borehole geometry, which is neither perpendicular to the reservoir bedding nor to the fracture planes.

The core was in a solid and good shape because the Arab carbonates are mechanically competent. This quality of the rock helped to differentiate the core breakages such as DIFs from the reservoir fractures. In general, DIFs are typically confused with reservoir rock fractures in 1) damaged core samples by drilling, 2) core of non-competent rock such as shale or loosely consolidated sandstone, and 3) core from highly stressed rocks when the core and borehole walls are fractured in a certain pattern upon releasing the confining stress by drilling. These issues were not present in the study area, reservoir rocks, and at the depth of investigation (< 1.5 km). Exceptions were small broken sections that represent about 2% of the core length. Interpreting barren fractures in these small core sections was difficult, and hence these sections were excluded from the interpretation. These sections may include some fractures, but they should not have any significant effect on the modeled fracture spacing.

Fractures were re-interpreted and counted from tied core and borehole images (Fig. 3.14), following the first stage of identification of reservoir fractures, DIFs, bedding planes, and stylolite

planes. This was done for cross-correlations of observed features in both types of datasets. This iterative approach is typically performed when interpreting reservoir datasets using different methods.

Fractures were also described from both core and borehole images for mineralization and geometry. Furthermore, the fractures interpreted from the core were digitized from the optical scans up to 0.1 mm (measuring resolution) of core dimensions using a CAD-based commercial software.

3.3.3.1 Mineralization

Fracture types, based on mineral fills and lack thereof, were identified and described from core and boreholes. The following classification is adopted for the classes of fractures based on mineralization:

- 1) Barren—fractures that are barren of filling minerals.
- 2) Partly mineralized—fractures with coexisting mineral fills and pores (crystal bridges).

This class is difficult to describe from core, and therefore this research does not include under this class the fractures with partial loss of mineral fills that are caused by possible chemical dissolution or mechanical breaks during core handling or thin section preparation.

- 3) Mineralized—fractures with a complete mineral fill in core, thin sections, and borehole images. The fractures identified under this class are visually distinct in true color and shape from host-rock fabrics. Mineralized fractures are further divided based on the type of filling minerals. Common filling minerals in carbonate fractures are calcite, gypsum, and dolomite.

The above classification is comparable to the one presented in Waldschmidt et al. (1956) and often used in recent studies of the Arabian carbonate reservoirs (e.g., Ameen, 2014).

Following core descriptions, mineralized fractures, stylolites, and their host rock were sampled from the core for petrographic and chemical analyses. The petrographic description is focused on the identification of mineral types, degree of fills, and associations of mineral fills to the host rock lithology. Although micro-fractures were observed in the sampled thin sections

under the microscope, they were not studied to provide systematic descriptions of their properties other than reporting their obvious mineralization types. The chemical and isotopic analyses were conducted to identify the possible classes of mineralized fractures from chemical and isotopic signatures. The chemical analyses included measurements for the stable isotopes ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) and strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) using ground powder from the calcite veins, see (Ch. 10). Some calcite crystals from the samples were also used for the uranium radioactive dating analyses, but no results were obtained because the uranium was either absent or of a very small quantity in the crystals that survived the acid treatment in laboratory. Vein sampling for the chemical analyses was generally limited because of two factors: (i) the limited number of the veins in the core and (ii) the difficulty of extracting pure fracture fills from less than 2 mm-width veins without contaminating samples with the host rock minerals.

3.3.3.2 Orientations (Dips and Strikes)

Dips and strikes (orientations) of the reservoir fractures are a byproduct of interpreting fractures in borehole images, because the imaging tools are oriented for measuring any planar feature in the borehole. The frequency distributions of the fracture strikes are corrected, because the boreholes typically minimize the fractures that nearly parallel them. The correction is based on a density weighting method (Palmström, 1996). This method is preferred to the 1-D Terzaghi correction (Terzaghi, 1965) because the boreholes traverse multiple layers and different fracture orientations.

The dip measurements of fractures, bedding planes, and stylolites using borehole images have certain ranges of errors that may reach up to 10° . The precision of dip measurements is particularly reduced for the features with low dip angles such as bedding planes. The range of errors has been recognized in the measurements of fractures in the Arabian carbonate reservoirs and elsewhere. The geological mapping between the wells typically displays smaller dips than what is obtained from borehole images. The errors are associated with the accuracy of the tool magnetic field reference, and sometimes related to the precision of fitting sine curves to the borehole structural features (e.g., Genter et al., 1991).

Measuring fracture orientation was not possible from the core, because it was not

oriented, and it was not possible to orient the core using borehole images. Although the core was not oriented, it was possible to relate the dips of observed fractures to the dips of the reservoir layers and borehole orientations.

3.3.3.3 Size (Width)

The fracture sizes were measured for fracture widths (width of mineralized fractures and aperture of barren fractures). The apertures of barren fractures and widths of mineralized fractures in the core were measured from the digital profiles of fractures (Fig. 3.15 and Fig. 3.16). Sections of maximum and minimum portions along fracture profiles were estimated using a digital scale comparator (Ortega et al., 2006). From borehole images, mechanical and hydraulic apertures were measured using the Techlog software and the methods described in previous studies (Luthi and Souhaité, 1990).

The mechanical and hydraulic apertures of the fractures were measured from borehole images using the methods described in Luthi and Souhaité (1990), see (Fig. 3.17). The mechanical aperture of a fracture is the size of fracture opening between the fracture walls. The hydraulic aperture of a fracture is estimated theoretically from the fracture mechanical aperture, roughness, and pressure gradients of fluid flow (Barton, Bandis, et al., 1985). The measuring methods of apertures are available in the software applications (e.g., Techlog) that are used in processing and interpreting borehole images. The fracture mechanical aperture (W) from borehole images is measured (in millimeters) using the relationship

$$W = cAR_m^b R_{xo}^{1-b}$$

as a function of the integrated additional mud current, A ; the resistivity of the formation, R_{xo} ; and the resistivity of the mud, R_m ; through the measuring tool-dependent coefficients b and c (Luthi and Souhaité, 1990). The mean mechanical aperture (W_m) of a fracture can be measured as

$$W_m = \frac{\sum W^3 n}{n},$$

the sum of apertures (W) (from sampled points) along the fracture trace averaged over fracture length (n) in boreholes (e.g., Luthi and Souhaité, 1990). The mean hydraulic aperture (W_h) from borehole images is measured as

$$W_m = \sqrt[3]{\frac{\sum W^3_n}{n}},$$

the cubic mean of the mean of the cubes of mechanical aperture. This calculation method is provided by the imaging tool manufacturer based on production data; as such, the hydraulic aperture is equal or greater than mechanical apertures if fracture walls are not perfectly matching. This calculation differs from the rock mechanical methods, in which hydraulic aperture is expected to be either equal or smaller than the mechanical aperture if fracture walls are mismatching (e.g., Barton et al., 1985).

3.3.3.4 Roughness and Wall Mismatch

Roughness and degree of wall matching were measured for the fractures interpreted from the core using a new computational technique that was developed jointly with Dr. S. I. Ozkaya during this research. It was not possible to measure fracture roughness for the fractures in borehole images. However, the methods of measuring apertures from borehole images provided information on the nature of roughness and wall mismatching of open fractures.

Fracture roughness has long been described using various empirical, statistical, and fractal methods (e.g., Tatone and Grasselli, 2010; Weissbach, 1978; Lee et al., 1990; Barton and Choubey, 1977; Schmittbuhl et al., 1993; Haneberg, 2007). Among these methods, roughness is widely described by visually comparing 2-D profiles of fracture surfaces to the typical 10 profiles of the joint roughness coefficients (JRCs) (Barton and Choubey, 1977), see (Fig. 3.5). The values of the JRCs range on a scale from 0 (very smooth) to 20 (very rough) (Barton, 2013).

Roughness has been also described numerically using statistical parameters that were proposed to overcome the simple and subjective nature of laboratory visual techniques (e.g., Tatone and Grasselli, 2010; Li and Zhang, 2015). Nevertheless, the visual and statistical techniques cannot be used to measure roughness and wall mismatch of mineralized and barren fractures in a cylindrical directional core.

The visual techniques are limited in use to the barren fractures. Walls of veins are not accessible, and breaking core or dissolving mineral fills to precisely expose the host rock walls is unfeasible. Furthermore, the available statistical techniques require presenting core fractures in a

digital format of flattened profiles from their actual different elliptical traces around core circumference. To overcome these challenges, a novel combination of efficient and non-destructive techniques was developed during this research to describe roughness and wall mismatch of fractures. These techniques provide a new solution to describe both types of mineralized and barren fractures from geometrical core. Calcite veins and barren fractures were digitized from the optical scans of the core, up to 0.1 mm (measuring resolution) of core dimensions, using a CAD-based commercial software (Fig. 3.16 and Fig. 3.18). The fracture digitization was done manually. It was not possible to extract precise profiles for the core fractures using image processing techniques such as pattern recognition and edge detection.

The shape of a digitized fracture profile resembles a sine wave produced by the intersection plane of the fracture with the drill core cylinder (Fig. 3.16). The shapes of digitized profiles encompass information about fracture geometry (strike, dip, amplitude, and roughness) with intersection to core geometry (strike, dip, height, and diameter) (Fig. 3.16). The lengths of fracture profiles vary, according to their elliptical intersection perimeters, and mostly range between 25 cm and 35 cm.

Numerical techniques were then developed in a spreadsheet-based application to measure the profile deviations in the x-y space from a fitting smooth curve (Fig. 3.16). The techniques can be used to compute statistical parameters of fracture roughness such as Z_2 . The Z_2 is among several numerical parameters that have been used to describe profile undulations (e.g., Myers, 1962; Tatone and Grasselli, 2010). The Z_2 measures the root mean square of the first derivative of the surface profile from a centerline average:

$$Z_2 = \left[\frac{1}{L} \int_{x=0}^{x=L} \left(\frac{dy}{dx} \right)^2 dx \right]^{1/2}.$$

The measured Z_2 values can be converted to the JRCs and other numerical parameters using established relationships (e.g., Li and Zhang, 2015). Other statistical parameters of roughness and their relations to the JRC scale are also possible to use in the same fashion. The Z_2 values are converted to the JRC scale using the following relationship (e.g., Li and Zhang, 2015):

$$JRC = 55.7376Z_2 - 4.1166.$$

Reporting values on the JRC scale is preferred here, because values of the typical JRC profiles provide visual reference with empirical relationships to the rock hydromechanics (e.g., Barton, 2013).

The wall mismatch was analyzed using three methods from analyzing top and bottom profiles (profile pair) of each fracture (Fig. 3.16). The first method estimates the difference of JRCs between profile pairs. The second method calculates the standard deviations of apertures (STDEV-A) between profile pairs after flattening and resampling the profile pairs to be at the same x-y coordinates. The third method is to use the flattened and resampled profiles for a quantitative correlation, from which we can relate mismatch coefficients (MCs) ranging between 0 and 1. A value of 0 means perfectly matching fracture walls.

The obtained measurements on roughness were correlated with the host rock lithology, which is described in detail (~5-cm interval) from core and thin sections following a modified version of the Dunham classification (Dunham, 1962). In addition, the measurements were correlated to the results obtained from borehole imaging of barren fractures using two methods: (i) calculations of mechanical and hydraulic apertures and (ii) correlations between apertures and fracture strikes. These measurements were performed to evaluate if fracture apertures are sensitive to the stress field and stress-dependent permeability in the subsurface.

3.3.3.5 Displacement Mode

Mode of fracture displacements were described from core and borehole images. The description is based on the use of bedding planes, stylolites, and other rock markers (i.e., fossils) at fracture intersection. The geometry of the boreholes means that any shear displacement along fracture planes can be observed and described for magnitude and type (normal or strike slip) from core and borehole images.

3.3.3.6 Abundance

Fracture spacing was initially measured along the boreholes (core and borehole images). The depths of the core and borehole images were marked every foot (30.5 cm) for the measured depth (MD), which is the distance along the borehole from the surface. The MD is typically

converted to the total vertical depth (TVD) of the subsurface using the borehole drilling survey and trigonometric functions. The locations of fractures in the core or borehole images were typically marked with a certain depth, typically in the MD format. The spacing was obtained for the distance between fractures for the MD along the boreholes, and for the horizontal distance between the fractures at the rock intervals traversed by the borehole.

Fracture abundance was described using two approaches (Fig. 3.19). The first was to report the number of fractures per borehole length, from core and borehole images. This approach disregards the mechanical stratigraphy of the rocks that possibly control the height of fractures above or below the borehole. The second approach was to divide the reservoir rocks into lithological units so the number of fractures can be reported according to the length of the horizontal distance traversed by the borehole along the host units (Fig. 3.19). This approach provides a “corrected fracture spacing”, similar to fracture spacing in outcrops. The measurements of fracture abundance are correlated and discussed from the context of the dataset types (core and borehole images), host rock lithological type, borehole orientation, and geologic setting of the carbonate rocks in the platform interior.

3.3.3.7 Lithological Descriptions of Reservoir Rocks

The datasets of rock lithological and stratigraphic descriptions that are included in this research are based on previous descriptive work. Two types of reports were used: descriptions of the Arab carbonates across the platform (e.g., Powers et al., 1966; Al-Husseini, 2009; Al-Awwad, 2013) and descriptions of the Arab reservoirs in the dome (e.g., Powers et al., 1966).

The most recent study of the Arab reservoir lithology in the dome was based on the core description of the X-03 borehole (Aramco internal report, 2015). This study described rocks based on lithological facies, porosity, and permeability. The reservoir lithofacies was described from the slabbed core and thin sections, following a modified version of the Dunham classification described in previous studies (e.g., Al-Awwad and Collins, 2013). The results are integrated in this research with other previous studies on the Arab reservoirs in the dome to build a general stratigraphic column for the lithofacies based on the Dunham classification (Fig. 3.20).

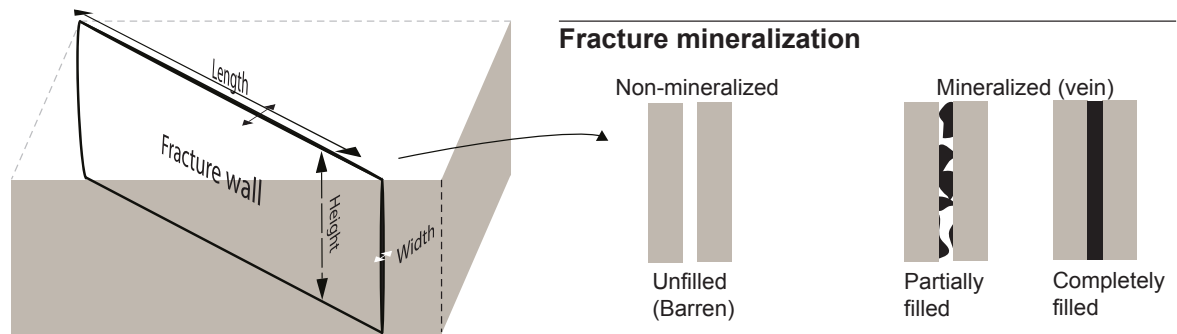


Fig. 3.1: Sketches demonstrate the fracture mineralization properties.

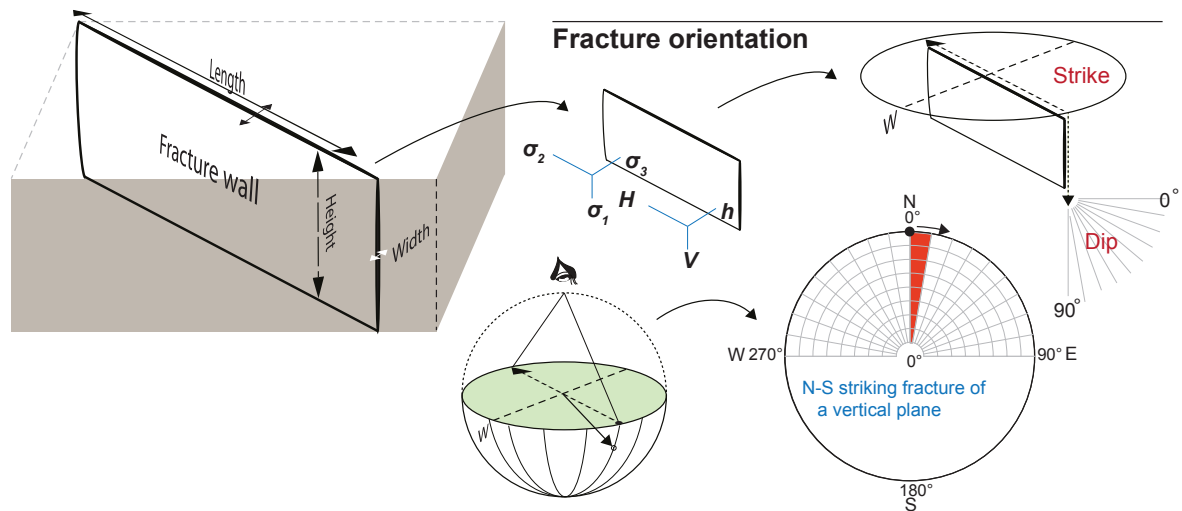


Fig. 3.2: Sketches demonstrate the fracture orientation properties.

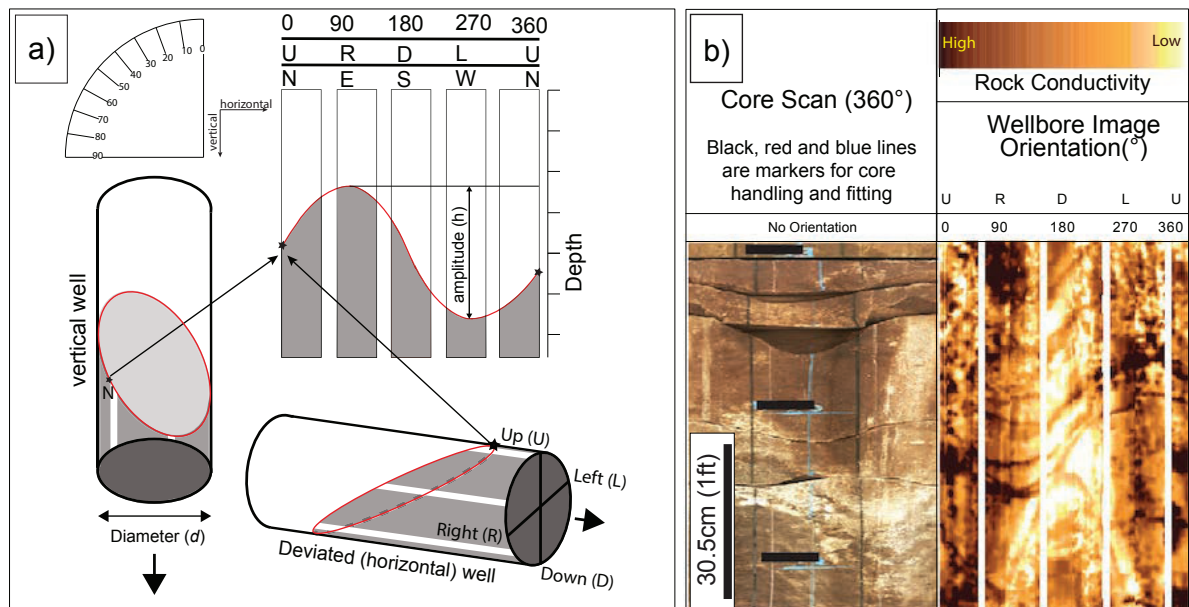


Fig. 3.3: a) Graph demonstrates how dips of planer features, such as fractures, are displayed and measured for dips and azimuths from oriented core and borehole images; b) an example of 360° layouts of core and electrical borehole images.

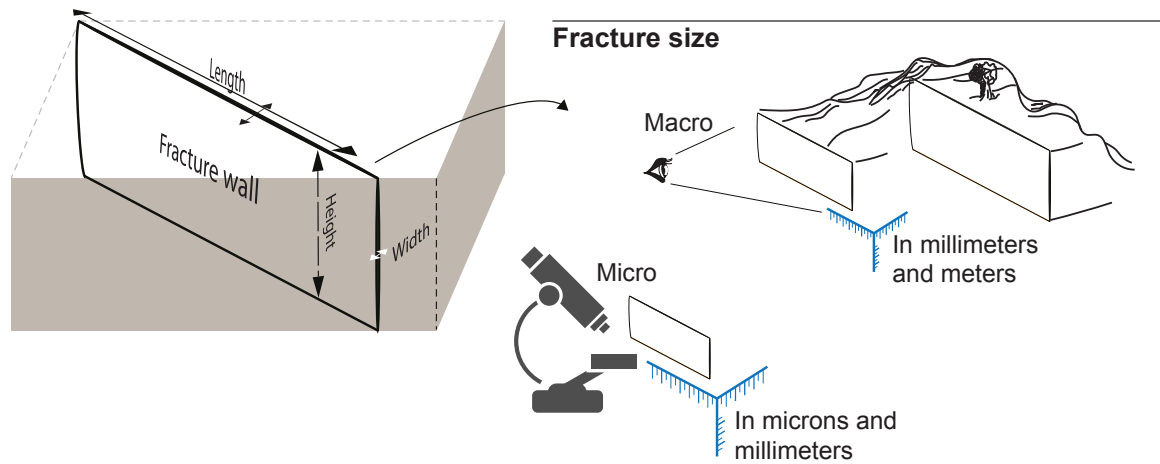


Fig. 3.4: Sketches demonstrate the fracture size properties.

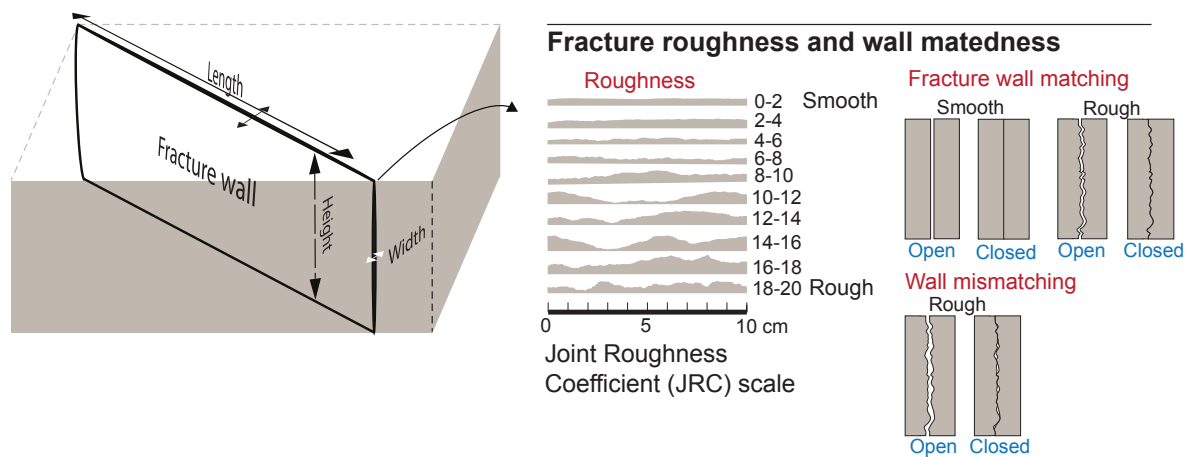


Fig. 3.5: Sketches demonstrate properties of fracture roughness and wall matedness (also called wall matching). Fracture roughness is typically described for outcrop fractures using the JRC scale.

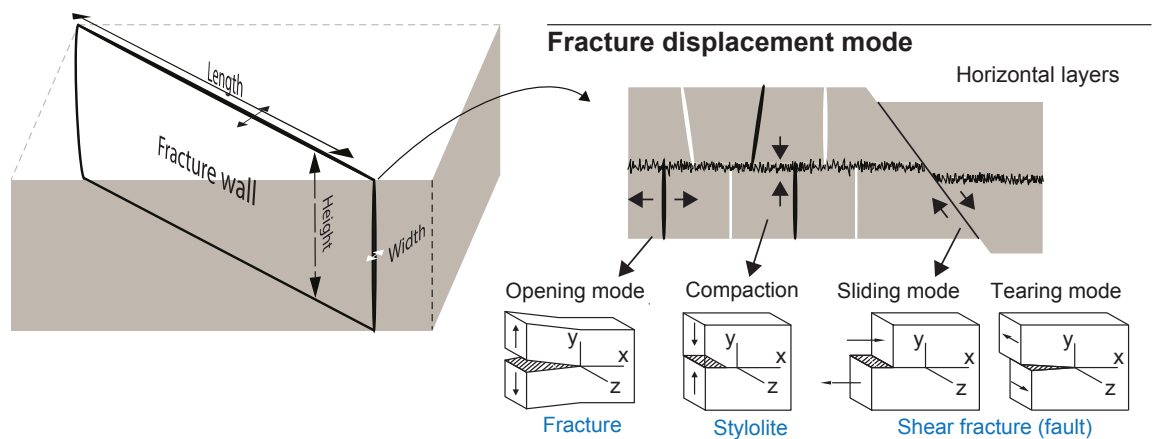


Fig. 3.6: Sketches demonstrate general properties of fracture mode displacement.

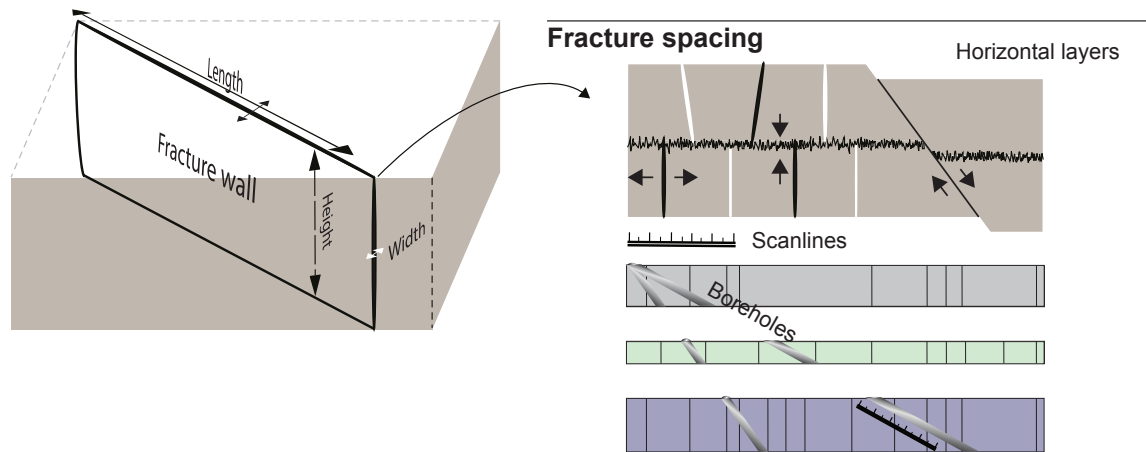


Fig. 3.7: Sketches demonstrate how fracture abundance is typically measured in layered rocks. Fracture spacing is the typical method of measuring fracture abundance along scanlines and boreholes.



Fig. 3.8: Photographs of part of the Arab-D carbonate outcrops at Wadi Malham, Site 1 (N 25° 09' 14" N, 46° 12' 28" E) and Howtat Bani Tamim, Site 4 (23° 28' 19" N, 46° 52' 11" E). The viewer is looking west in the first photograph and northeast in the second photograph.

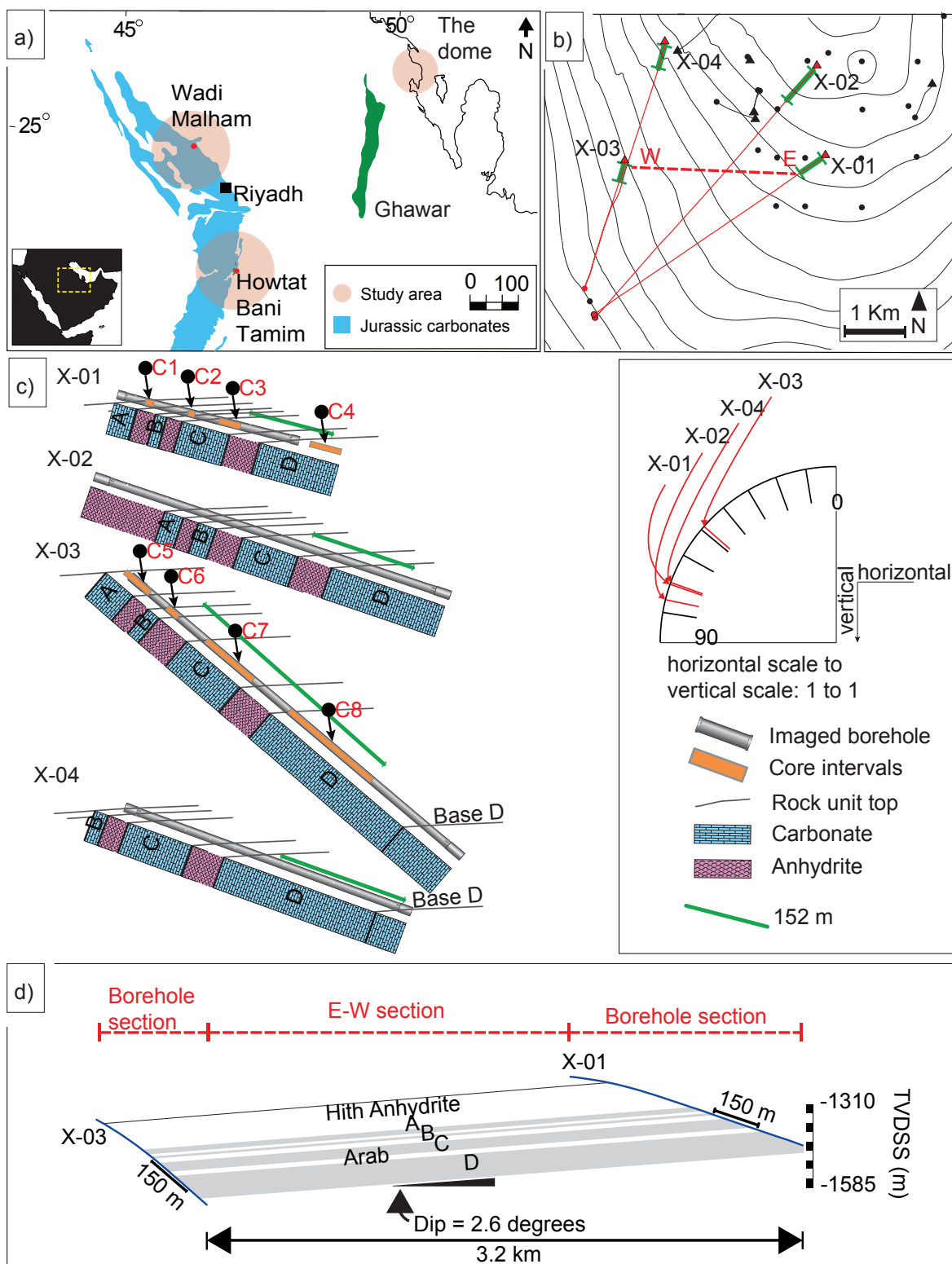


Fig. 3.9: a) Map of study areas in Eastern and Central Arabia; b) map shows the location of the directional boreholes in the southwestern area of the dome; c) cross-sections of the directional boreholes drilled in the Arab reservoirs (A, B, C, and D); d) E–W cross-section demonstrates the very low structural dips of the Arab carbonates in the dome between boreholes, X-03 in the dome flank, and X-01 near the dome crest.

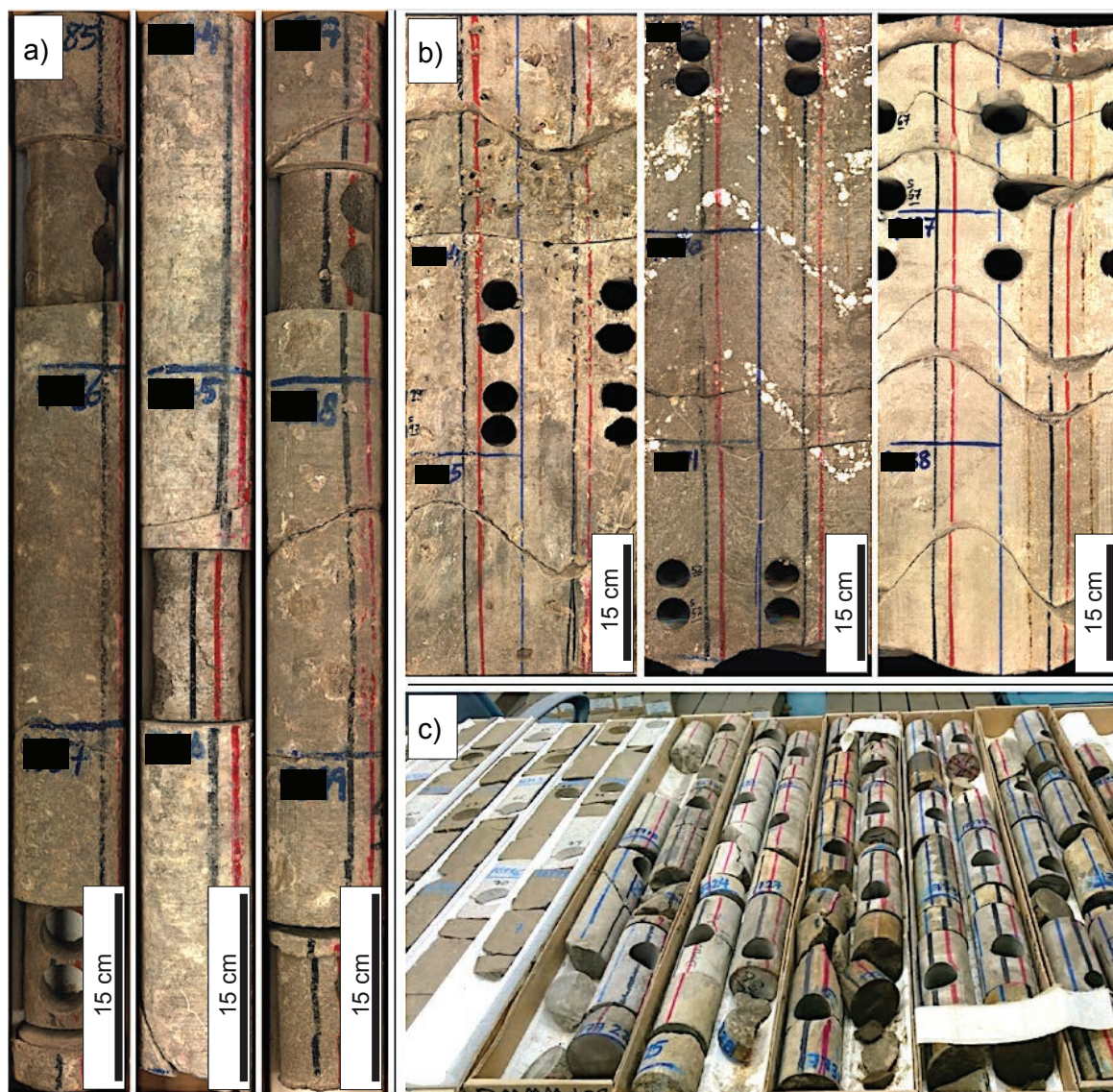


Fig. 3.10: Core photographs for a) whole core sides; b) 360-degree optical scans; and c) slabbed core. The core is mostly in its solid and whole cylindrical shape.

Borehole	Borehole deviation	Borehole azimuth	FMI length	FMI in carbonate	FMI in anhydrite	Cored interval	Damaged core	Core recovery factor
	Degrees	Degrees	m	m	m	m	m	(%)
X-01	71	55	481.3	274	207.3	91.4	1.4	98%
X-02	76	42	665.1	495	170.1			
X-03	48	16	271.0	198.1	72.8	189.0	3.6	98%
X-04	70	16	388.3	331.3	57.0			

Tab. 3-1: Borehole datasets of core and borehole images.

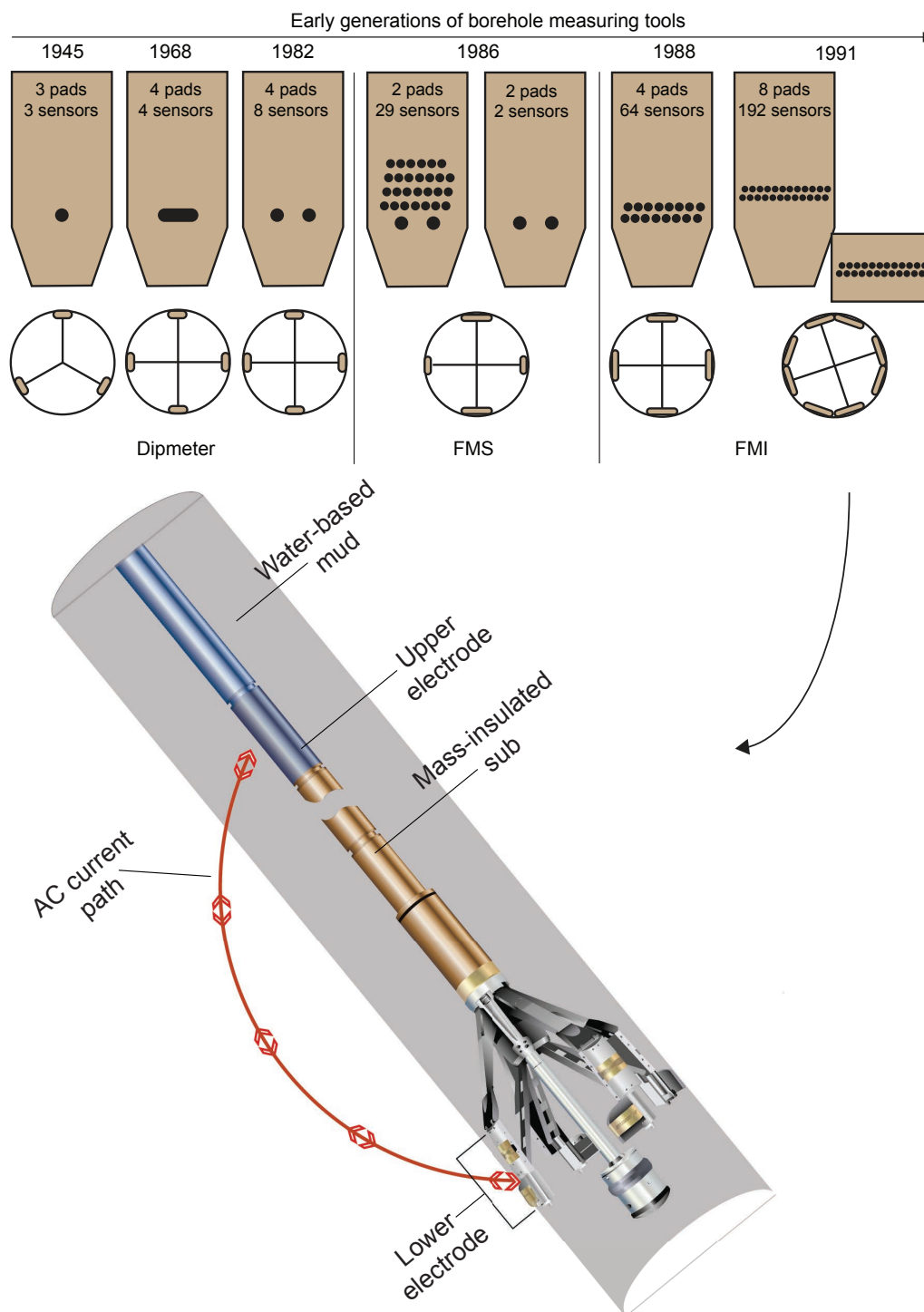


Fig. 3.11: The electrical borehole imagers (FMS and FMI) and the concept of electrical measurements, modified from Oil Field publications of Schlumberger.

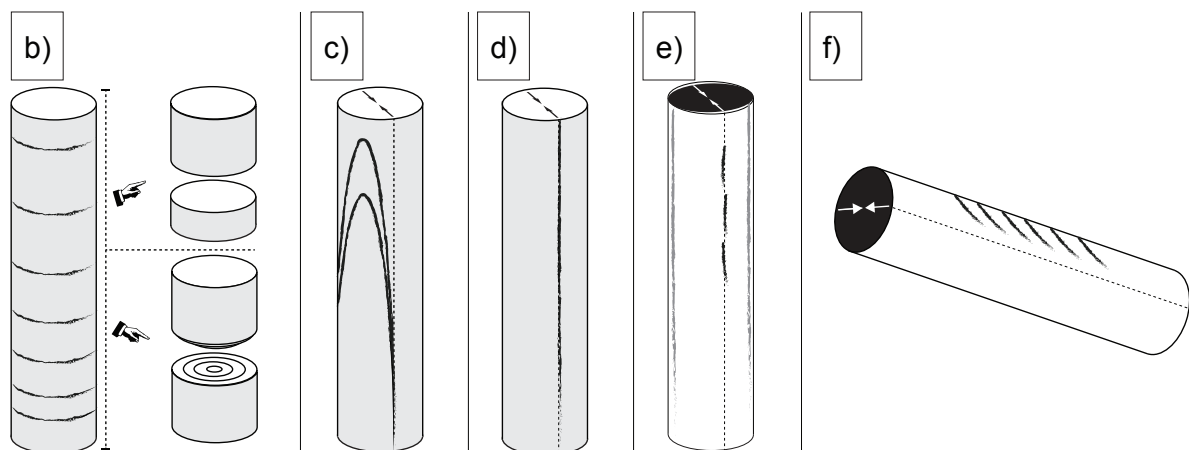
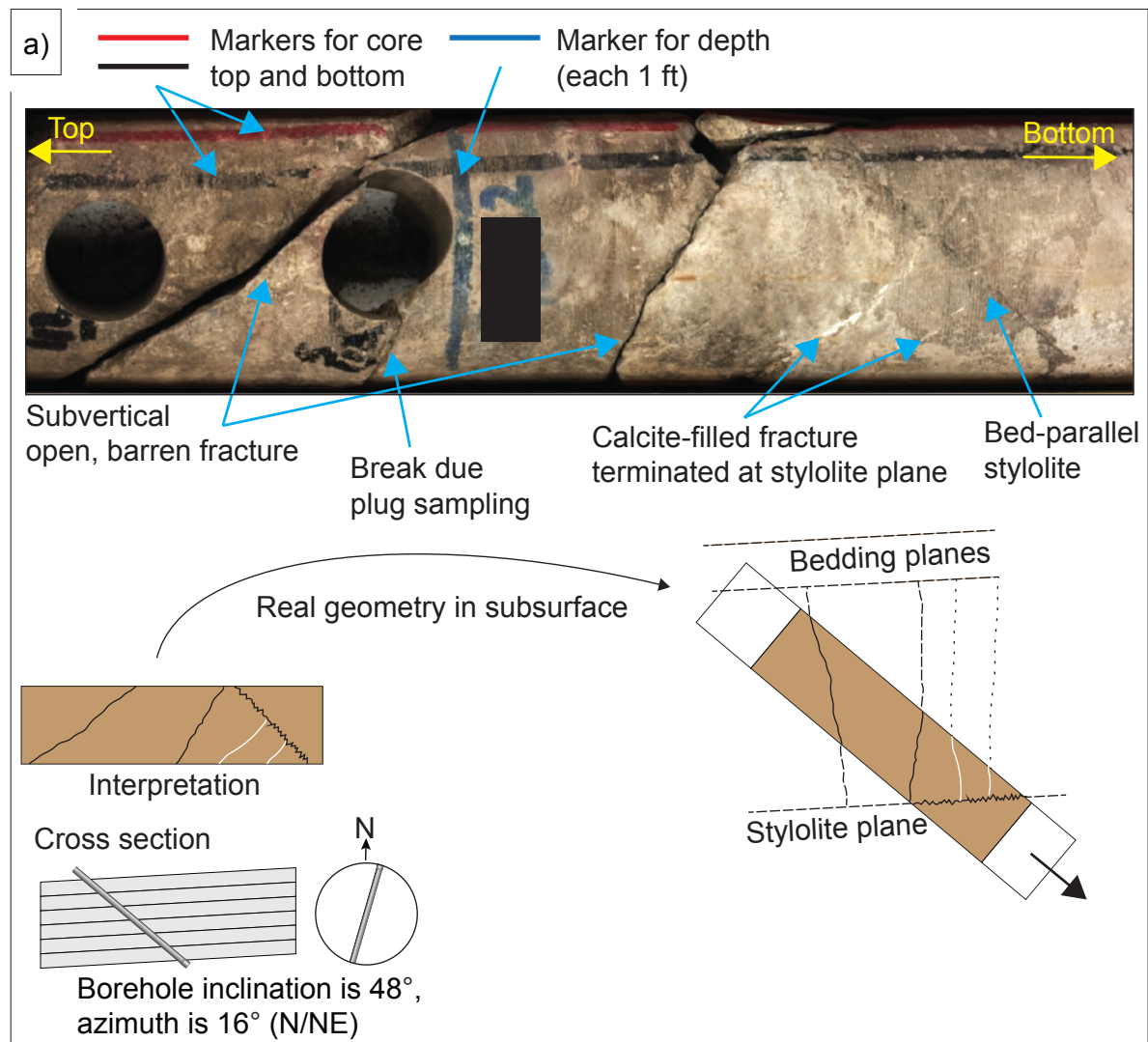


Fig. 3.12: Interpretation of core and borehole images.

a) Geologic features in core samples and the markers used on the core; b–f) typical types of drilling-induced fractures (DIFs); b) core diskings, which typically develops as flat surfaces and sometimes as cup-shaped diskings (lower hand pointer); c) core petal fractures, which grow from the core edge toward the core bottom; d) centerline fractures; e) breakouts (gray), tensile wall-fractures (black); f) tensile en echelon wall-fractures in deviated boreholes. The graphs are drawn to reflect models presented in numerous papers in the geoscience literature (e.g., Zheng et al., 1989; Kulander et al., 1990; Aadnøy and

Bell, 1998; Li and Schmitt, 1998; Haimson and Cornet, 2003; Jia et al., 2013).

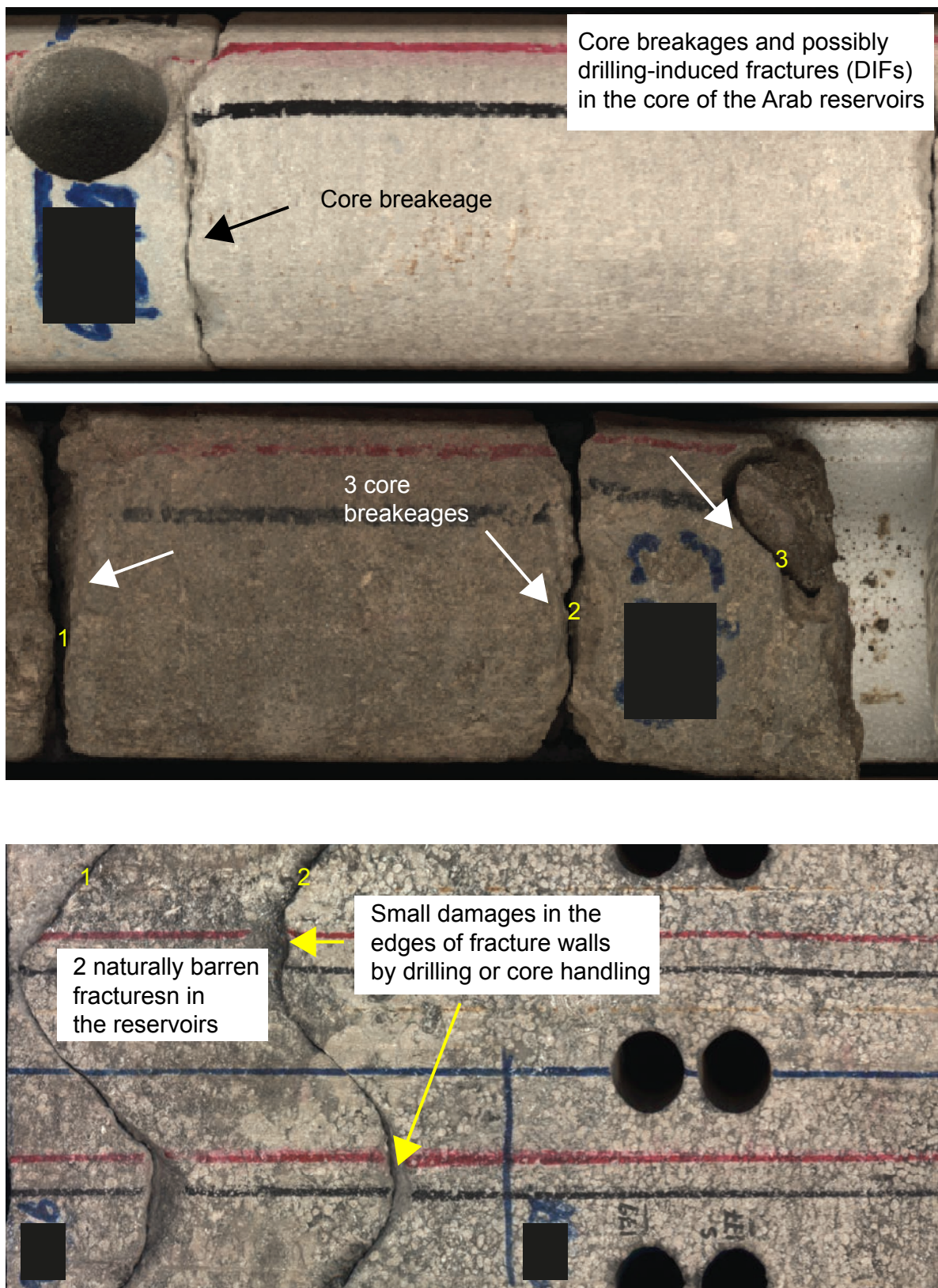


Fig. 3.13: Core pictures display some of the geometrical criteria used to differentiate between the reservoir fractures and the core breakages induced by drilling or core handling. The lower picture also shows the small damages in the edges of the barren fractures. These damaged fractures were excluded from the measurements of fracture size, roughness, and wall mismatch.

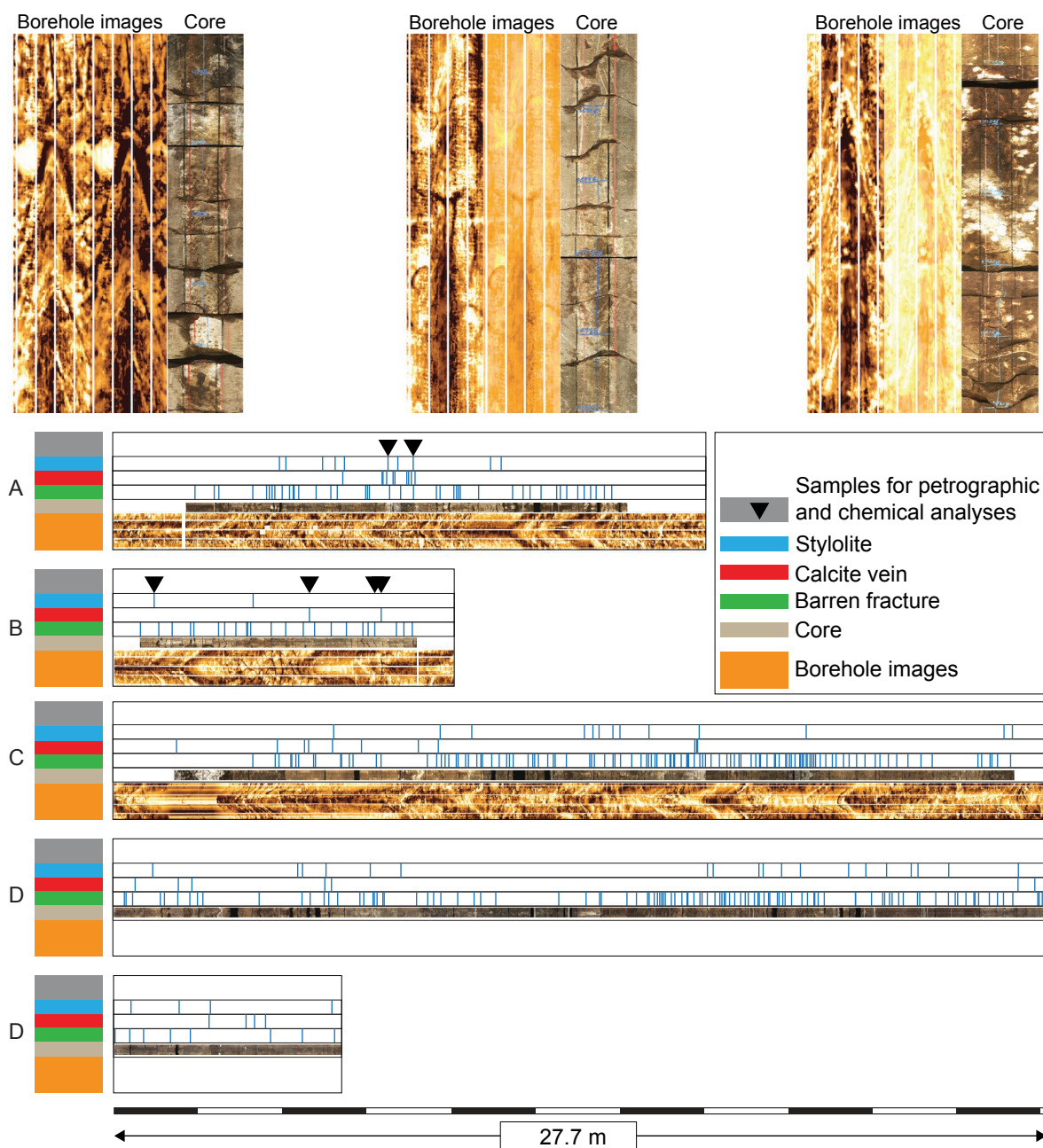


Fig. 3.14: Examples of layouts for core tied with borehole images that are compared for fracture descriptions.

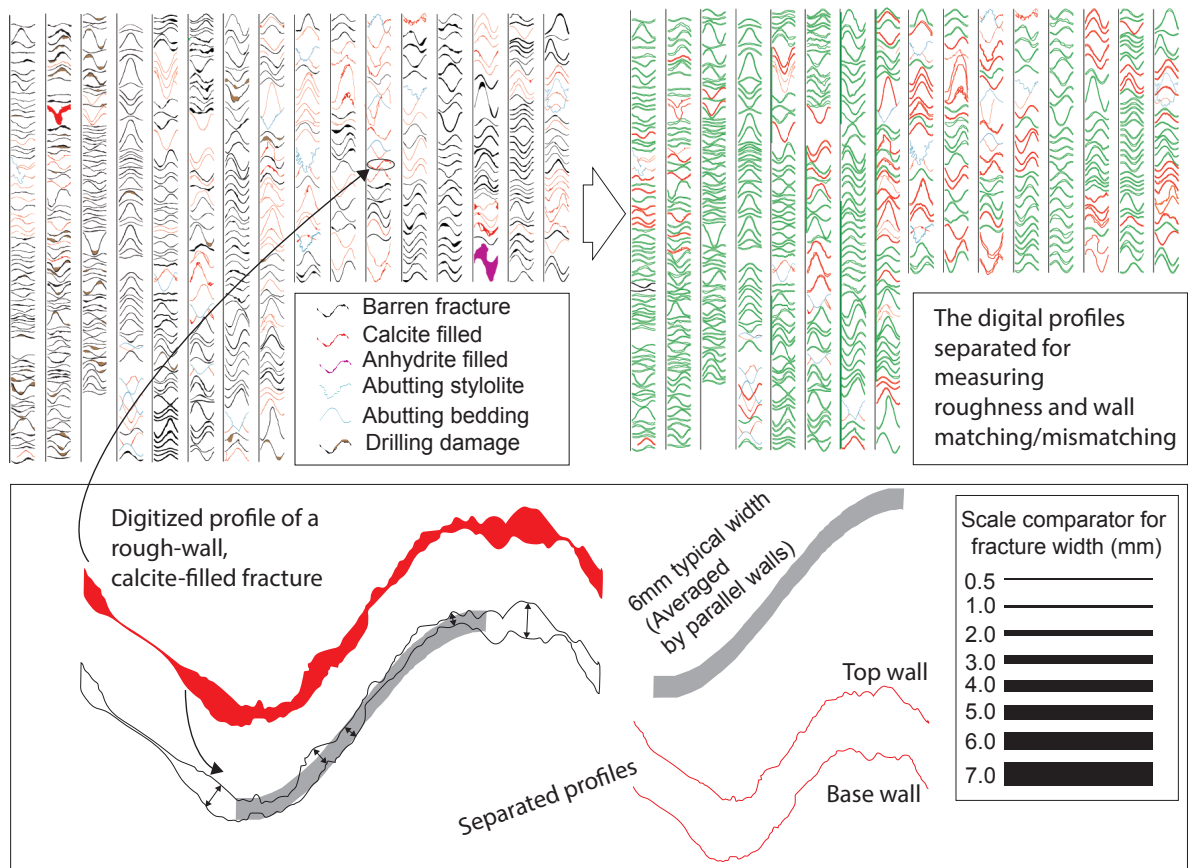


Fig. 3.15: The profiles of barren fractures and veins digitized from the optical scan of close-fitting core and used for size and roughness, and wall mismatch measurements. Below, a diagram displaying an example of measuring width of a rough calcite vein.

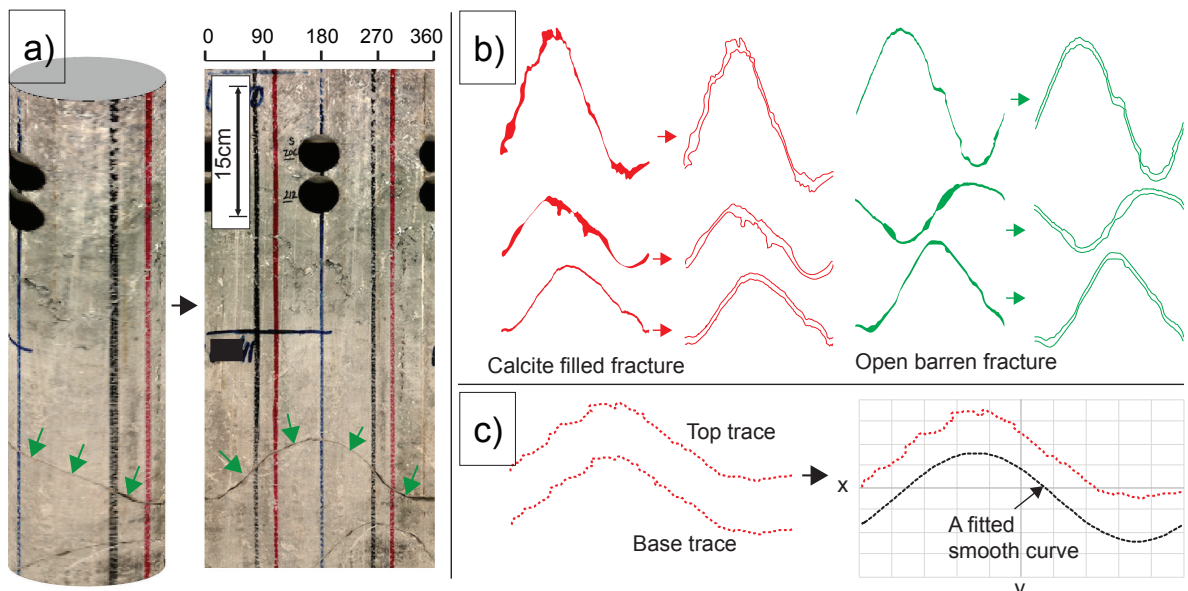


Fig. 3.16: a) Photographs display a core sample with a barren fracture (green arrows) and the core sample as unrolled from the 360-degree photographic scan; b) six examples of digitized profiles of veins and barren fractures and their separated top and base profiles; c) a simple sketch demonstrates how a fracture digital profile is used to measure roughness by computing the Z_2 statistical parameter of the profile deviations in x-y dimensions from a fitted smooth curve of zero roughness.

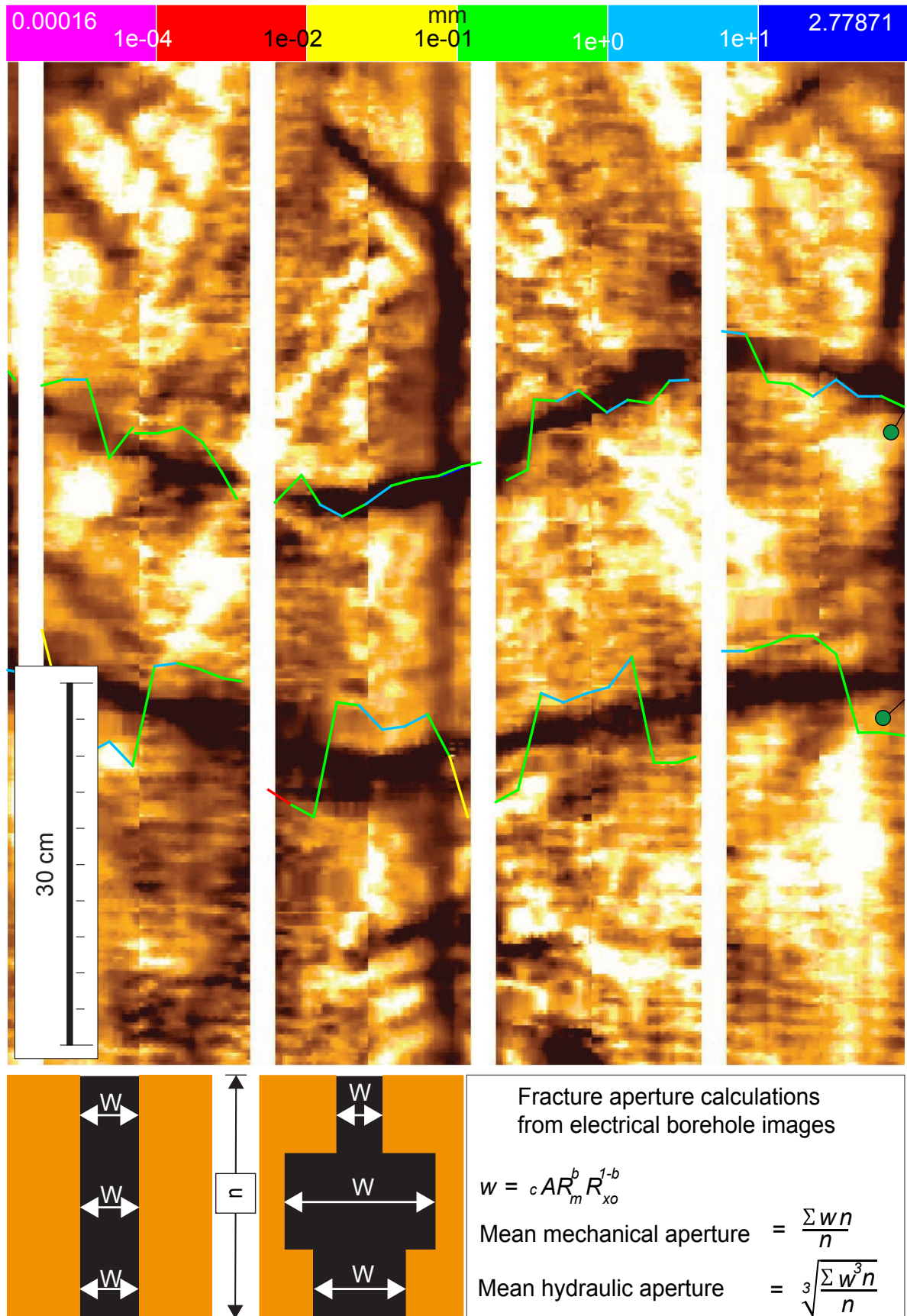


Fig. 3.17: a) The method of measuring mean sizes of mechanical apertures and hydraulic apertures for two barren fractures in the borehole images. The equations are described in the text.

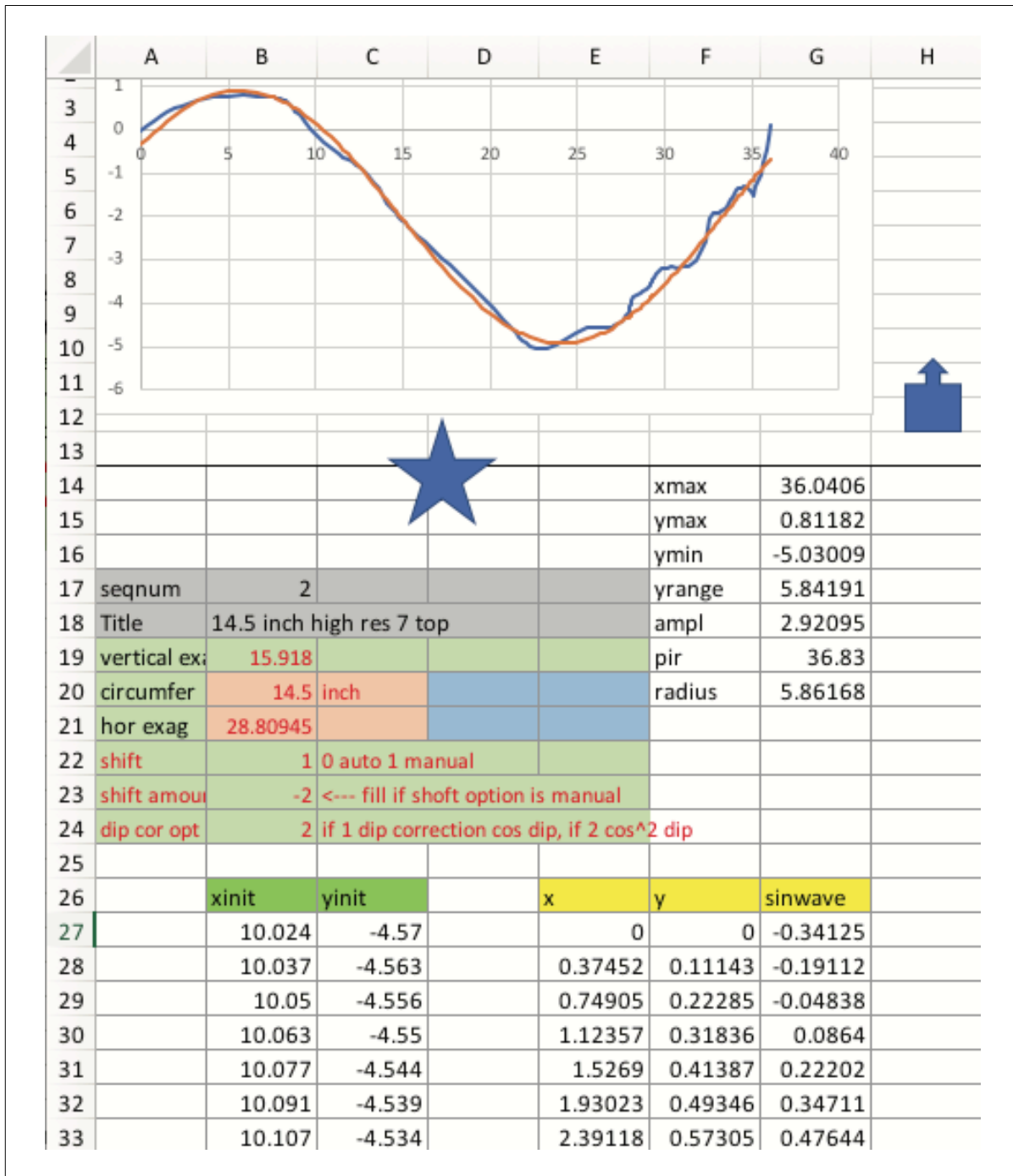
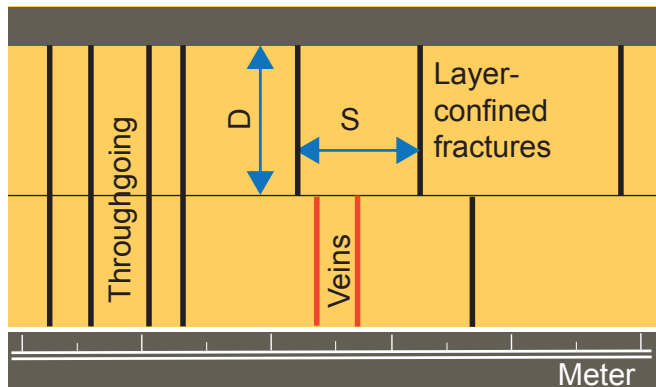
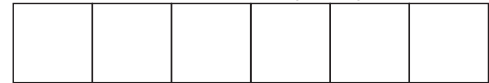


Fig. 3.18: Snapshot of the developed spreadsheet program used to compute fracture roughness.

Fracture spacing concepts



Balanced saturation ($S=T$)



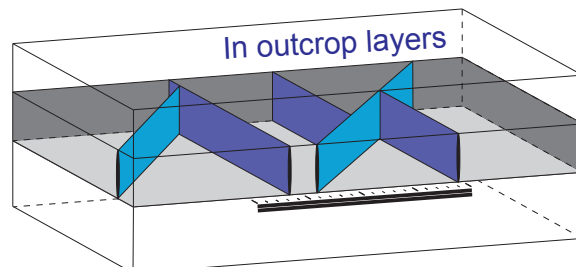
Over-saturation ($S<T$)



Under-saturation ($S>T$)

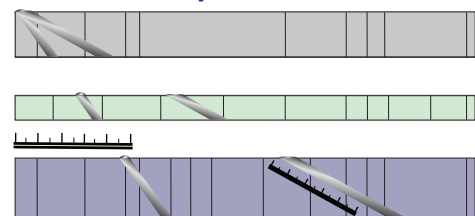


Fracture spacing



Fracture spacing is measured between all fractures intersected by scanlines parallel to the layer sections

In reservoir layers



Spacing is measured between fractures along boreholes (from core and borehole images)

Corrected spacing of fractures in core obtained from geometrical boreholes

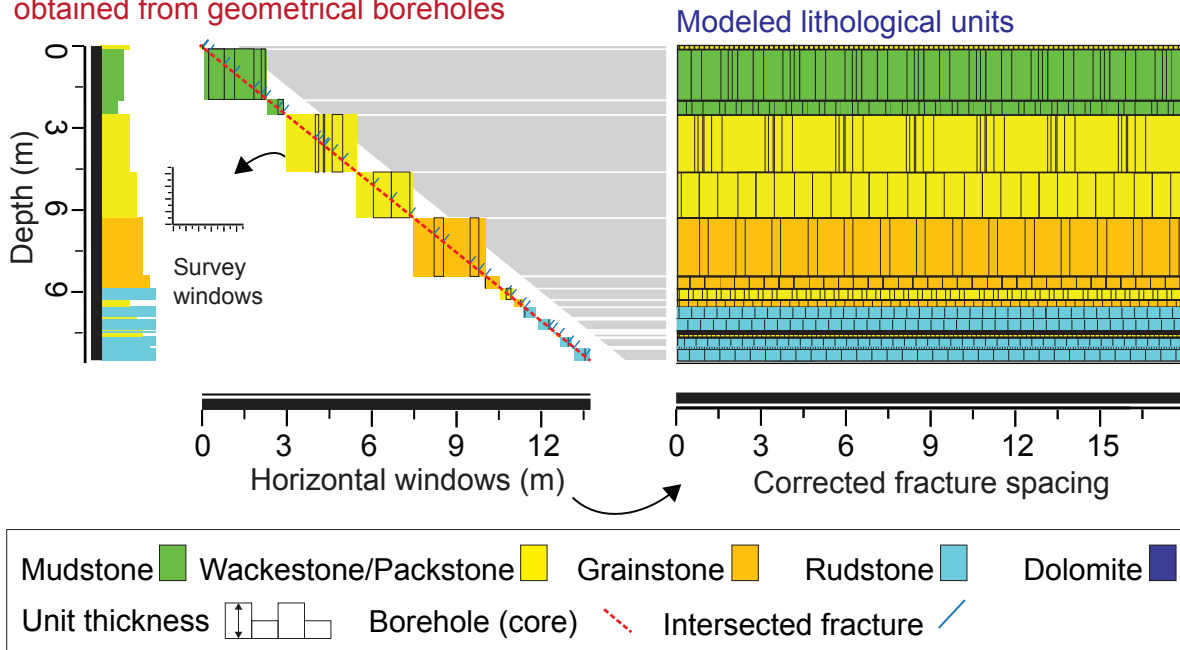


Fig. 3.19: Illustrations of the concepts and methods used in this research to describe fracture abundance in outcrops and subsurface reservoir rocks.

Depositional Texture recognizable					Depositional texture, not recognizable Crystalline carbonate (Subdivide on physical texture or diagenesis) Crystalline carbonate
Original components not bound together during depositions			Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices. Boundstone		
Contains mud (particles of clay and fine silt size)		Lacks mud, and is grain-supported			
Mud-supported					
Less than 10% grains	More than 10% grains				
Mudstone	Wackestone	Packstone	Grainstone		

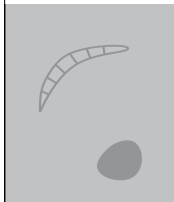
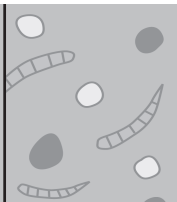
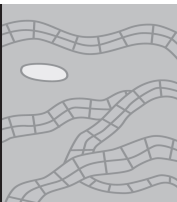
Mudstone	Wackestone	Packstone	Grainstone	Boundstone	Crystalline carbonate
					

Fig. 3.20: Dunham's classification of carbonate lithology, modified from Dunham (1962).

4

4 FRACTURE SYSTEMS AND THEIR ABUNDANCE IN THE ARAB CARBONATE RESERVOIRS AND OUTCROPS

ABSTRACT

Describing fracture properties is essential to categorize fracture systems and relate their abundance in carbonates. This chapter includes descriptions of fractures and their abundance in exhumed and buried areas of the Arab carbonates in Eastern and Central Arabia. The areas are part of the nearly flat Arabian Platform interior, which has been considered less susceptible to fracturing than the platform margins. Fractures in the buried Arab carbonates were described from a low-relief dome, in which the Arab carbonates (A, B, C, and D) are major reservoirs. Fractures were also described from the Arab-D carbonate outcrops in two regions located in the homocline, to the north and south of the CAG region. Many systematic characteristics were drawn on mineralization, orientation, and abundance of fractures, although some exceptions occur. About 80% of the reservoir fractures in the dome are barren; the remaining are calcite veins. The two fracture systems are opening mode of subvertical dips to the gently dipping strata. The barren fractures

mostly strike toward the NW–SE, NE–SW, and E–W azimuths. These orientations are consistent with the major systems of barren fractures that were previously documented in Eastern Arabia. The fractures in the outcrops in the homocline are opening-mode, barren, subvertical, and mostly confined to the flat host layers. They exhibit three dominant strikes, NW–SE, NE–SW, and E–W, which indicate trends of regional systems in the Arabian Platform interior. Although fractures occur ubiquitously in the Arab carbonates, the outcrop fractures are notably less abundant than the reservoir fractures. The described properties of the fractures led to identifying the major fracture systems and evaluating their relative abundance in the platform of the Arab carbonates as a case study for gently deformed carbonates.

4.1 INTRODUCTION

This chapter includes measurements and descriptions of fracture systems and their abundance in areas of the Arab reservoirs and outcrops described in Ch. 2.6 and Ch. 3.3.

In brief, fractures, lithology, bedding planes, stylolites, and drilling-induced fractures (DIFs) were described from the reservoir datasets (core and borehole images), using the methods described in Ch. 3.3. The presented descriptions of fractures include mineralization or lack of thereof, orientations, mode of displacement, and abundance. The outcrop fractures were described on each site for mineralization (if mineralized or barren), dip, strike, height, and displacement mode. The descriptions of the reservoir and outcrop rocks include measurements and relationships between fractures and thickness, and lithofacies of rock layers.

The results on fracture properties were presented in illustrations and statistical charts to facilitate comparison between different dataset types, boreholes, and study areas in the Arab carbonate platform. This approach helped to evaluate variabilities in the described fracture properties, specifically in the nature of fracture mineralization, orientation, and abundance. The prevalence of certain properties was used to identify a system, or multiple systems, of fractures. The levels of variability in measurements that cannot be resolved from the datasets, especially core and borehole images, were overlooked in this chapter to focus on first-order categories, described in Ch. 3.2.

4.2 RESULTS: PROPERTIES OF ARAB RESERVOIRS

4.2.1 Bedding, Stylolite, Borehole Breakages, and Lithofacies

The layers of the Arab reservoirs (A, B, C, and D) generally dip toward southwest (SW) with dip angles mostly less than 10° in the study area of the dome. These dips are averaged from measurements of 1473 bedding planes from the four borehole images (Fig. 4.1). The reservoir layers also exhibit less common dips between 10° and 20° .

Stylolites were commonly observed in the Arab reservoirs, especially in the core because the signatures of stylolites were difficult to distinguish in borehole images (Fig. 4.2). Only 23 stylolite planes were recognized in the long sections of the borehole images, against 103 stylolite zones in the core sections (Fig. 4.2). The stylolite planes in the core were found to be parallel, and their teeth normal, to the reservoir bedding planes. The orientation measurements using the borehole images show that the stylolite planes dip toward the SW with dips mostly less than 10° (Fig. 4.1). The 103 stylolites that were identified in the core were also observed to be bed-parallel.

The SW azimuth of the bedding and stylolite planes is consistent with the geological mapping of the southwest region of the dome (see Fig. 2.10 in Ch. 2). The bedding dips in the borehole images are generally higher than the bedding dips estimated about 5° from geological mapping. The high dips of the reservoir layers from the borehole images are typical errors associated with borehole imaging measurements (see Ch. 3.3.3.2).

Some sections of the borehole walls display small (typically between 30- and 50-cm long) tensile wall fractures (TWFs). The total number of the TWFs from the four boreholes is 361. The TWFs are, however, more abundant in X-01 and X-04 than in X-02 and X-03. The four boreholes do not show any sign of breakouts. Many core breakages were identified; some appear to be resulting from loss of cohesion of high-porosity and soft rock intervals. Some of the core breakages were connected to some barren fractures. The orientations of the TWFS display a dominant E–W to NE–SW azimuth (Fig. 4.1). These orientations are consistent with the present-day S_{Hmax} in Eastern Arabia (e.g., Ameen et al., 2010).

The sequences of the Arab reservoirs are divided into several lithological units and zones,

using the methods described in Ch. 3.3.3.3 (Fig. 4.3, Fig. 4.4, and Fig. 4.5). The Arab A reservoir is divided into 12 lithological units. The lithological units make up three zones in the reservoir: Zone 1, 2, and 3, in descending stratigraphic order. Zone 1 is composed of mostly crinkled and bioturbated mudstone with lamina of wackestone and peloidal packstone. Zone 2 is composed of packstone and grainstone of vuggy, ooidal, and peloidal facies. Zone 3 is composed of mainly skeletal, stromatoporoid, peloidal rudstone, and small intervals of packstone lithofacies.

The sequence of the Arab B reservoir is divided into six lithological units. These units make up two distinct zones in the reservoir, Zone 1 (upper) and Zone 2 (lower). The upper zone is composed of vuggy, ooidal, peloidal grainstones and slightly dolomitized grainstones. The original limestone fabrics were preserved where the dolomitization developed. The lower part of the Arab-B reservoir is composed of dolomitized limestone of peloidal and cryptal algal packstone lithofacies.

The sequence of the Arab C reservoir is divided into 32 lithological units. The units make up four zones, Zone 1, 2, 3, and 4, in descending stratigraphic order. Zone 1 is composed of mainly mudstone to wackestone lithofacies. The zone includes intervals of limestone of dolomitized, ooidal, and peloidal facies. Zone 2 is composed of vuggy, ooidal, peloidal limestone of well-bedded packstone with some grainstone lamina of high porosity, exceeding 20%. Zone 3 is conductive vuggy, ooidal, peloidal limestone of high porosity, exceeding 30%. Zone 4 is composed of mostly cryptal algal limestone with high percentage of dolomitization, reaching 50%.

The sequence of the Arab D reservoir is divided into 38 lithological units that make up nine zones of facies, from Zone 1 to Zone 10 in descending stratigraphic order. Zone 1 is mainly composed of an alternation of mud-supported limestone layers of mudstone, wackestone, and dolomitic packstone lithofacies, and less presence of grainstone lithofacies of dolomitic limestone. The zone is of relatively low porosity (8–12%). Zone 2 is composed of mainly mudstone lithofacies of dolomitic limestone and minor presence of intraclastic and skeletal grain-supported lithofacies of rudstone. Zone 3 is composed of mainly porous dolomite of variable porosity that exceeds 15% in most intervals. The lower intervals of this zone are composed of dolomitic limestone of muddy facies. Zone 4 is composed of extensively vuggy facies of skeletal intraclastic

rudstone. This zone is of very high porosity, exceeding 25%. Zone 5 is composed of mostly units of packstones and subordinate units of vuggy skeletal intraclastic rudstone. Zone 6 is composed of mostly rudstone units and subordinate units of grainstones. Zone 7 is mainly composed of units of packstone and grainstone limestone, and less common mud-supported facies of mudstone toward the lower part of the zone. Zone 8 is composed of highly porous (sucrosic) dolomite and dolomitic limestone facies. Zone 9 is composed of mainly mudstone and dolomitic limestone of fine-grained lithofacies.

The average porosity is relatively lower in mud-dominated lithofacies because of the dominance of mud contents and absence of large pore systems in the rock matrix. The grain-supported lithofacies and dolomite display higher porosity because of the presence of vugs, connected vugs, intraparticle pores, and interparticle pores. The dolomitic zones of the reservoirs are generally very porous, with porosity higher than 15%. The measured porosity and permeability of the reservoir lithofacies in the laboratory are very variable, displaying a range of 5–30% for porosity and 1–1000 mD for permeability (Aramco internal report).

The Arab reservoir lithofacies types were deposited on a large ramp, with variations in depositional environments, which are reflected in the different lithofacies ranging from mud-supported to rudstones. The lithofacies of the Arab-A reflects mostly lagoonal environments. Arab-B was mostly deposited in a shoal depositional environment. The thick reservoirs (Arab-C and Arab-D) display varieties of lithofacies, and hence reflect changes in the depositional environments between outer, inner, and mid-ramp lithofacies. These include lagoon, tidal flat, and shoal facies.

4.3 RESULTS: PROPERTIES OF ARAB RESERVOIR FRACTURES

4.3.1 Presence and Absence of Mineralization in Fractures

Fractures were observed and interpreted in the core and borehole images of the Arab reservoirs (A, B, C, and D) as barren and mineralized, according to the criteria described in Ch. 3.2.1 and Ch. 3.3.3.1.

4.3.1.1 Barren Fractures

The barren fractures part the core and exhibit no filling minerals or traces of mineral cement on the fracture walls (Fig. 4.6). Their walls exhibit the fabrics of the host rocks and oil stains in the porous rock intervals.

In the borehole images, the barren fractures appear as conductive (dark) planar features that indicate the infiltration of drilling mud into the fracture apertures (Fig. 4.7). Their apertures exhibit no trace of resistive minerals. These fractures are interpreted as barren-open, because they display conductive (open) apertures in the borehole images and correspond to barren fractures in the core.

4.3.1.2 Mineralized Fractures

Mineralized fractures in the core are veins of minerals that are distinguishable in true color and texture from the minerals of their host rock (Fig. 4.8). The veins can be traced along the whole circumference of the core. Some of the veins terminate at the bedding and stylolite planes in the core. The core was not parted along the veins, indicating that the filling minerals strongly bond surrounding rock walls. The filling mineral of the veins is calcite, except for a relatively large vein that was found to be filled by anhydrite (Fig. 4.9). The filling degree of the calcite mineralization is full in the veins, leaving no obvious pores. Calcite minerals (cement) were also observed to be filling the matrix pores in the rock intervals hosting the calcite veins.

In the borehole images, the mineralized fractures appear as resistive (light) planar features that cut the bedding planes of host rocks (Fig. 4.10). The mineralized fractures appear as resistive (impermeable) to the infiltrating drilling mud (Fig. 4.10). They exhibit no pores (i.e., no dark conductive features) along their traces (Fig. 4.10). The mineralized fractures were identified to be calcite veins from corresponding core intervals.

4.3.2 Orientations of Reservoir Fractures

4.3.2.1 Barren Fractures

Barren fractures in the core exhibit subnormal dips (about 90°) to the rock bedding planes

(Fig. 4.11 and Fig. 4.12). The fractures were noted as sets of parallel planes in the core. The parallel planes reflect similar dips and strikes in the core and borehole images (Fig. 4.6).

The barren-open fractures in the borehole images dominantly dip with angles higher than 80° (Fig. 4.13 and Fig. 4.14). The strikes of fractures have certain ranges that need to be described here from each borehole (Fig. 4.13 and Fig. 4.15). From boreholes X-01 and X-02, the barren fractures exhibit a range of strikes between 90° and 180° , but most fractures strike around 130° . From X-03, the barren fractures range from 40° to 180° , and most of the fractures strike NW–SE between 110° and 150° . From X-04, the strikes of the barren fractures range from 30° to 180° , with two dominant strikes between 70° – 90° and 140° – 160° , respectively. The barren fractures from X-03 and X-04 exhibit a range of strikes that is wider than the strikes of barren fractures from X-01 and X-02.

4.3.2.2 Mineralized Fractures

The calcite veins in the core mostly exhibit high dip angles (70° – 90°) to the bedding planes (Fig. 4.11 and (Fig. 4.12). The branches of calcite veins are inclined to the bedding planes displaying lower angles of dips, in the range of 50° and 60° .

The veins in the borehole images mostly exhibit dips of high angles greater than 70° (Fig. 4.16). The majority of the calcite veins in the borehole images display different strikes, ranging between 80° and 130° . In X-01, seven veins were interpreted, two of which strike nearly north–south, and other five strike northwest–southeast between 100° and 140° . In X-02, only one vein with a large width was observed with strike of 140° azimuth. In X-03, 24 veins were interpreted, with strikes ranging between 60° and 170° . Their histograms display peaks at 90° and 110° , although there are no obvious dominant angles for strikes. In X-04, 20 veins ranging in strikes between 30° and 150° were interpreted, and without obvious dominant angles for strikes. The combined probabilistic plotting of veins from all boreholes shows that most of these fractures range in strikes between 80° and 130° .

4.3.3 Mode of Displacement

The barren fractures and calcite veins were observed to cut the rock bedding markers in

the core and borehole images without signs of shear displacement (see Fig. 4.17, Fig. 4.18, and other figures in this chapter). The fractures were observed as layer discontinuities that did not result in displacing bedding, lamina, and stylolite planes in normal or strike slip directions. The barren fractures and veins were accordingly interpreted as opening-mode fractures.

4.3.4 Petrography and Chemical Analyses of Calcite Veins

4.3.4.1 Petrography of Calcite Veins

Analyses of sampled thin sections of mineralized fractures and their host lithology resulted in some common characteristics, although there were several notable exceptions. The systematic features of the described mineralized fractures are as follows. The mineralized fractures were identified to be calcite veins, except the case of the anhydrite vein presented in Fig. 4.9. The mineralization of the calcite veins was complete between the fracture walls, with no obvious macro- or microporosity in the vein bodies. The pores in host rocks are completely filled with calcite cements. These host rocks are of wide-ranging lithofacies of mudstones, packstones, and grainstones (Fig. 4.19, Fig. 4.20, and Fig. 4.21).

The calcite veins have varying textural features. Specifically, the crystals of calcite veins vary in shape and size (Fig. 4.19, Fig. 4.20, Fig. 4.21, and Fig. 4.22). The crystals range from small (10 micron) equant crystals to elongated 100-micron crystals. The textural features do not seem to display any correlation with host rock lithofacies. Furthermore, variations in shape and size of calcite crystals exist in the same vein and within the small dimension of a thin section (<40 mm). The elongated crystals do not exhibit preferred orientations to the orientations of veins or host rock walls. Some veins are linked to, or associated with, micro (hairline) veins that are filled with micro calcite cement.

Calcite veins exist frequently in intervals that include stylolite zones. Where the core displays intersections of a calcite vein and a stylolite plane, the calcite veins are of two types: terminating at the stylolite and crossing the stylolite (Fig. 4.8 and Fig. 4.17). The intersections between calcite veins and stylolite zones display that the calcite cements are mixed with the stylolite organic-rich (black) materials (Fig. 4.23 and Fig. 4.24). The extent of the mixing zones

varies between 1 mm and 2 mm. The organic materials of the stylolite zones do not extend into the main calcite veins away from the intersections. The calcite veins appear as of pure calcite cements away from these intersections. The stylolite zones include the calcite cements in various shapes and sizes, with no specific crystal size, shape, or orientation for the sampled intersections. Some calcite veins are connected to the stylolite through micro veins and the rock matrix pores filled by calcite cements. The main bodies of the calcite veins exist with normal dips to the stylolite planes, which are bed parallel. Core orientations indicate that the veins exist below the stylolite zones (i.e., extending downward) (Fig. 4.11).

4.3.4.2 Chemical Analyses of Calcite Veins

The calcite veins display negative (light) oxygen isotope values (-3.5 to -8.3‰ $\delta^{18}\text{O}$) and positive (heavy) carbon isotope values (2.1 to 3.1‰ $\delta^{13}\text{C}$) (Fig. 4.25, Tab. 10-1, Tab. 10-2, and Tab. 10-3). The vein isotopic signatures are generally similar to those of the Arab-D reservoirs in Ghawar and Abu Dhabi (Cantrell et al., 2001; Swart et al., 2005; Morad et al., 2012), and different to those of the Arab-D and Jubaila outcrops (Eltom et al., 2014). Swart et al. (2005) reported that the dolomite in the Arab-D reservoir in Ghawar displays a wide range of $\delta^{18}\text{O}$ values, between -1 and -6.5‰ , and a narrow range of $\delta^{13}\text{C}$ values, between $+1.5$ and $+3.5\text{‰}$. By comparison, the calcite veins display a similar range of $\delta^{13}\text{C}$ values, and a narrower range of low $\delta^{18}\text{O}$ values, between -4 and -8‰ .

The $^{87}\text{Sr}/^{86}\text{Sr}$ values of the calcite veins are mostly between 0.7069 and 0.7071 , which is the same range of values as those of their host rocks and stylolite material (Fig. 4.26). The $^{87}\text{Sr}/^{86}\text{Sr}$ values display a trend that is relatively decreasing with increasing depth of the samples. A similar trend, although much weaker, appears in a previous study on the Hith and Arab reservoirs (A, B, C, and D) (Azer and Peebles, 1998) (Fig. 4.26).

This depth relation is expected, because deeper reservoir rocks are older (i.e., of low $^{87}\text{Sr}/^{86}\text{Sr}$ values according to the curves of the Late Kimmeridgian seawater) than shallower reservoir rocks. The depth relation could not be quantified from the dataset, but it was used qualitatively in two hypothetical scenarios, S1 and S2 in Fig. 4.26. In S1, the samples are assumed

to linearly span the Late Kimmeridgian only. In S2, the samples are linearly aligned to the curve slopes of the Late Kimmeridgian. The higher values (green bar) in S1 and S2 suggest the age of the vein cements is Early Tithonian, which may indicate diagenetic dissolutions in the Early Tithonian. The lower values in S2 suggest the age of some vein cements is Middle Kimmeridgian, which is a possible age for the rocks at the lower section of the Arab-D reservoirs.

4.3.5 Abundance of Reservoir Fractures

The total number of interpreted fractures from the core is 665 barren fractures, 153 calcite veins, and 1 anhydride vein. The total number of fractures interpreted from borehole images is 2124 open-barren fractures and 52 calcite veins. The number of fractures per length of the boreholes is presented in Fig. 4.27 and Fig. 4.28 from the core and borehole images.

4.3.5.1 Comparing the Abundance of Barren and Mineralized Fractures

Some general observations can be made on fracture abundance from examining Fig. 4.28, despite the difference in observations between the core and borehole images.

Firstly, barren fractures are clearly the dominant fracture system. This is clear from correlating observations according to the type of dataset (core and borehole images), borehole (X1, X2, X3 and X4), and reservoir (A, B, C, and D). The ubiquity of barren fractures indicates the following: the longer the sampled sections of the borehole, the more fractures are expected to be intersected regardless of borehole orientation, type of reservoir lithofacies, and method of observation (whether core or borehole images).

Secondly, comparing the abundance of barren fractures between boreholes, cores, and borehole images indicates some variability. These domains of investigation do not yield the same number of fractures. The barren fractures are more abundant in the core of X-01 than in the core of X-03. The barren fractures in the borehole images of X-04 are more abundant than those in the images of other boreholes.

The number of mineralized fractures that were interpreted from the core and borehole images is small relatively to the number of barren fractures. But the mineralized fractures were found in the four Arab reservoirs (A, B, C, and D). The following observations can be made

regarding their abundance:

- 1) The mineralized fractures described from the core are all calcite veins, except one anhydrite vein.
- 2) The mineralized fractures described from the core are calcite veins, where there was equivalent core. The others were interpreted as calcite veins based on their similar resistive and geometrical properties in the borehole images.
- 3) The abundance of calcite veins is relatively high in the core of the Arab-D that was obtained from X-03 and in the Arab-B borehole images of X-01. The veins were not observed in the borehole images of X-02.

4.3.5.2 Fracture Spacing along Boreholes

Measurements of spacing between barren fractures along the core are presented in Fig. 4.29.

The following observations can be highlighted from this spacing statistical model:

- 1) Fracture spacing is dominantly less than 1 m along the core of X-01 and X-03.
- 2) The cumulative distributions of the fracture spacing along the core show that 80% of the fracture spacing is less than 50 cm in X-01 and 70 cm in X-03.
- 3) The mean value of fracture spacing from the core is 35 cm.

Measurements of spacing between barren fractures along the borehole images are presented in Fig. 4.30 and Fig. 4.31. The following observations can be highlighted from the obtained frequency distributions:

- 1) Fracture spacing is dominantly below 30 cm along the four borehole images of X-01 and X-03.
- 2) Measurements from short reservoir sections (A and B) are more difficult to fit to a model than measurements from the longer sections (C and D).

The spacing measurements along the core and borehole images demonstrate some agreements and differences. The spacing that is based on the core observations is slightly different, apparently because the two cored boreholes have different orientations and inclinations. The frequency distributions of spacing measurements from borehole images vary according to the

length of the imaged sections and reservoirs. The spacing does not seem to be affected by borehole orientation.

4.3.5.3 Fracture Corrected Spacing

Fracture spacing along boreholes is corrected to be described according to the lithofacies of host layers (see Ch. 3.3.3.6). The following observations can be made about fracture abundance according to the modeled lithological units:

- 1) The barren fractures and calcite veins were observed in all carbonates types, from muddy to grainy lithofacies, and from tight to porous rock intervals (Fig. 4.32 and Fig. 4.33).
- 2) The calcite veins display low abundance in all types of rock lithofacies.
- 3) The abundance of the calcite veins displays no obvious relationships to the reservoir lithofacies (Fig. 4.33).
- 4) The barren fractures are more abundant in the mud-supported limestone than in grain-supported limestone (Fig. 4.33). The results indicate that fracture abundance increases toward the muddy lithofacies to reach about three fractures per meter, which is equivalent to about 33-cm fracture spacing. By comparison, the rudstone lithofacies displays the lowest fracture abundance of about one fracture per meter, and the dolomite lithofacies displays a median value of about two fractures per meter.
- 5) The spacing values of barren fractures have an arithmetic means of about 31 cm and standard deviations of 24 cm (Fig. 4.34).
- 6) Fracture spacing measurements do not show linear relations to the modeled unit thicknesses (Fig. 4.34). These thicknesses are not equivalent to the mechanical thicknesses in outcrops.

4.4 RESULTS: PROPERTIES OF ARAB-D OUTCROP FRACTURES

4.4.1 Wadi Malham Sites

The outcrops at Site 1 and Site 2 display an alternating sequence of competent and non-competent carbonate layers. The rock layers formed terraces due to their different resistance to

weathering conditions. The top and base boundaries of the layers are well defined for measurements of fractures and layer thicknesses.

The competent layers consist of grain-supported limestone and dolomite lithofacies. The competent layers are part of the Arab-D member that makes up the tops of the terraces. The non-competent units consist of mud-supported lithofacies of limestone that typically exists at the lower section of the outcrops. These are part of the lower Arab-D and Upper Jubaila.

The surveyed outcrop sequences are conformable and exhibit no faults, folds, or karst along a distance of several kilometers along two sides of Wadi Malham. Most of the surveyed layers are traceable for long distances and display the typical layer-cake stratigraphy of the Arab carbonates in the Arabian Platform (e.g., Azer and Peebles, 1998; Al-Nazghah, 2011).

4.4.1.1 Wadi Malham - Site 1

Barren fractures are common features of the outcrop layers. Mineralized fractures and stylolites were neither observed along the scanlines nor encountered in the other outcrop layers. Barren fractures typically cut the layers from the base to the top, and spatially extend across the top layer surfaces to either proceed and disappear under the overlain layers or terminate at other fractures.

The fractures are of vertical dips (mostly around 90°), normal to the flat strata of the outcrops. The azimuth of the fracture strikes varies, although the fractures display some orthogonal patterns in the tops of layers. The strike measurements of the fractures are presented in Fig. 4.35 and Fig. 4.36, from seven carbonate units: two mudstone layers, two wackestone-packstone layer, one grainstone layer, one rudstone layer, and one dolomite layer. These surveyed carbonate layers are not on top of each other; they are separated by other layers. The thicknesses of the scanned layers range between 0.6 m and 1.1 m (Fig. 4.35).

Although variabilities exist from one layer to another, the azimuth measurements demonstrate that the outcrops are mostly fractured by NE–SW, NW–SE, and E–W trending fractures. The NE–SW and NW–SE fractures are more abundant than the E–W trending fractures. The orientation of the outcrop axis is NE–SW, about 70° azimuth. The surveyed

outcrop is not a sharp straight cut, and some local changes exist along the trend of its axis.

The spacing between the fractures is irregular. The spacing measurements are presented in statistical distributions in Fig. 4.36. The figure demonstrates a wide range of spacing, from about less than 0.5 m to 5 m. The fracture spacing is generally greater than 2 m. The low values of spacing are between fractures at their crossing points or near crossing points. Intersections of two orthogonal fractures are frequently encountered along the scanlines. The intersections are commonly followed by greater spacing along the scanlines. A few cases of large spacing (> 5 m) are due to lateral changes in lithofacies: a reef buildup at Site 1, and heavily burrowed lithofacies at Site 2 (Fig. 4.37). Such lateral changes in lithofacies are uncommon for these carbonates because their layers are mostly laterally continuous in the field.

4.4.1.2 Wadi Malham – Site 2

Many of the described properties of fractures and lithofacies at Site 2 are similar to those described at Site 1. Site 2 is located about 1 km away from Site 1. The surveyed layers at Site 2 are not the same layers surveyed at Site 1.

Barren fractures are the most common features in the outcrops. Mineralized fractures and stylolites were neither observed along the scanlines nor encountered in the outcrops. Barren fractures have normal dips (mostly around 90°) to the flat layers. They typically cut the layers from the base to the top, and spatially extend across the top layer surfaces to either disappear under the overlain layers or terminate at other fractures. Measurements and observations of the fracture strikes display some orthogonal patterns from the different layers in the outcrop. The strike measurements of the fractures are presented in Fig. 4.35 and Fig. 4.36, from eight carbonate layers: three mudstone layers, three wackestone-packstone layers, one grainstone layer, and one dolomite layer. The thicknesses of the scanned layers range between 0.4 m and 0.9 m (Fig. 4.35). These scanned carbonate layers are not on top of each other; they are separated by other layers.

Similar to the layers at Site 1, the layers at Site 2 show some variability in the strikes of fractures from one layer to another, but the azimuth measurements demonstrate that the outcrops are mostly fractured by NE–SW, NW–SE, and E–W trending fractures. The NE–SW and NW–

SE fractures are more abundant than the E–W trending fractures. The orientation of the outcrop axis is NW–SE, about 290° azimuth. The surveyed outcrop is not a sharp straight cut, and some local changes exist along the trend of its axis.

The spacing of the fractures is variable along the scanlines. The spacing between the fractures is not regular. The spacing measurements are presented in statistical distributions in Fig. 4.36. The figure demonstrates a wide range of spacing, from about 0.5 m to 8.5 m. The fracture spacing is generally greater than 2.5 m. The low values of spacing are for the spacing between fractures at their crossing points or near crossing points. Intersections of orthogonal fractures are frequently encountered, followed by greater spacing along the scanlines. The spacing of 8.5 m between two fractures is occupied by a heavily burrowed lithofacies (Fig. 4.37). This lateral change in lithofacies was not encountered in other layers at the site. Most of the surveyed layers are laterally continuous in the outcrop.

4.4.2 Howtat Bani Tamim Sites

The Arab-D outcrops in Howtat Bani Tamim demonstrate a flat setting of multilayered carbonates of different lithofacies and thicknesses.

The outcrops display an alternating sequence of units that, due to their different resistance to weathering processes, formed small terraces. The boundaries of each mechanical layer are well defined for measurements of unit thicknesses.

The outcrop sequences are conformable and exhibit no faults or folds in the surrounding areas of the Shu'aib Allassaf, the gully. The lithofacies of the layers is limestones of fine-grained (mudstones) to course-grained (grainstones).

4.4.2.1 Howtat Bani Tamim – Site 3 and Site 4

Barren fractures are common features of the outcrop layers. Mineralized fractures and stylolites were neither observed nor encountered in the other outcrop. Barren fractures typically cut the layers from the base to the top. Some fracture clusters traverse multiple layers. All fractures found in limestone lithofacies are barren.

The fracture measurements are presented in Fig. 4.38 and Fig. 4.39 from seven limestone

layers: two mudstone layers, three wackestone-packstone layers, and two grainstone layers. The layers at Site 3 are the same ones at Site 4. The thickness of the layers ranges between 0.3 m and 1.1 m. The thickness of these surveyed layers changes slightly between Site 3 and Site 4.

The fractures are typically of vertical planes that are normal to the flat and horizontal strata. The rose diagrams in Fig. 4.38 and Fig. 4.39 display different orientations for fractures. The azimuth degrees of the fracture strikes are generally similar for each site. Fracture strikes at Site 3 display two dominant degrees of azimuth, NE–SW and E–W. Much fewer fractures were observed with NW–SE degrees of azimuth for their strikes. At Site 4, fracture strikes mostly display NW–SE azimuth. Other fractures strike toward NE–SW and E–W. Comparing the two sites indicates that fractures of NW–SE azimuth are rarely observed at Site 3, but observed in the same layers at Site 4. Fractures of E–W trends are also observed in small numbers at Site 4. The orientation of the outcrop axis at Site 3 is NW–SE, about 290° azimuth. The orientation of the outcrop axis at Site 4 is E–W, about 90° azimuth. Measurements of fracture strikes were affected locally by the orientation of the outcrop wall. But the measurements can be compiled for the sites, given that the measurements are made on the same layers. The compiled results demonstrate that the fractures in the two sites in Howtat Bani Tamim are of NE–SW, NW–SE, and E–W trends.

The statistical distributions in Fig. 4.39 demonstrate a wide range of spacing, from a few centimeters to about 5 m. Low values of zero (or nearly zero) spacing are for the spacing between fractures that were sampled by the scanlines at their crossing points. Site 4 includes a cluster of four throughgoing fractures that cut most of the outcrops. These throughgoing fractures are rare. The spacing between the outcrop fractures is irregular; the average fracture spacing is nearly 2 m.

4.4.3 Systematic Properties in the Arab-D Outcrop Fractures

The properties of the Arab-D outcrop fractures in Wadi Malham and Howtat Bani Tamim are presented in Fig. 4.40, Fig. 4.41, Fig. 4.42, and Fig. 4.43. The fractures are barren and exhibit subnormal dips to the host horizontal layers (Fig. 4.40). The compiled strikes of the fractures in the two regions display two primary sets of NE–SW and NW–SE fracture systems, in addition to a secondary E–W fracture system (Fig. 4.40). About 85% of the fractures are confined

to a layer, and the remaining cut through several layers to terminate above and below the host layers (Fig. 4.41). The spacing of the fractures is larger than the thickness of their host layers, except for the thin mudstone layers of less than 30 cm (Fig. 4.42). The spacing measurements display no linear relationship to the lithology or thickness of the host layers (Fig. 4.43). The abundance of the fractures is clearly undersaturated in these regions in the northern and southern limbs of the homocline (Fig. 4.43).

4.5 SYSTEMATIC PROPERTIES OF FRACTURES IN RESERVOIRS AND OUTCROPS

4.5.1 Presence and Absence of Mineralization

The Arab reservoirs in the dome are fractured by binary systems. Categorizing the fractures into more, or smaller, classes than the two categories of barren fractures and calcite veins was not possible for two reasons.

Firstly, analyses of the core, borehole images, and thin sections indicate that partially mineralized fractures do not exist in the reservoirs. Secondly, the reservoir rocks seem to lack veins other than calcite veins, and so no further categorization can be made based on mineral fill types. About 80% of the fractures are barren, and the remaining 20% are calcite veins (Fig. 4.44). This yields a 4:1 ratio, which is consistent with the proportion of dominant open-barren fractures to minor mineralized fractures, previously documented in the Arab, Hanifa, and Khuff carbonate reservoirs in Eastern Arabia (Ameen et al., 2010; Ameen, 2014; Alghamdi et al., 2016; and Aramco internal reports).

The Arab-D outcrops in the homocline in Central Arabia are fractured by an extensive system of barren fractures. Veins were not encountered in the outcrops in Wadi Malham and Howtat Bani Tamim, in the north and south of the CAG region. In the CAG region, previous studies reported that over 90% of the fractures are barren, and the remaining are calcite and gypsum veins in the outcrops of the Arab and other Mesozoic carbonates (Al Kadhi and Hancock, 1980; Abdilmutilib and Abdullatif, 2017). Given that the results of this research show limited occurrences of veins that are consistent with previous reports, fractures are expected to be mostly barren in the reservoirs and outcrops of the Arab carbonate platform.

4.5.2 Orientation

4.5.2.1 Fracture Dips

The barren fractures in the core and borehole images are consistently subvertical, with dips between 80° and 90° , regardless of the orientation and location of boreholes. Categories of inclined and bed-parallel barren fractures were not present, although such fractures are uncommon in layered sedimentary rocks. The calcite veins in the core and borehole images are mostly subvertical, with dips between 70° and 90° (Fig. 4.16). Inclined veins, or vein branches, with dips less than 70° exist, but in small percentages (Fig. 4.16). No observations of bed-parallel veins from the core and borehole images were made. Dip measurements are not biased by the degree of borehole inclination (i.e., deviation from the vertical reference) (Fig. 4.14). The frequency distributions of fracture dips in Fig. 4.14 show that fractures could have been missed if the borehole inclinations were less than 15° from the vertical reference (0°).

The dips of the fractures in the Arab-D outcrops in the homocline are normal ($\sim 90^{\circ}$) to the flat bedding planes (Fig. 4.40). The dominant occurrences of subvertical dips for the described fractures and veins are considered a systematic property for the fractures in the reservoirs and outcrops of the Arab carbonate platform, because the bedding dips in the platform interior are very low, between 0° and 5° . The observations that fractures are mostly normal to bedding planes are common for fractures in sedimentary layered rocks (e.g., Price and Cosgrove, 1990).

4.5.2.2 Fracture Strikes

The statistical distributions in Fig. 4.15 indicate that the boreholes minimized or missed the fractures that are parallel to the borehole trajectories. The boreholes of X-01 and X-02 display a dominant NW–SE system, and missed the NE–SW and E–W fracture systems, because of their orientations. The boreholes of X-03 and X-04 indicate the presence of NW–SE, NE–SW, and E–W fracture systems. The combined plot demonstrates that most barren fractures have NW–SE strikes at a range between 120° and 150° . The NE–SW trending fractures would have been more pronounced in the statistical distributions in Fig. 4.15 if the boreholes were drilled with NW–SE

orientations (i.e., normal to the NE–SW fractures). Nevertheless, observing fractures with these strikes in the boreholes in both flank and crest of the dome substantiates that the fractures extend as systems beyond the borehole locations.

The strikes of the fractures in the Arab-D outcrops in the homocline seem to slightly vary from one location to another, and from one layer to another. But the compiled histograms in Fig. 4.45 clearly show three dominant NW–SE, E–W, and NE–SW sets. These orientations do not seem to be a matter of coincidence; rather, they indicate extensive systems in the northern and southern limbs of the homocline despite the difference in location, layer thickness, and lithofacies. Previous studies reported similar fracture trends in the central part of the homocline in the CAG region, although other trends were also reported (Abdlmutalib and Abdullatif, 2017). The NW–SE, E–W, and NE–SW orientations of fractures are consistent with orientations of the reservoir fractures in the dome and other areas in Eastern Arabia (e.g., Ameen et al., 2010). It is suggested here that the fractures with NE–SW, NW–SE, and E–W strikes are part of regional systems in the platform interior in Central and Eastern Arabia.

The veins exhibit E–W to NW–SE strikes, but the measurements are based on limited observations. Therefore, it is difficult to propose some regional trends for a minor system of fractures.

4.5.3 Abundance

Fractures in the reservoirs in the dome must have been intersected by the boreholes and expected to be expressed in the core and borehole images, unless the spacing of fractures in the reservoir layers is larger than the horizontal sampling windows of boreholes. Combining measurements from core and borehole images was useful to constrain the possible range of fracture abundance in the Arab reservoirs, despite the core and borehole images displaying some significant mismatches (see Ch. 5). Several scenarios of statistical distributions were tested to fit measurements of fracture spacing of barren fractures and veins in the Arab reservoirs in the dome and Arab-D outcrops in the homocline.

4.5.3.1 Abundance of Veins

The calcite veins in the Arab reservoirs in the dome were found to be limited in number for statistical distribution models, although the veins seem to exist in all reservoirs (A, B, C, and D) (Fig. 4.28). Based on information from the core and borehole images, the spacing between the calcite veins can range from 3 cm to 30 m. This range is rather difficult for a meaningful statistical model. The veins exhibit what can be considered random events along the borehole sections. Some calcite veins display clustering (i.e., in a short interval of the reservoir) that could result in small spacing if the core was only cut from those intervals. If each cluster of the veins was treated as a single fracture zone, the datasets would be limited by borehole length to model the spacing of these zones.

The calcite veins exist with variable abundance in the reservoirs but display an obvious increase in the lower reservoir sections, specifically in the Arab-D of the X-03 core. This observation must be accompanied with the fact that the core samples from the X-01 and X-03 were obtained from locations that differ in their structural position in the dome and its present-day fluid contents (oil and water) (Ch. 3.3.2).

The calcite veins are strongly associated with the rock stylolitization. The veins and their micro branches are directly connected as a network to the bed-parallel stylolite zones. Also, the calcite minerals that make up the veins were often observed to mix with the stylolite organic material in the vein-stylolite intersection regions.

The calcite veins exhibit aggregates of calcite crystals of different sizes and shapes. Categorizing the calcite veins into further classes based on the petrographic signatures was not possible, because of the low number of veins and varieties of crystal textures. It was also difficult to derive more categories for the veins based on isotopic signatures. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of the calcite veins are similar to those of the Arab reservoir rocks. This signature places the veins under one system. The negative $\delta^{18}\text{O}$ values in the Arab reservoirs are indications of a later rock alteration by warm fluids with the burial, stylolitization, and recrystallization in a closed system of a normal geothermal gradient (Swart et al., 2005). According to Swart et al. (2005), the Arab carbonate reservoirs would have had positive $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ($\delta^{18}\text{O}$ +2 to +4‰ and $\delta^{13}\text{C}$ +2 to

+4‰) of the normal marine fluids during the Late Jurassic period (approx. -1‰ SMOW). The diagenesis in closed systems would have changed the isotopic signatures of the oxygen, but not the carbon (Swart et al., 2005). The $\delta^{13}\text{C}$ values clearly differ from those of the Arab-D outcrops, which were altered in open systems of meteoric water circulation (Eltom et al., 2014), (Fig. 4.25).

The calcite veins exhibit a signature of strontium isotopes that is also similar to those of the host rock and stylolite, indicating a common strontium reservoir. The $^{87}\text{Sr}/^{86}\text{Sr}$ values of the calcite veins, as well as their host rock and stylolite material, demonstrate a close range of values that are not significantly different from the $^{87}\text{Sr}/^{86}\text{Sr}$ curves of the Late Kimmeridgian seawater (McArthur et al., 2012; Wierzbowski et al., 2017). The higher $^{87}\text{Sr}/^{86}\text{Sr}$ values (green bar) in both S1 and S2 in Fig. 4.26 may indicate diagenetic events (from overlying seawater) during Early Tithonian and before the deposition of the sealing Hith Anhydrite.

4.5.3.2 Abundance of Barren Fractures

Unlike modeling the abundance of veins, modeling the abundance of barren fractures is feasible from the reservoir and outcrop datasets. The spacing of the barren fractures in the reservoirs is dominantly less than 1 m, as measured along the core sections. This means that it is unlikely to drill a borehole and encounter unfractured reservoir sections greater than 1 m, except if the boreholes are subvertical ($<25^\circ$ from the vertical reference, 0°). The mean values of fracture spacing is around 35 cm, along a core that is geometrically traversing the thick and thin layers of the Arab A, B, C, and D reservoirs.

The majority ($\sim 80\%$) of the fracture spacing values along the borehole images are 30 cm. The remaining ($\sim 20\%$) of the fracture spacing values is mostly less than 1 m. These results from the borehole images are in a close range to the spacing of barren fractures in the core.

Although the borehole inclinations were ideal to intersect such vertical systems of barren fractures, the spacing measurements partly depend on fracture height (i.e., unit thickness for confined fractures). However, fracture height and thickness of mechanical units are missing information. There are several possibilities for the thickness of layers and spacing of fractures. The two extreme scenarios are that fracture spacing is regular and layer thickness is equal. Nevertheless, the obtained statistical distributions of fracture abundance do not indicate any of these extreme

scenarios. Instead, the statistical distributions indicate what can be considered of varying thickness from modeling lithofacies and fracture spacing.

The fractures along the boreholes are random and can only be best estimated using statistical distributions. The corrected fracture spacing is perhaps the best approach in this research to estimate fracture abundance in the reservoirs. The results indicate that the carbonate lithofacies exhibits different fracture abundances. Along a hypothetical 10-m scanline traversing the lithological units, mudstones would display 28 fractures (~0.3 m of fracture spacing), and rudstones would display 13 fractures (Fig. 4.33).

The mud-supported intervals seem to dominate the Arab reservoir lithofacies (Fig. 4.33). The values of corrected spacing reflect in part the tendency of some lithofacies to exist in certain ranges of thickness. If the outcrop observations are to be used to predict the subsurface reservoirs, the reservoir fractures are expected to be mostly confined to layers ranging from 0.1 m to 1.2 m. Within this range, the spacing of fractures is smaller than the thickness of layers, unless all reservoir layers are less than 0.3 m thick. This is unlikely possible, for two reasons. Firstly, modeling of the reservoir lithofacies does not indicate this possibility of dominant thin layers. Secondly, fractures in layers of 0.3 m could have been partially observed terminating in the domain of boreholes (in core and borehole images), because of their short height.

The fracture spacing in the outcrops is mostly between 1 m and 3 m. The abundance of outcrop fractures is apparently representative to the homocline region. The measurements of fracture abundance in the CAG regions do not seem to be remarkably different from the measurements of fracture abundance in Wadi Malham and Howtat Bani Tamim. According to Abdlmutalib and Abdullatif (2017), the most intensely fractured intervals of the Arab-D outcrops display 1.2 fracture per meter, and some lithological units display much lower abundances of fractures. By comparison, the results display that the barren fractures in the Arab reservoirs are more abundant than the barren fractures in the Arab-D outcrops (Fig. 4.46). The results clearly indicate that fracturing in the dome structure is more abundant than fracturing in the homocline. Unlike properties of mineralization and orientation, the abundance of barren fractures seems to vary significantly in the Arab carbonate platform.

4.6 CONCLUSIONS

The systematic properties that can be recognized about the Arab reservoir fractures in the dome are as follows:

- 1) About 80% of the reservoir fractures are barren, and the remaining are mineralized fractures (veins). The veins are predominantly calcite veins.
- 2) The two systems are found to be existing in the Arab A, B, C, and D reservoirs.
- 3) The barren fractures in the core that were detected in the borehole images exhibit apertures that are conductive for drilling fluids, and therefore are interpreted as permeable fractures for fluid flow under the subsurface confining pressure. Further analyses on the nature of barren fracture apertures are discussed in Ch. 5 and Ch. 6.
- 4) The veins display complete fills of calcite minerals that apparently choked the fracture porosity and are interpreted to be currently barriers for fluid flow in the reservoirs.
- 5) The barren fractures are subvertical, bed-perpendicular, and without shear displacement. Their characteristics mirror those of rock joints that have long been described from outcrops of sedimentary layered rocks.
- 6) The majority of the measured fractures are of NW–SE azimuth, and a minority of fractures strike mostly toward NE–SW and E–W. The fracture strikes exhibit systematic sets, which were clearly affected by the sampling biases of the borehole orientation. The barren fractures are apparently part of the previously documented regional NW–SE, NE–SW, and E–W systems in the subsurface carbonate reservoirs in Eastern Arabia.
- 7) The veins are mostly subvertical, bed-perpendicular, and without shear displacement. The veins have some branches with deviated dips to connect to other veins and the bed-parallel stylolite. These characteristics of the veins vary; in cases they resemble those of tension gashes associated with stylolites, and in other cases they seem to be formed from precipitation of mineral aggregates by fluids in dilational (i.e., barren fracture) sites.
- 8) The calcite veins were apparently formed in early diagenetic stages of the Arab sediment burial, stylolization, and dolomitization in the Late Kimmeridgian and Early Tithonian. The deposition of the Late Tithonian Hith Anhydrite apparently prevented open-system

diagenesis of later meteoric water. The carbonate units are sandwiched by non-porous anhydrite units that were proved to be an effective sealing system of the prolific hydrocarbons hosted in the carbonates. Oil migration into the dome structure, which started to form in the Cretaceous, halted mineralization in the reservoirs.

- 9) The timeframe for development of the barren fractures is much longer than for the calcite veins. The barren fractures were apparently developed under tangential stresses of the basin rock bending, then increased in abundance under the local bending of the dome. The evolution of the dome indicates multiple phases of growth ensued by a deeply seated salt body below the platform rocks (Al-Fahmi et al., 2014; 2016).
- 10) The fracture systems are found in all types of the reservoir lithofacies, indicating that all types of the carbonate facies were prone to fracturing. The carbonate lithofacies exhibits different degrees of barren fracture abundance. The calcite veins are frequently associated and mixed up with the stylolite materials.

The following are the systematic properties of fractures in the Arab carbonate outcrops in the homocline:

- 11) The outcrop fractures are extensively barren fractures. Mineralization and stylolitization were not encountered in the outcrops.
- 12) The fractures are vertical and mostly confined to the flat Arab-D layers in the four sites, at Wadi Malham and Howtat Bani Tamim.
- 13) The fractures can be categorized into NW–SE, NE–SW, and E–W systems.

The systematic properties of fractures in three areas of the Arab carbonates in the platform interior in outcrops and reservoirs are as follows:

- 14) The fractures are dominantly barren fractures, of normal planes to the nearly flat or gently dipping strata.
- 15) Most barren fractures have NW–SE, NE–SW, and E–W azimuths. These trends seem to represent earlier fractures that controlled the orientations of subsequent fractures.
- 16) Fracture abundance in the dome is apparently more representative to the domes and anticlines in Eastern Arabia than to the homocline outcrops in Central Arabia.

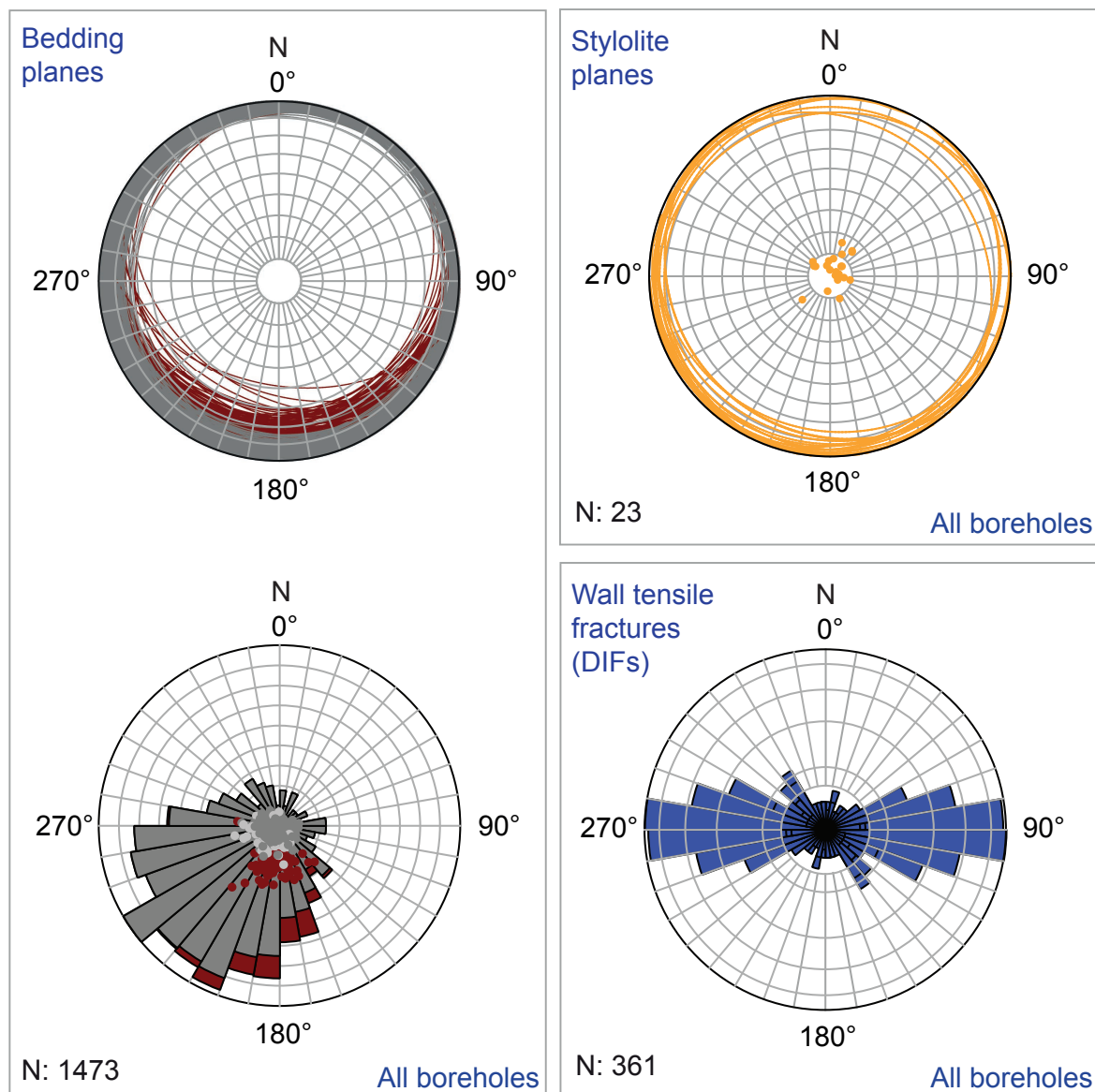


Fig. 4.1: Stereonets and rose diagrams compiled for measurements of the four borehole images for the bedding planes, stylolite planes, and TWFs (that are induced by drilling, DIFs).

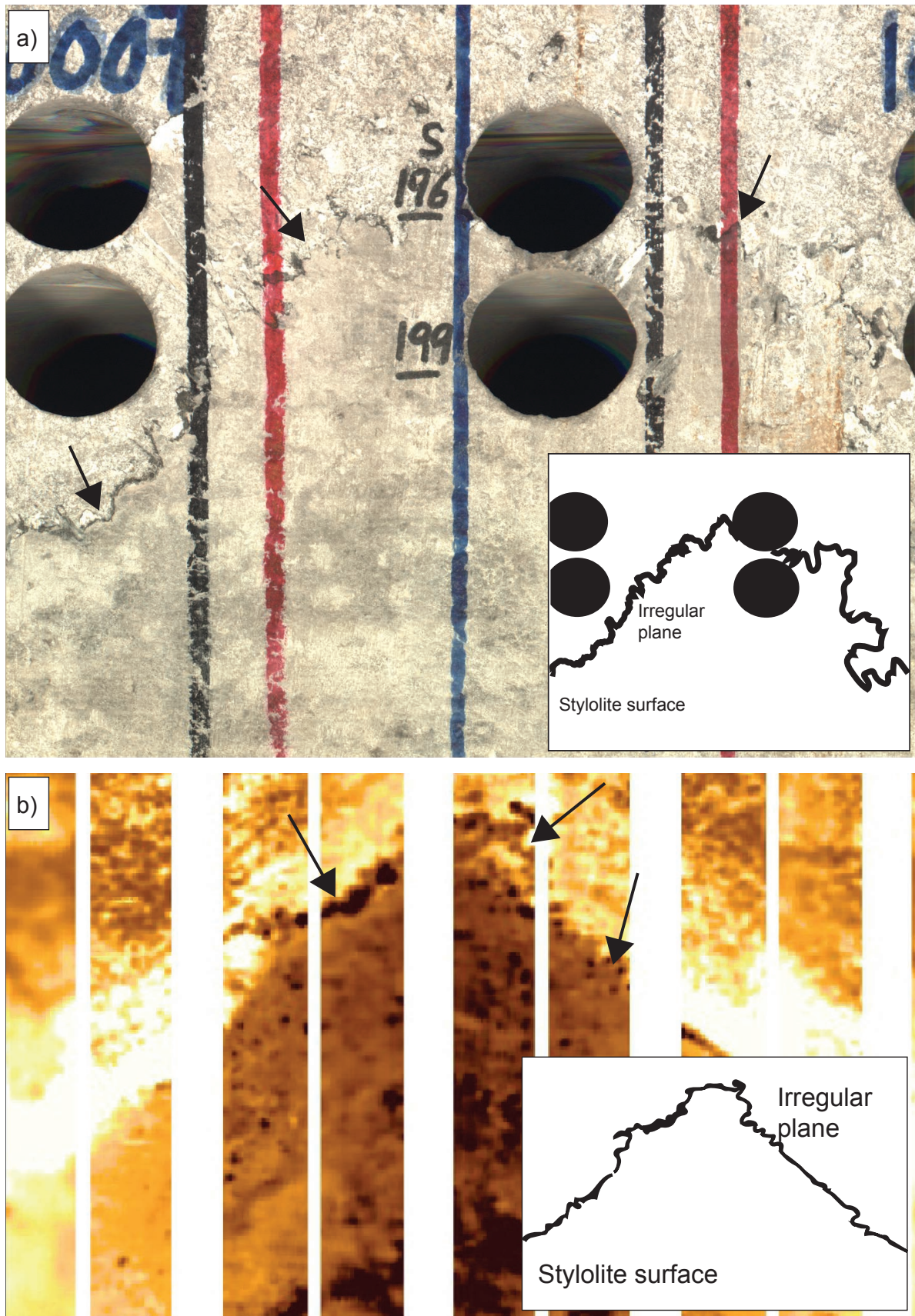


Fig. 4.2: Figures from a) core and b) corresponding borehole images, with drawings below of a bed-parallel stylolite. The stylolite zone is filled with calcite cement (white in the core and bright in the borehole images). Detecting stylolite zones in the borehole images was generally difficult.

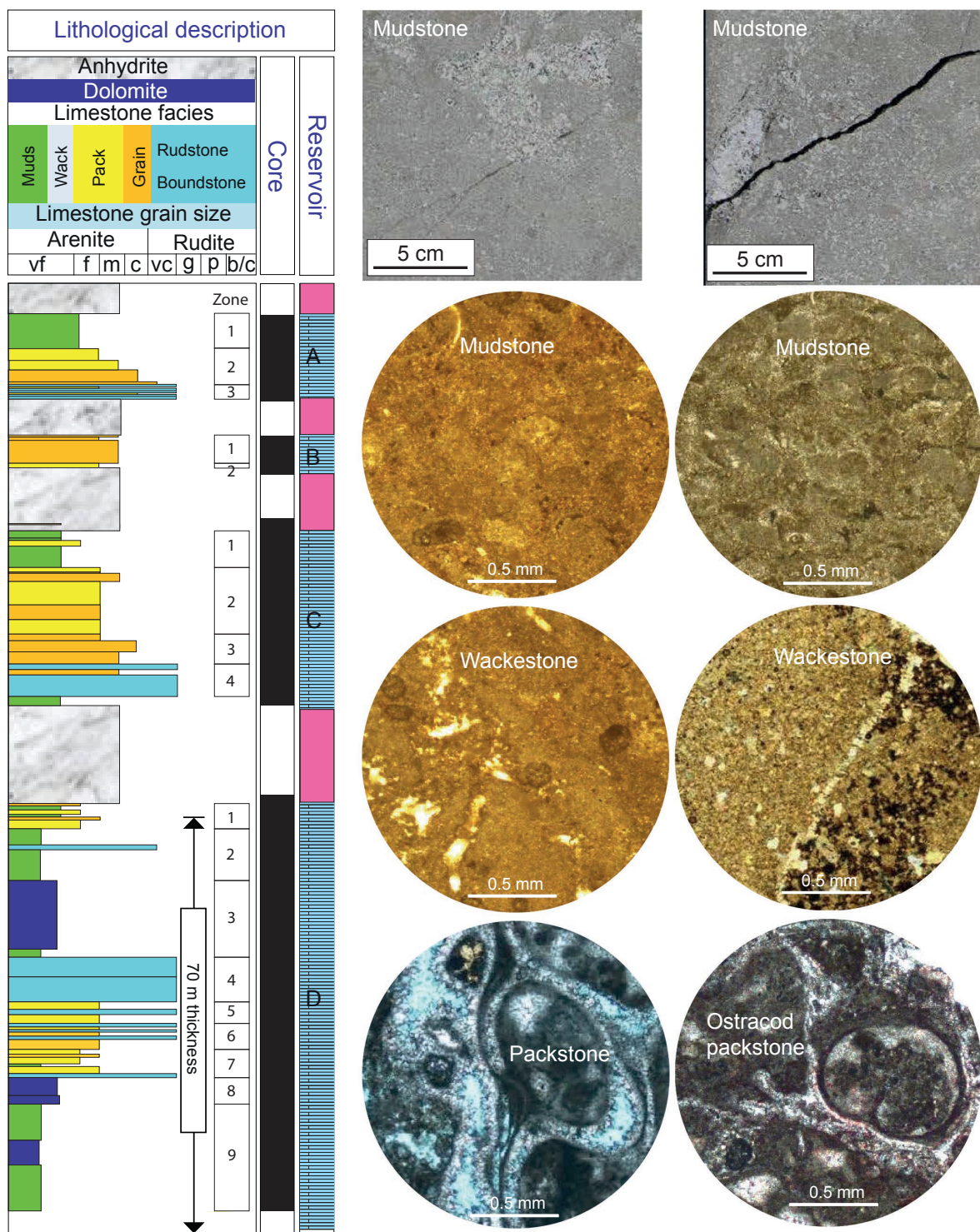


Fig. 4.3: Left, lithostratigraphy of the Arab carbonate reservoirs in the dome. Right, examples of micrographs for mud-supported lithofacies and grain-supported lithofacies.

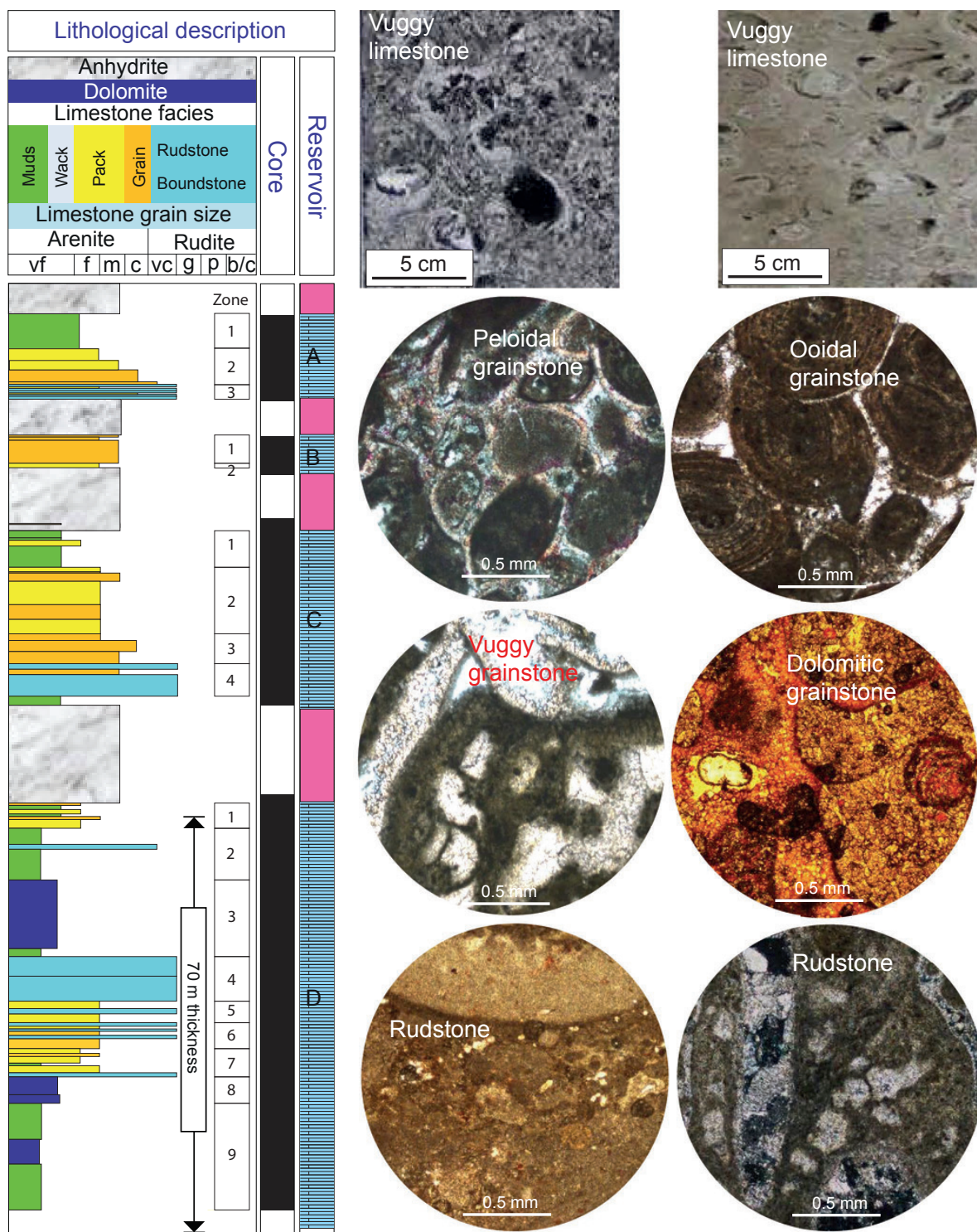


Fig. 4.4: Left, lithostratigraphy of the Arab carbonate reservoirs in the dome. Right, examples of micrographs for grain-supported lithofacies.

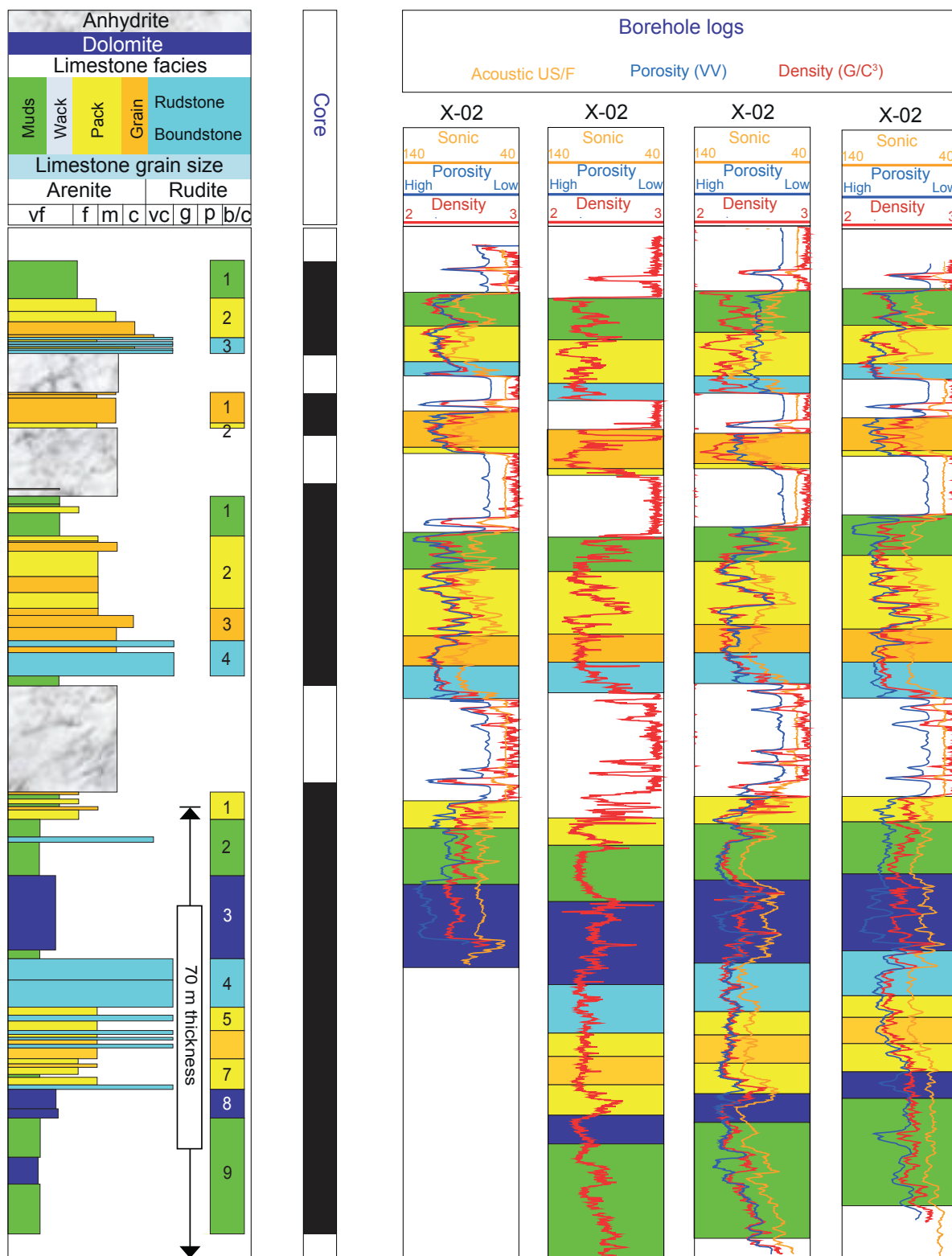


Fig. 4.5: Left, lithostratigraphy of the Arab carbonate reservoirs in the dome. Right, borehole logs of the sonic, density, and porosity of the modeled lithofacies.

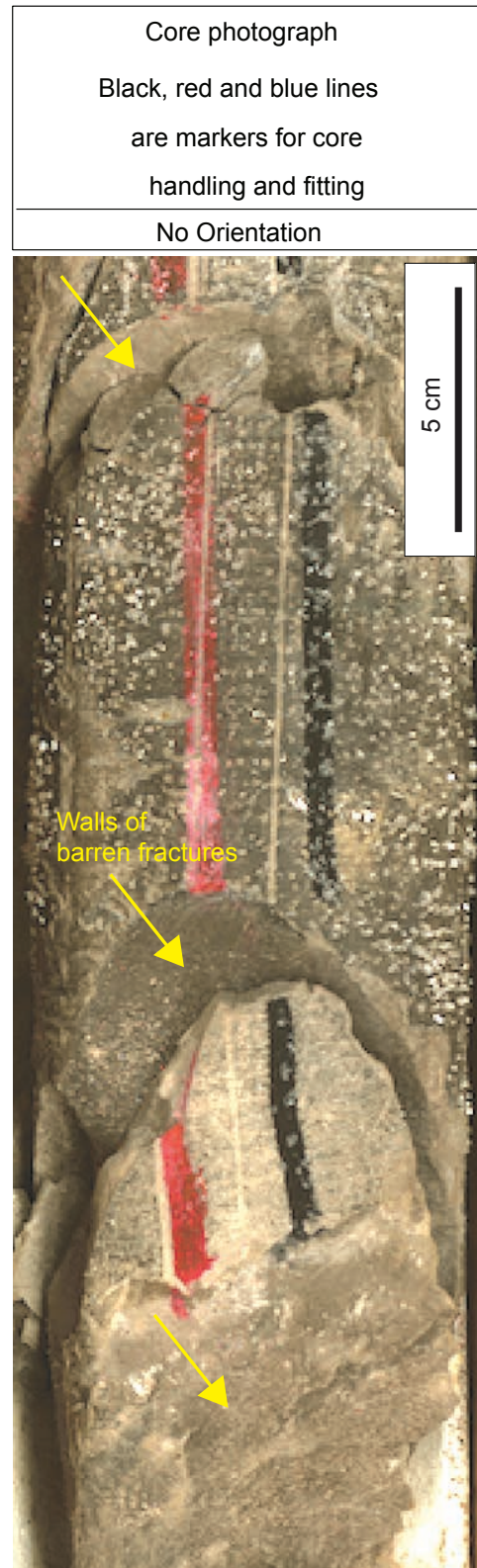
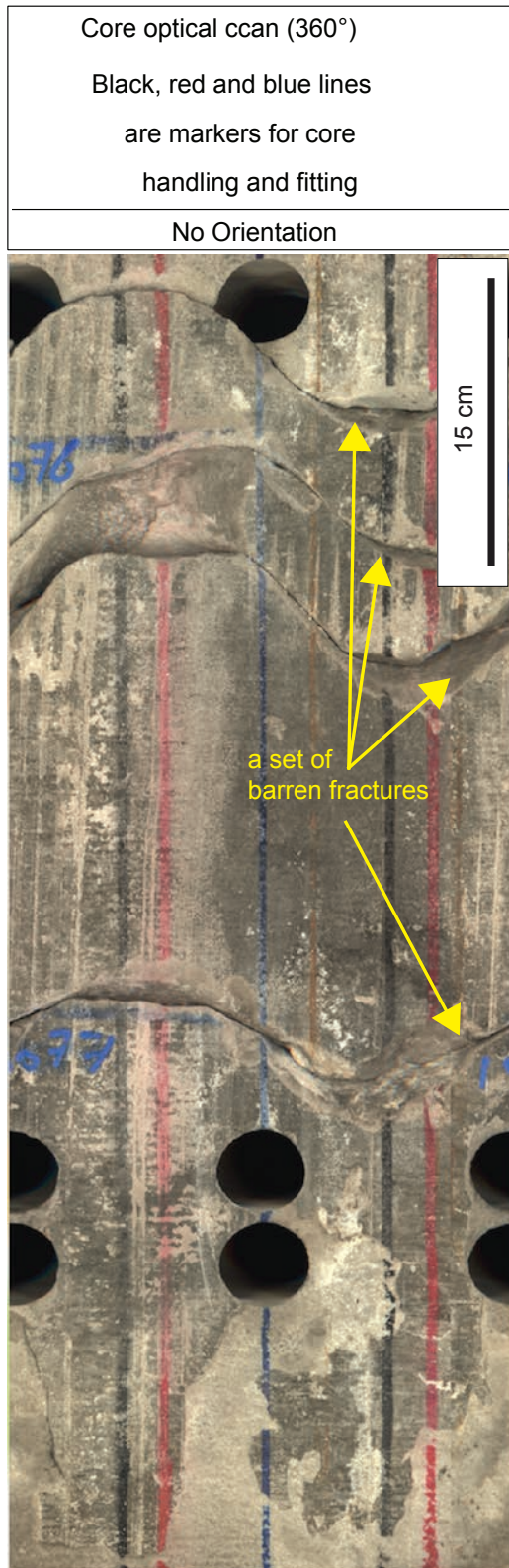


Fig. 4.6: Examples of the barren fractures in the Arab reservoirs in core samples. The fractures typically appear as sets of parallel orientation (parallel sine waves from the 360° images of the core) and of a typical surface (wall) that is barren of mineralization.

Rock Resistivity						Rock Resistivity					Rock Resistivity				
LowHigh						LowHigh					LowHigh				
Dynamic Image						Dynamic image					Static image				
Borehole image orientation (°)						Borehole image orientation (°)					Borehole image orientation (°)				
U	R	D	L	U		U	R	D	L	U	U	R	D	L	U
Deg (°)															

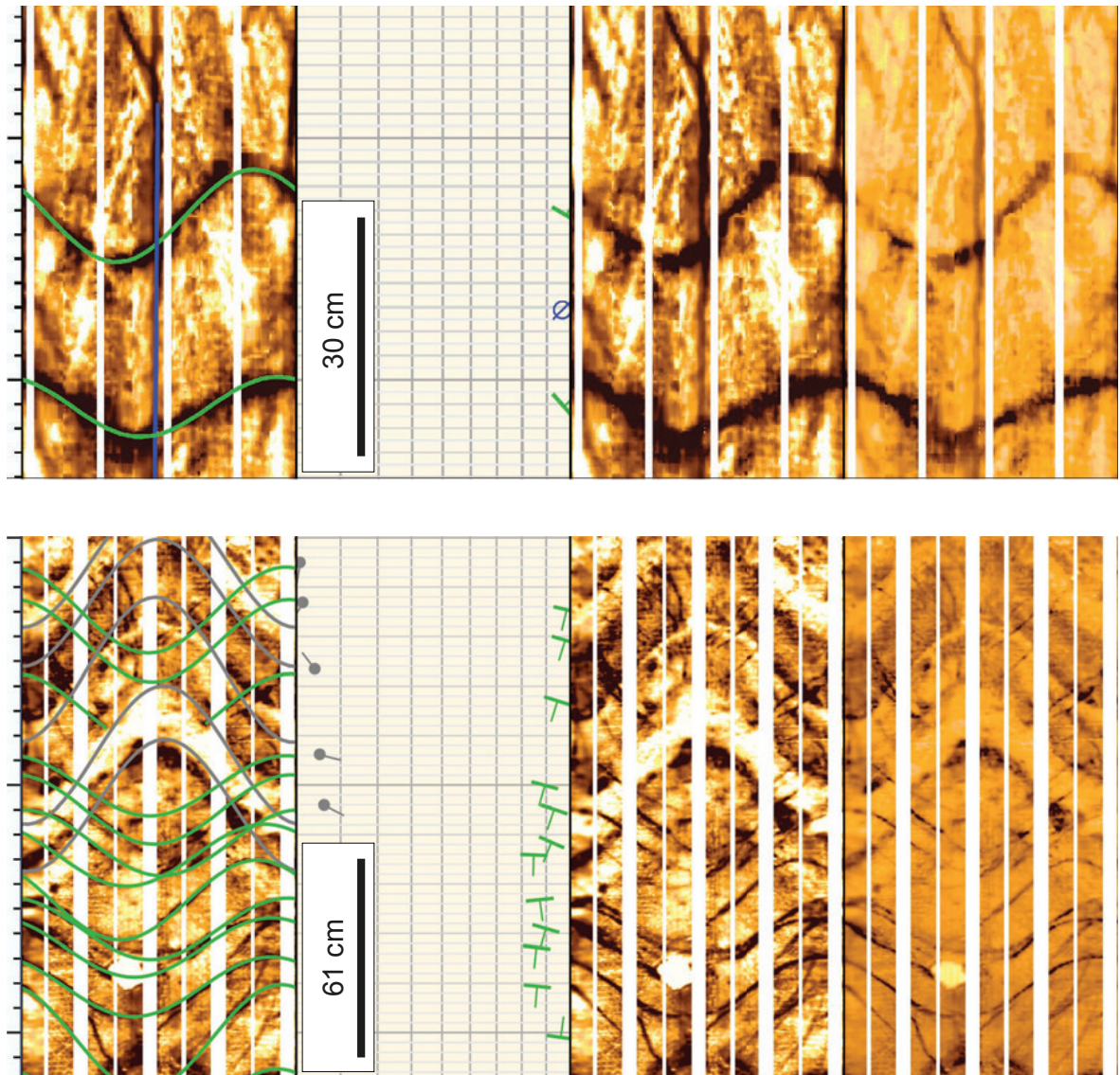


Fig. 4.7: Examples of the barren fractures in images of the boreholes in the Arab reservoirs. Fitted curves (green color) display barren fractures of high dips and NW–SE and E–W strikes. The fractures typically appear as sets of parallel orientation (parallel sine waves from the 360° images of the boreholes) and dark traces of apertures that indicate that fractures are open for conductive drilling fluid flow).

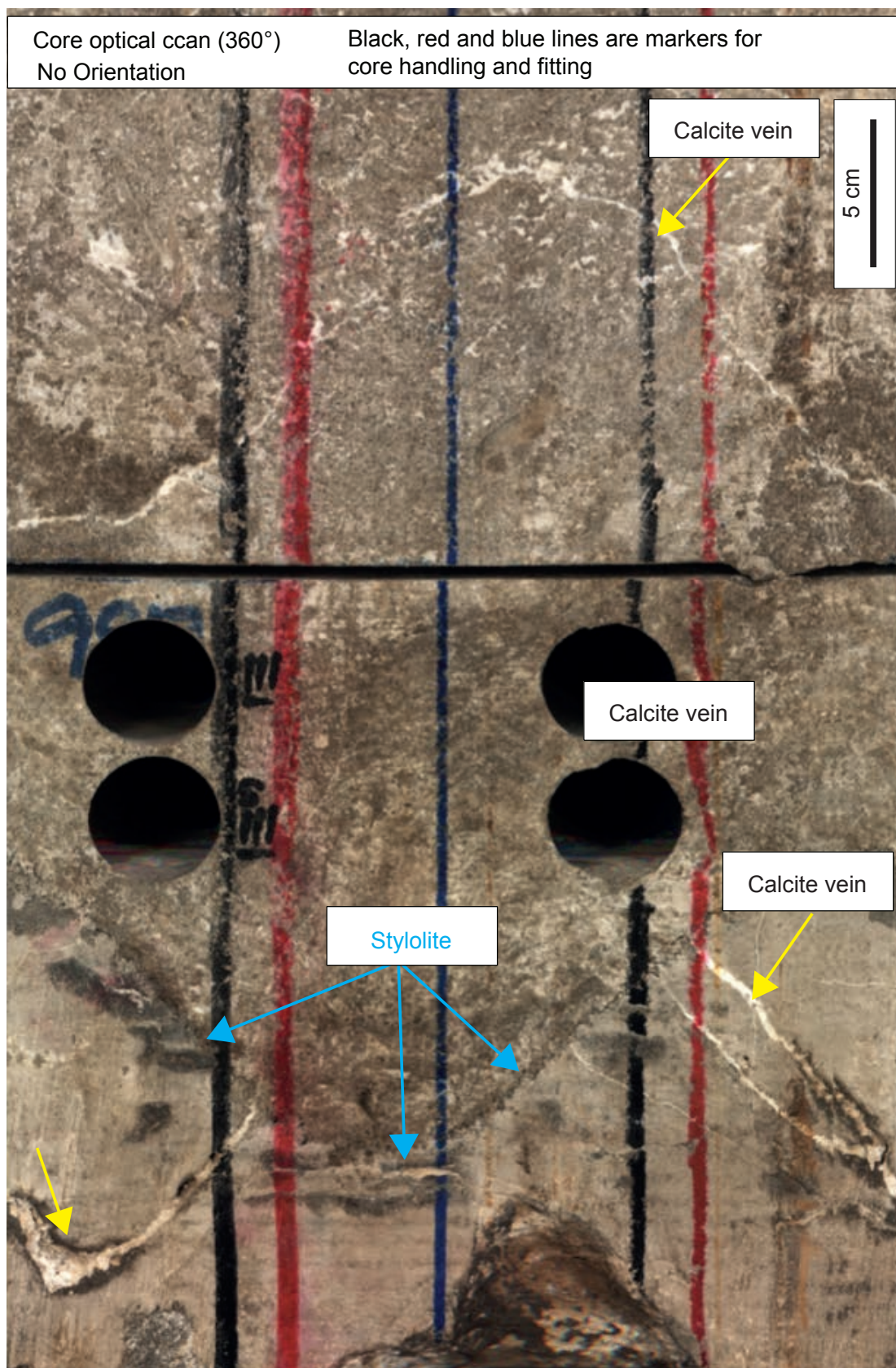


Fig. 4.8: Set of parallel calcite veins in the core. One calcite vein is terminated at a bed-parallel stylolite.

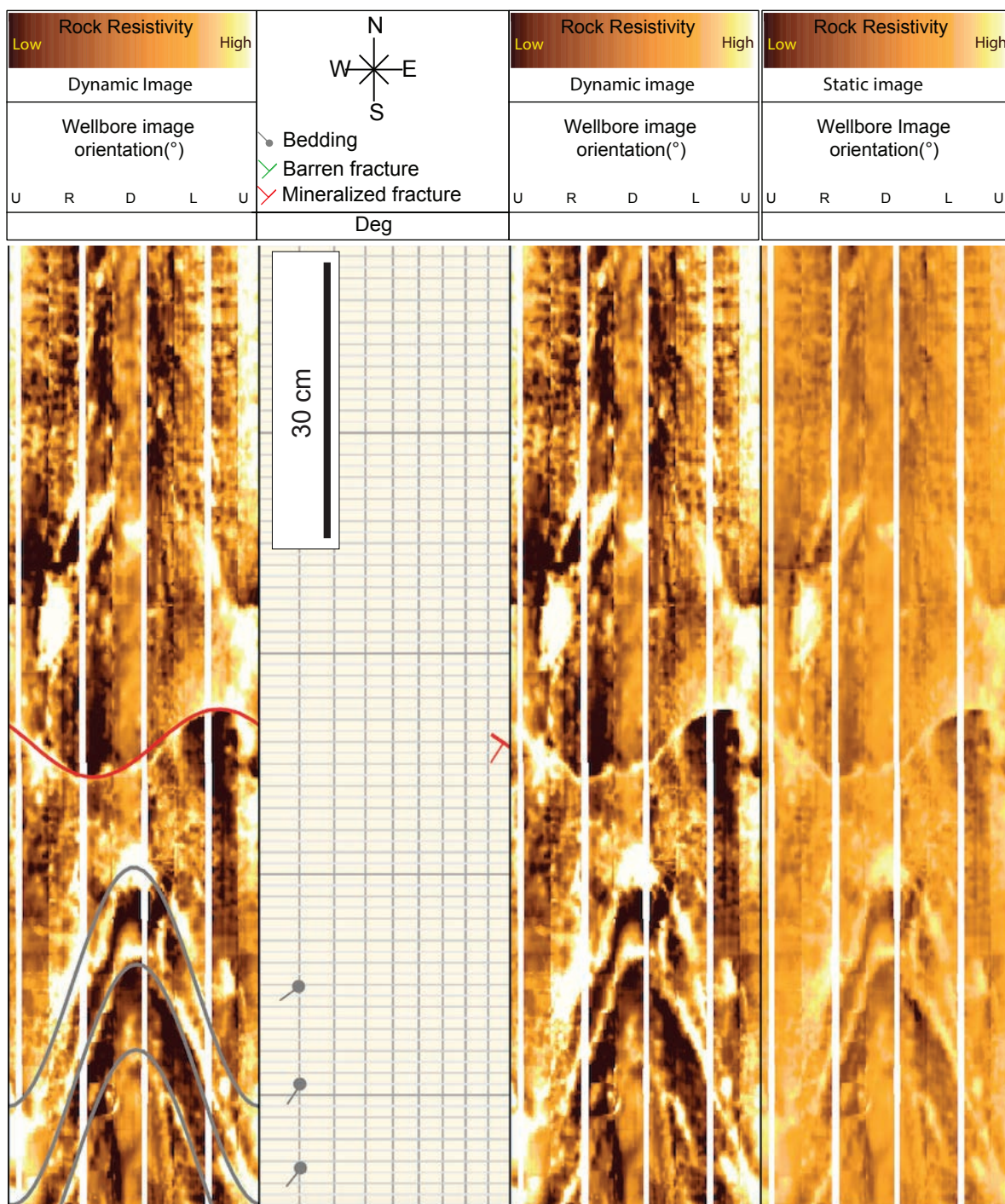


Fig. 4.10: Example of a mineralized fracture (calcite vein) in the borehole images in the Arab reservoirs. The vein is subvertical to bedding planes. The vein strike is NW–SE azimuth.

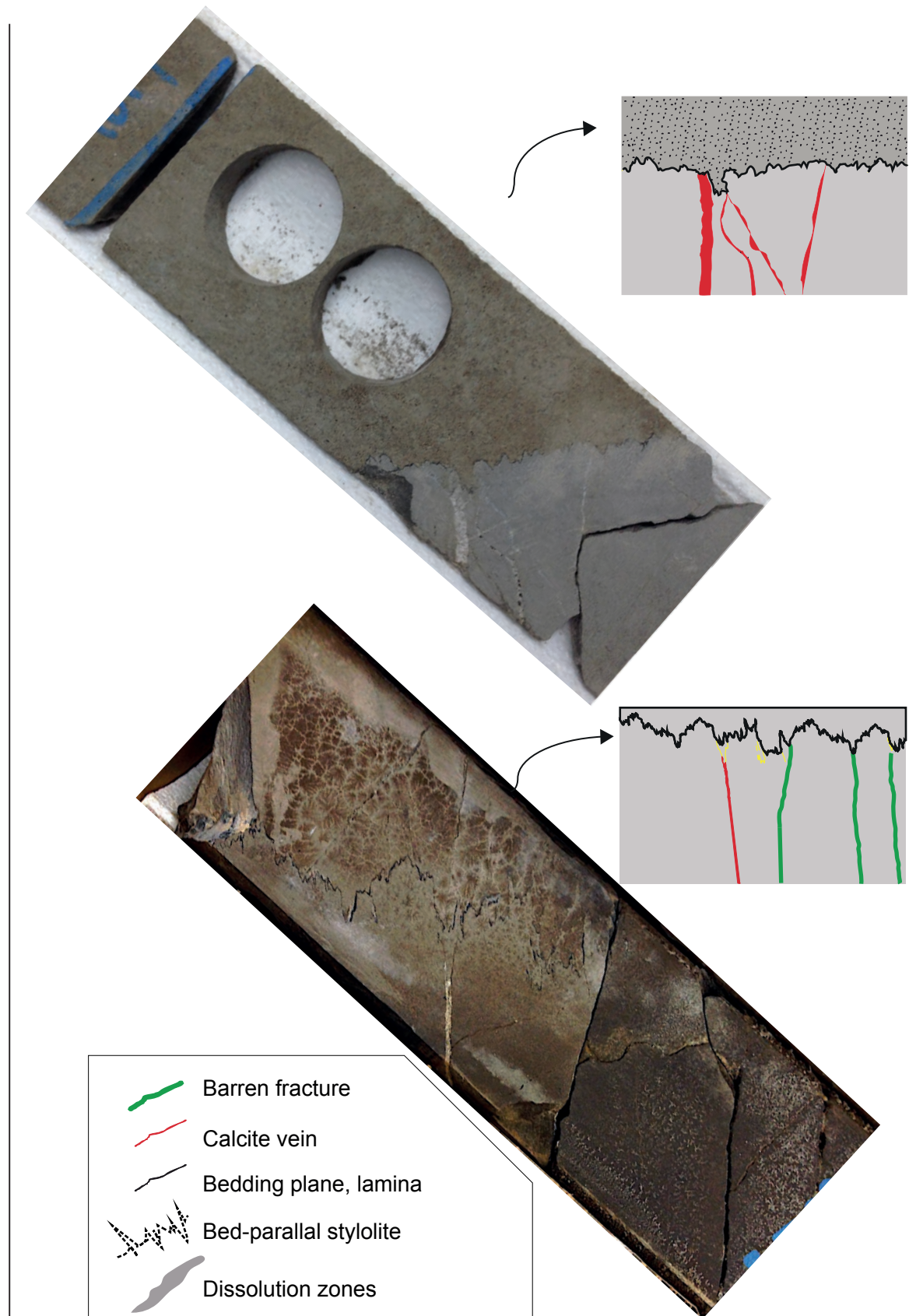


Fig. 4.11: a) Photographs of slabbed core samples (oriented to match the X-03 borehole deviation in the reservoirs) display intersections between a set of calcite veins, barren fractures, and stylolite planes.

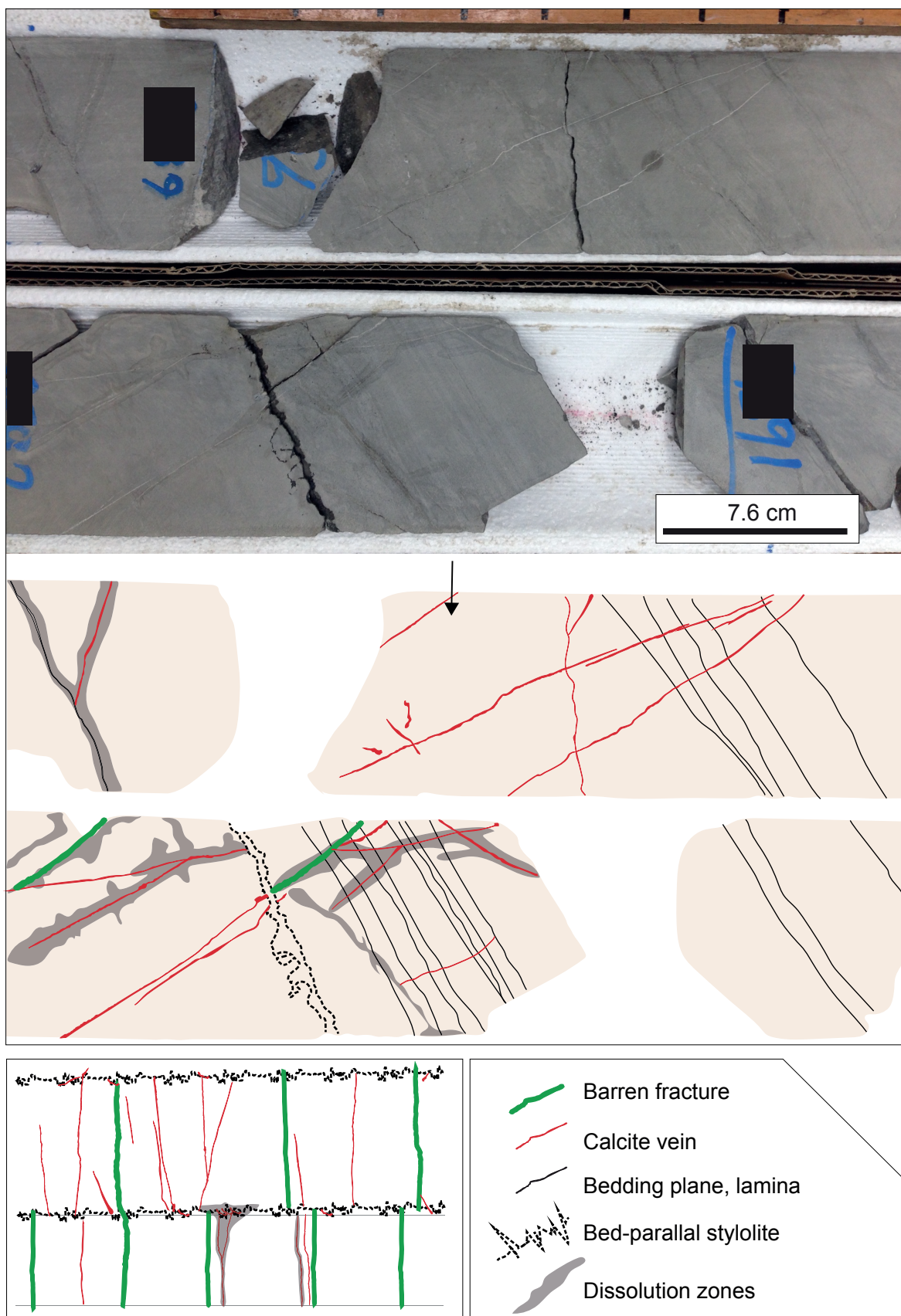


Fig. 4.12: a) Above, photographs and sketches of slabbed core display calcite veins and stylolites. Below, a sketch demonstrates the typical geometry of the calcite veins, barren fractures, and bed-parallel stylolites in the gently dipping layers of the Arab reservoirs.

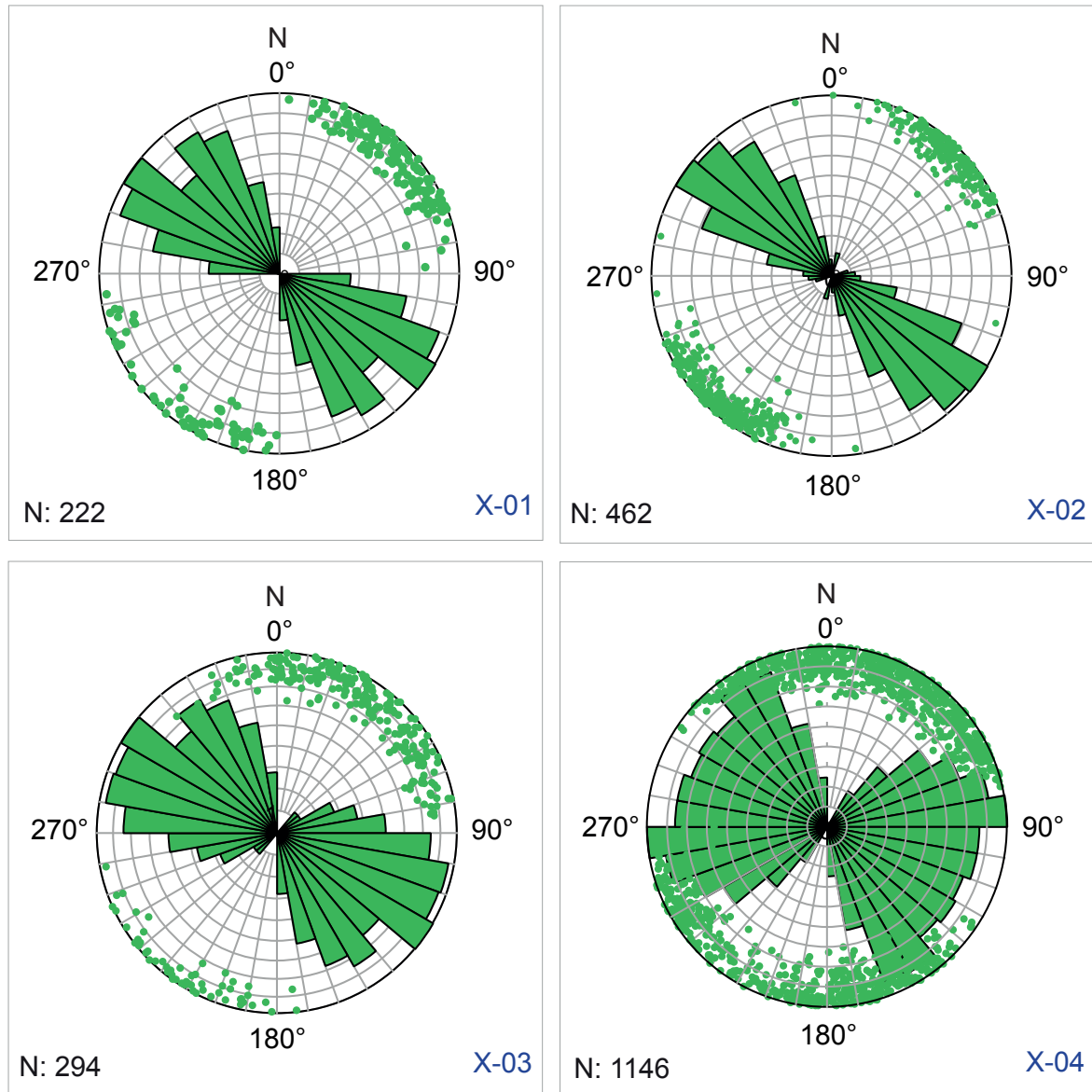
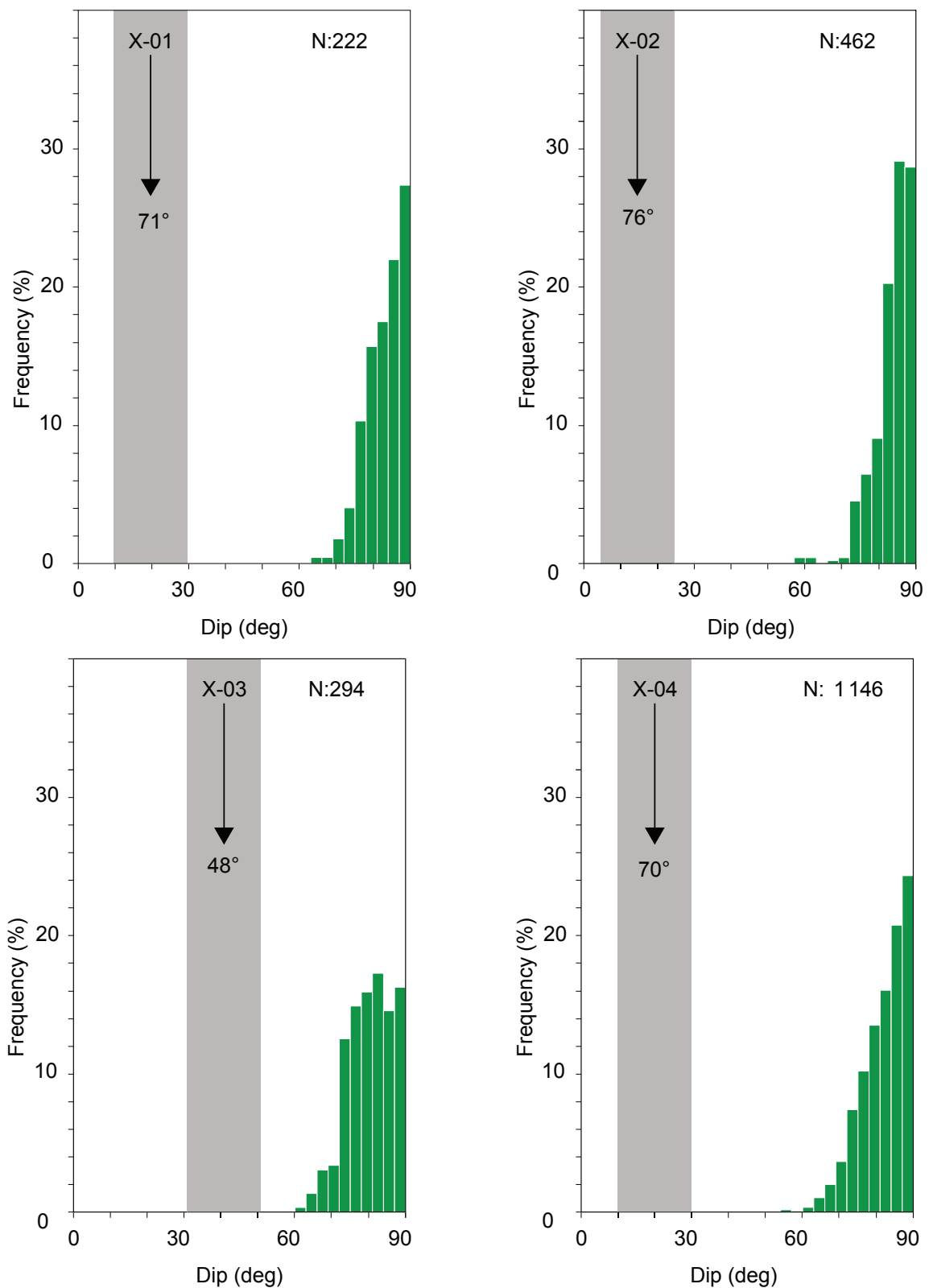


Fig. 4.13: Stereonets and rose diagrams of the barren open fractures that were interpreted from the borehole images. The rose diagrams are for fracture strikes, and the dots for fracture dips.



Angle of borehole deviation is measured from vertical 90°

Fig. 4.14: Histograms displaying distributions of the dips of the barren fractures measured from the borehole images of X-01, X-02, X-03, and X-04. Measurements from the four boreholes indicate that the barren fractures are dominantly subvertical ($>75^\circ$) in the Arab carbonate reservoirs.

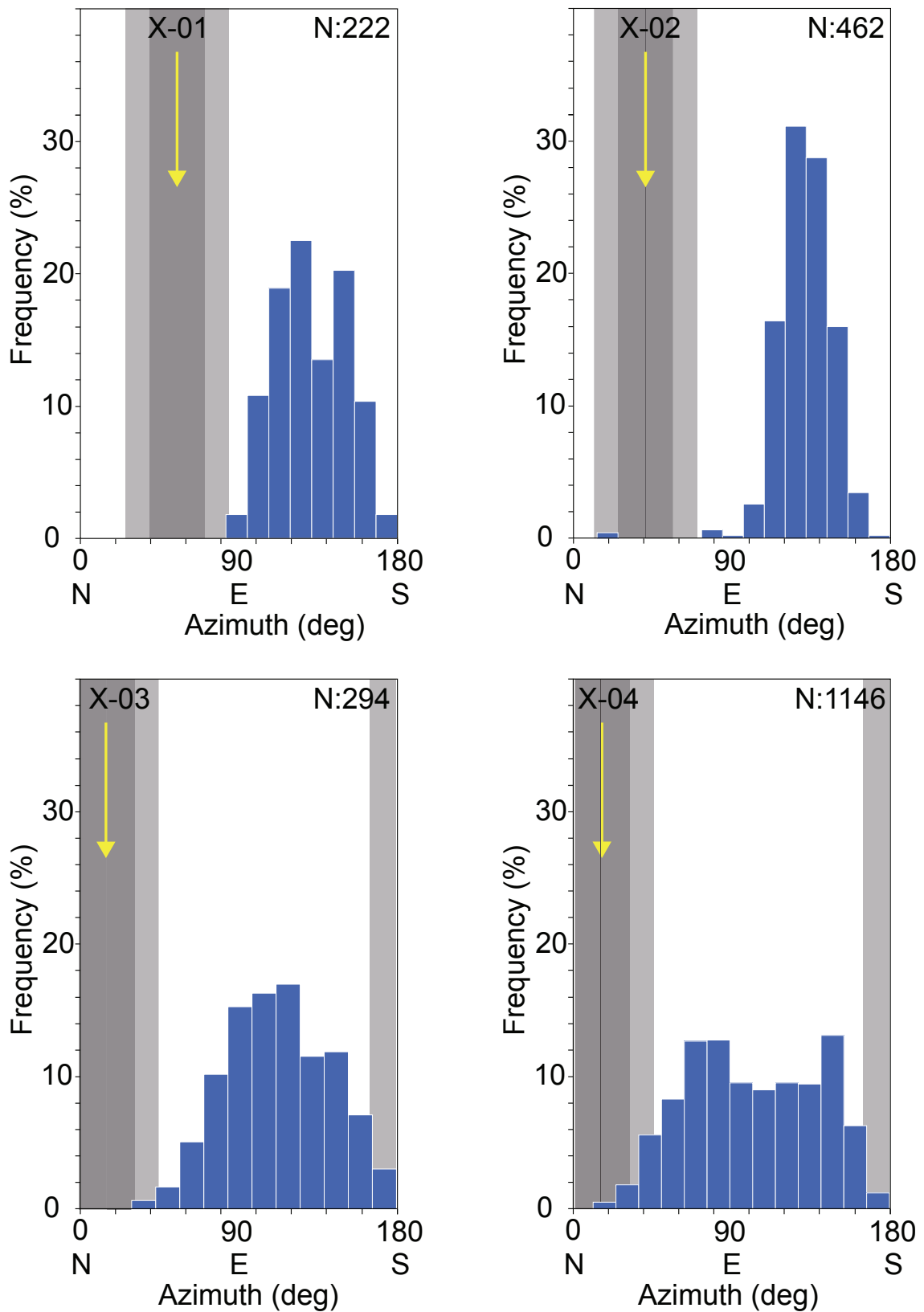


Fig. 4.15: Histograms display distributions of the strikes of the barren fractures measured from the borehole images. The boreholes of X-01 and X-02 missed the NE-SW and E-W fracture systems, and the boreholes of X-03 and X-04 indicate the presence and abundance of the system despite the boreholes being not completely normal to the system strike (between 60° and 80°).

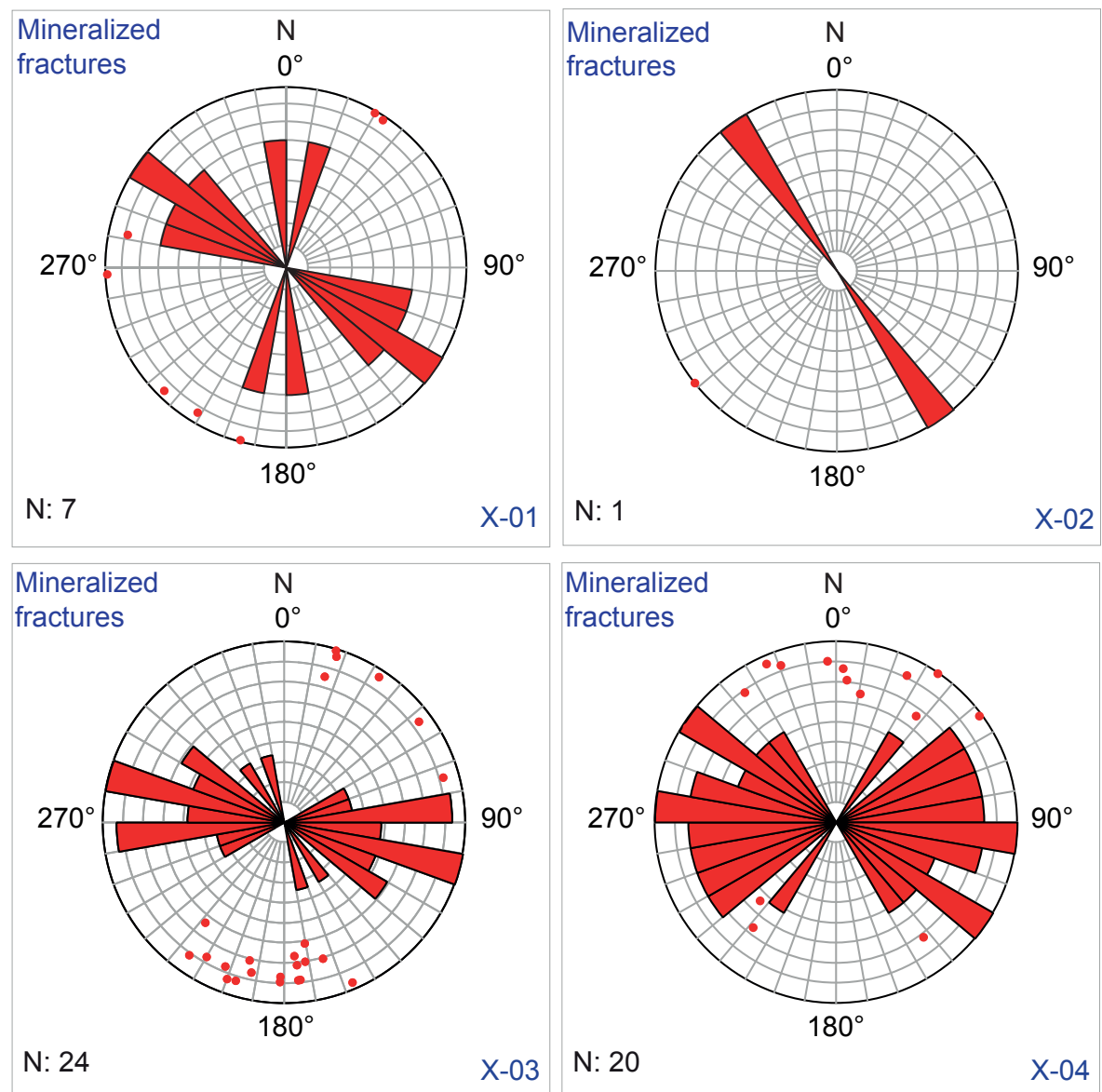


Fig. 4.16: Stereonets and rose diagrams of the mineralized fractures that were interpreted from the borehole images. The rose diagrams are for fracture strikes, and the dots for fracture dips.

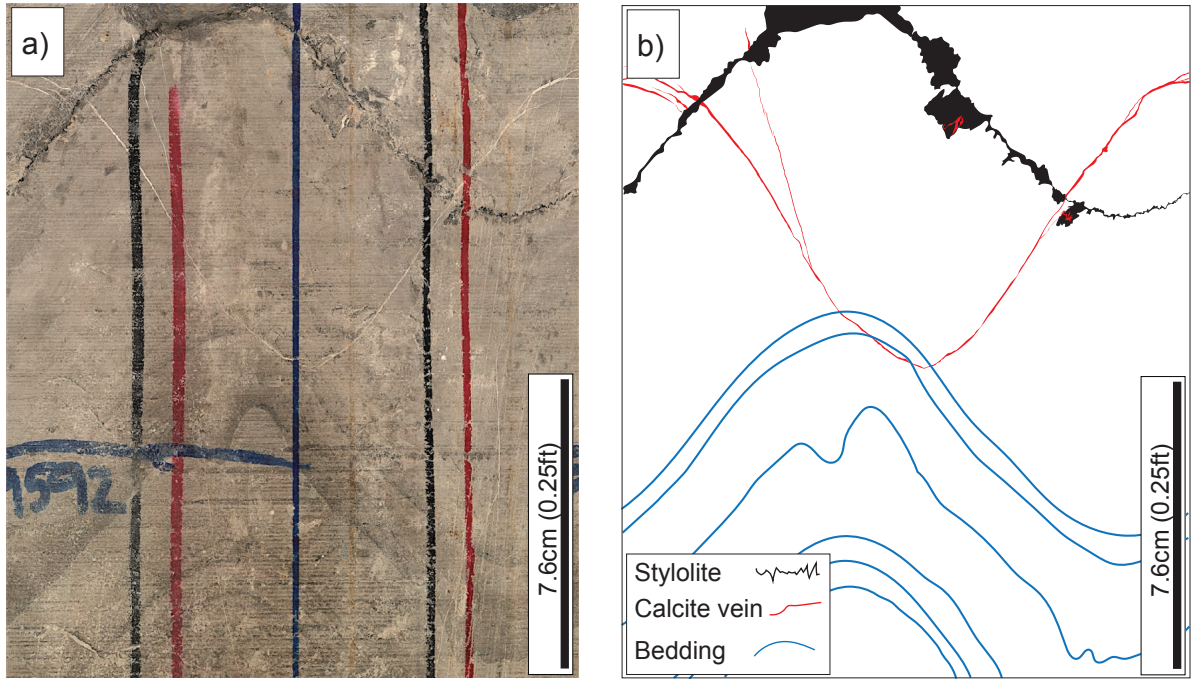


Fig. 4.17: Calcite vein that cuts through the carbonate lamina and a bed-parallel stylolite zone, without shear displacement.

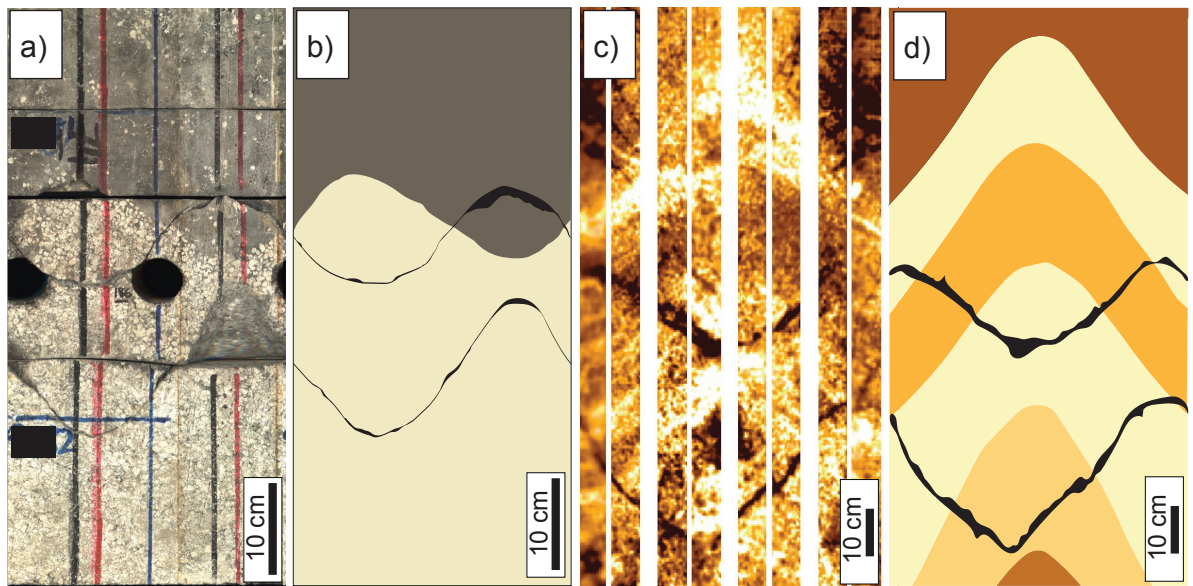


Fig. 4.18: Figures from a) core and c) corresponding borehole images, with drawings in (b) and (d) of a set of two NW-SE barren fractures that are normal to the bedding planes. The two fractures cut two different lithological units without shear displacement.

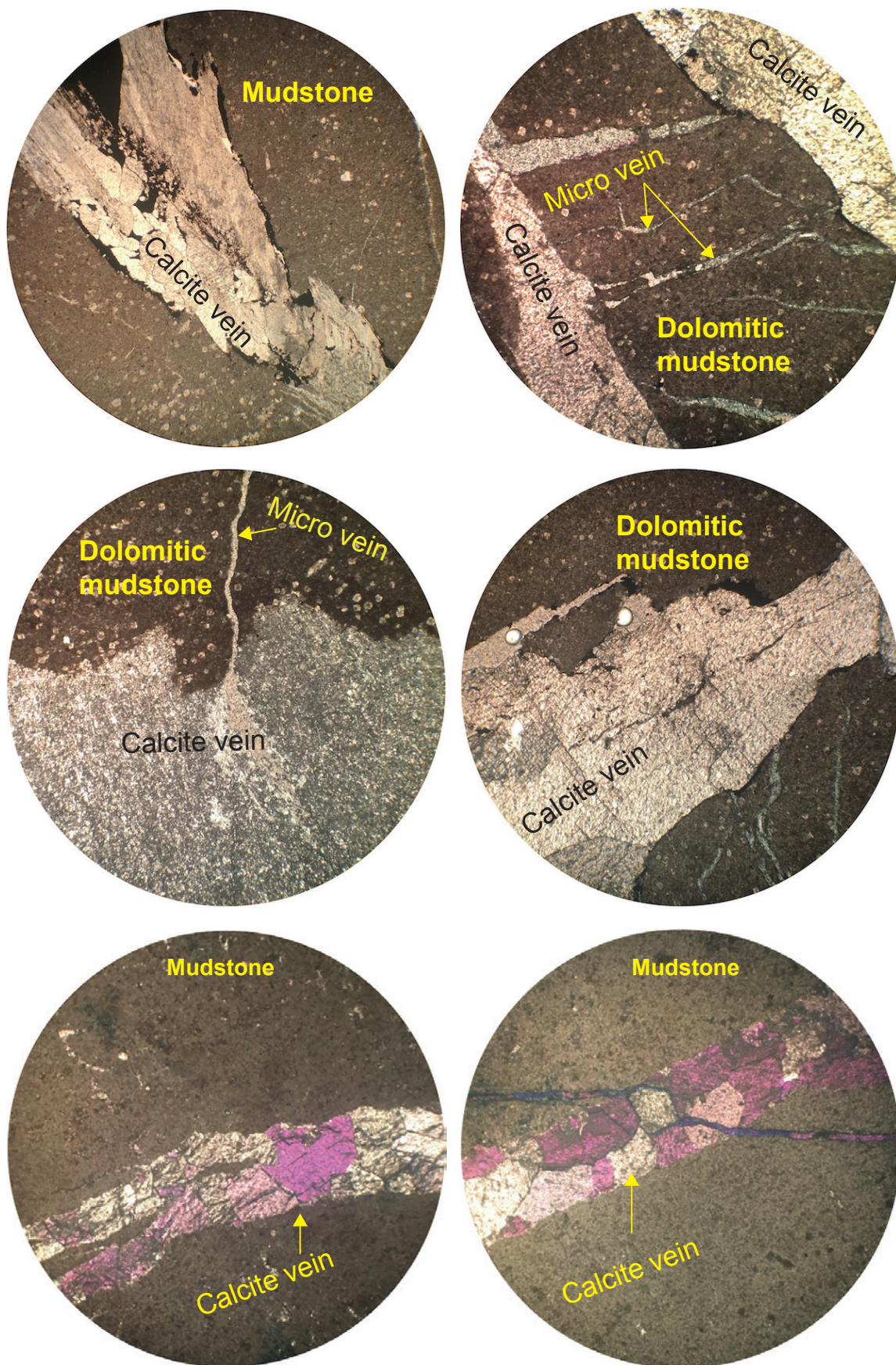


Fig. 4.19: Micrographs of calcite veins in mudstones. Note the varieties of crystal sizes and shapes.

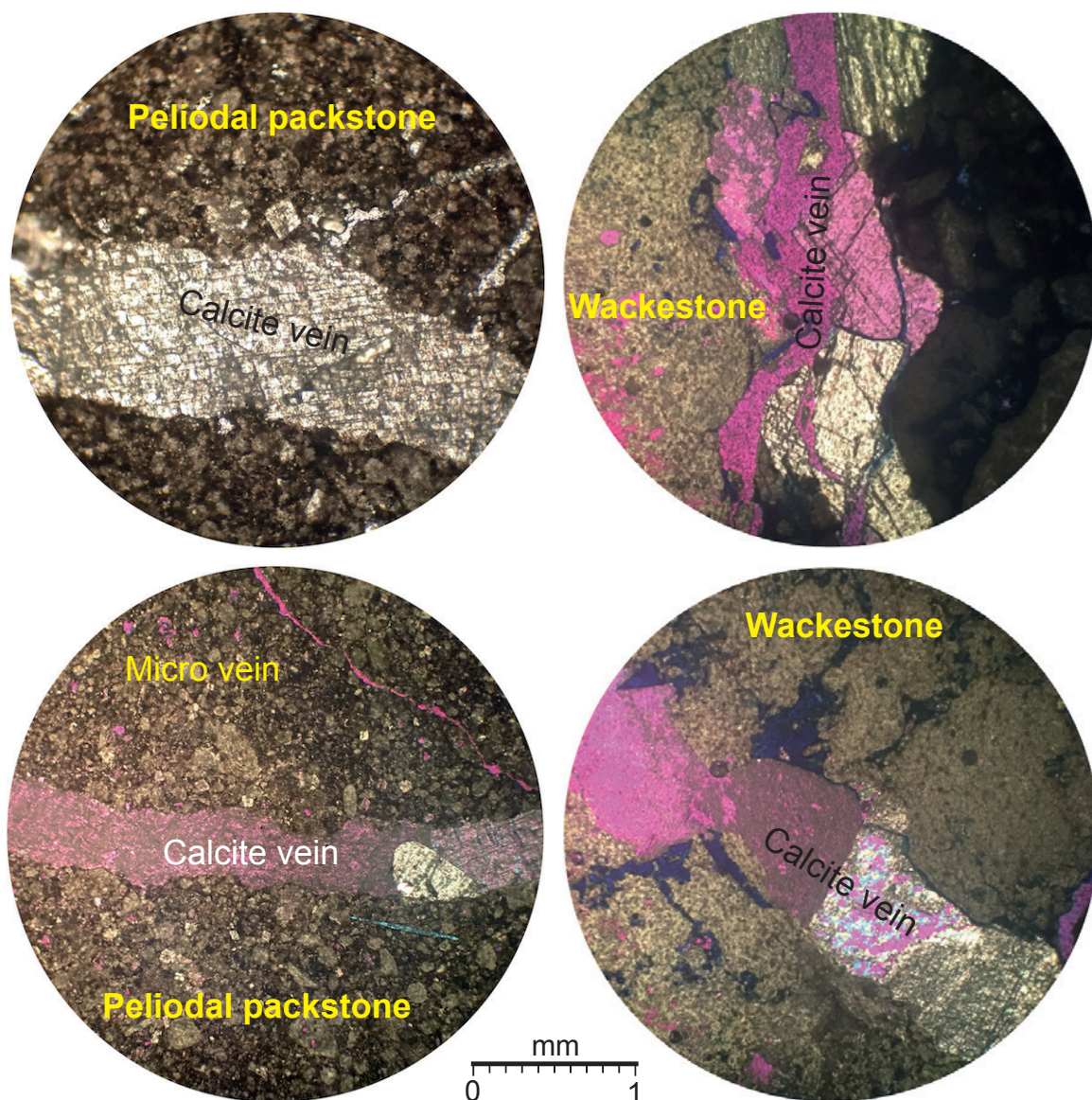


Fig. 4.20: Micrographs of calcite veins in lithofacies of wackestones and packstones.

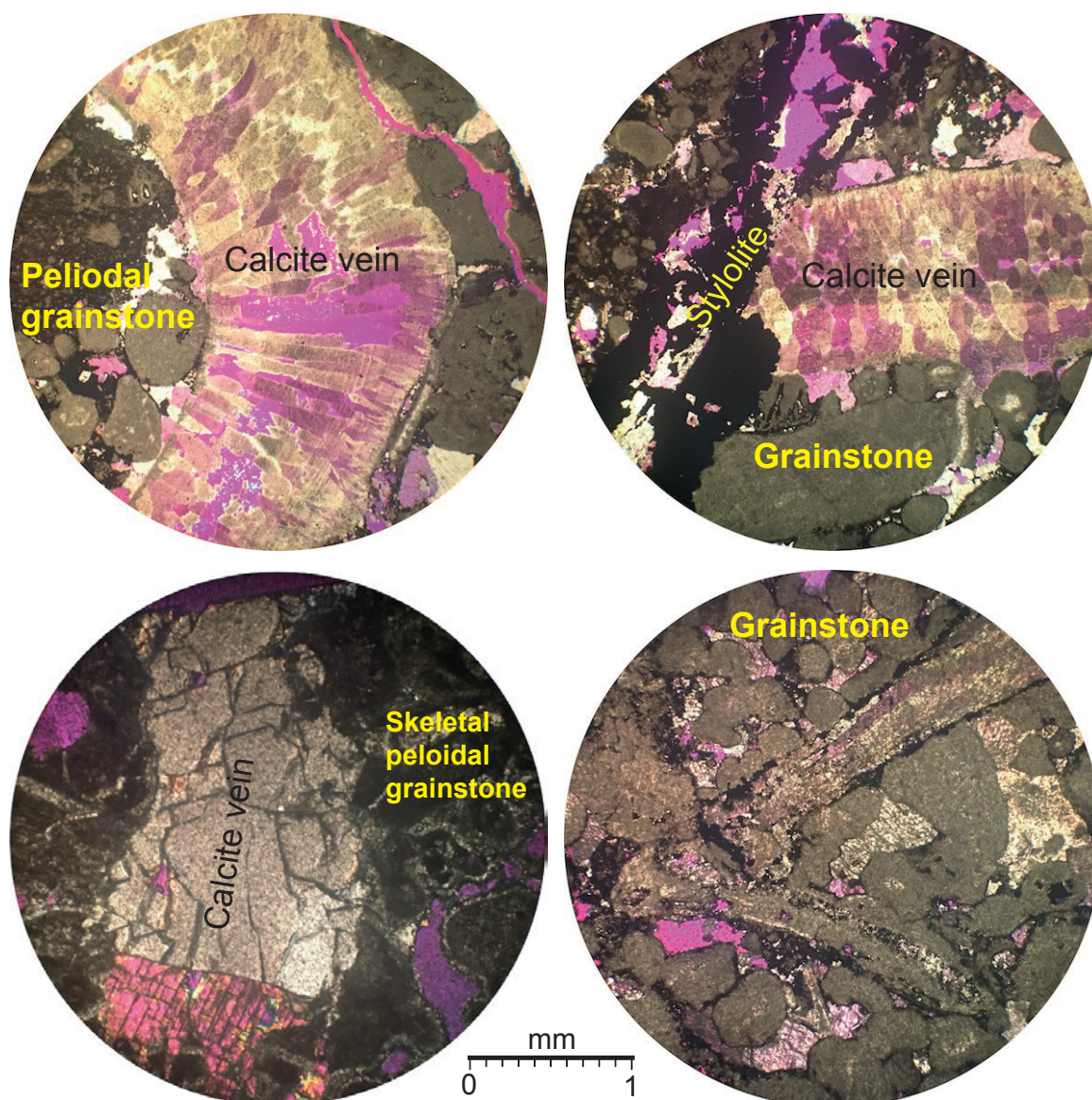


Fig. 4.21: Microphotographs of calcite veins in grainstones.

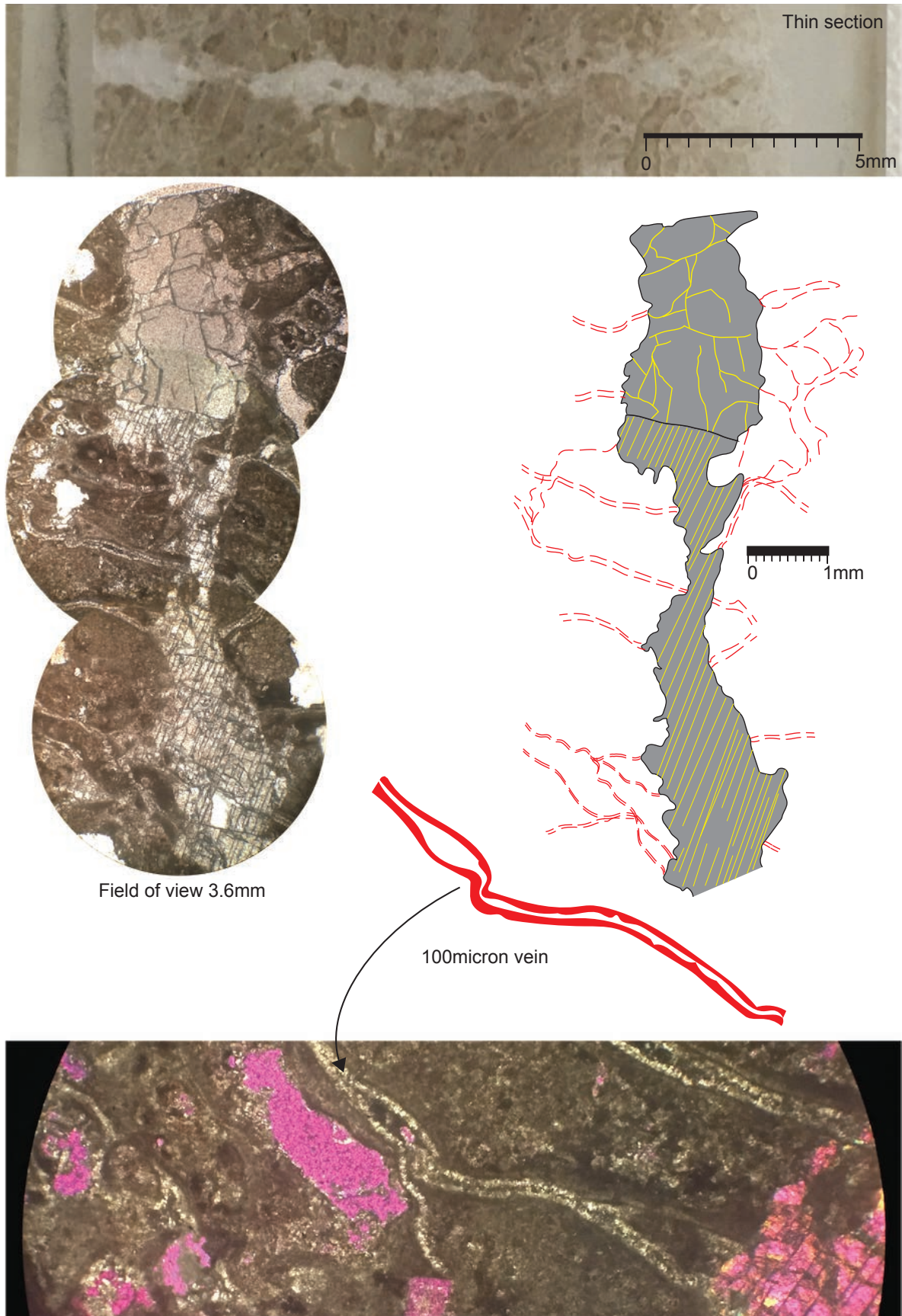


Fig. 4.22: Microphotographs of a calcite vein in skeletal wackestone display different shapes of calcite crystals in the vein, from equant crystals to elongated crystals, connected to hairline veins.

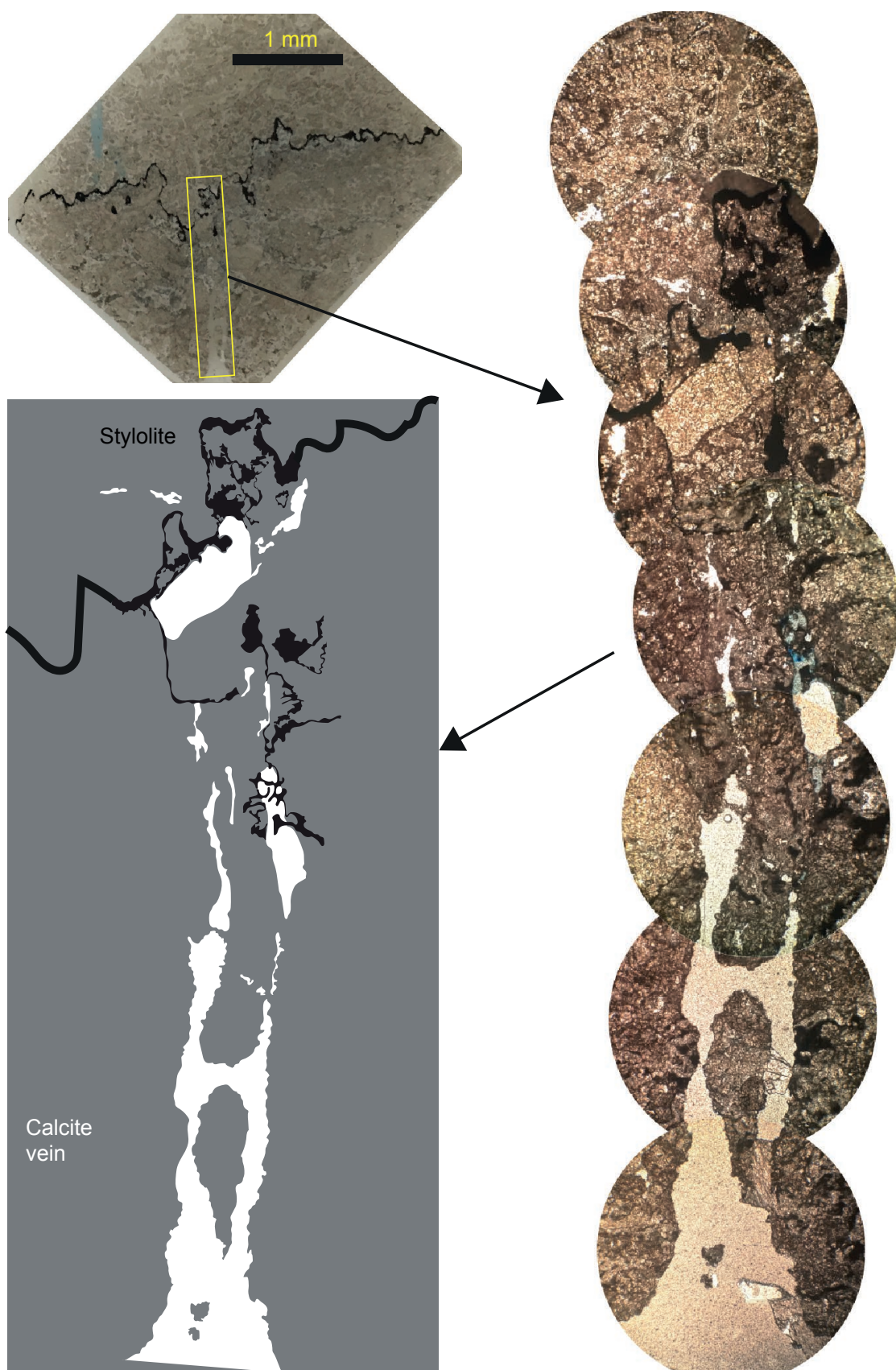


Fig. 4.23: Microphotographs of an intersection between a calcite vein and a bed-parallel stylolite zone.

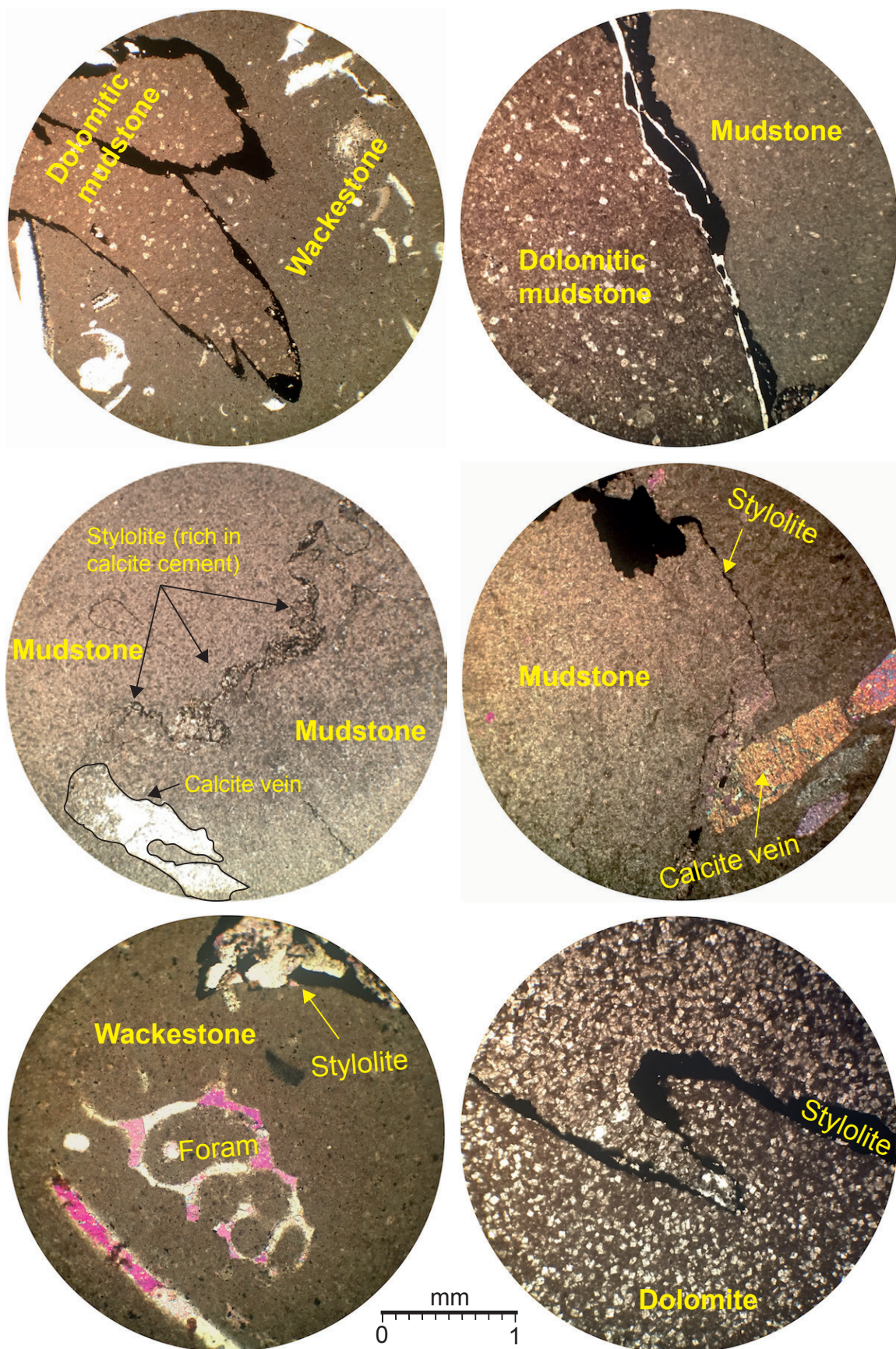


Fig. 4.24: Microphotographs of calcite vein contacts with a bed-parallel stylolite plane.

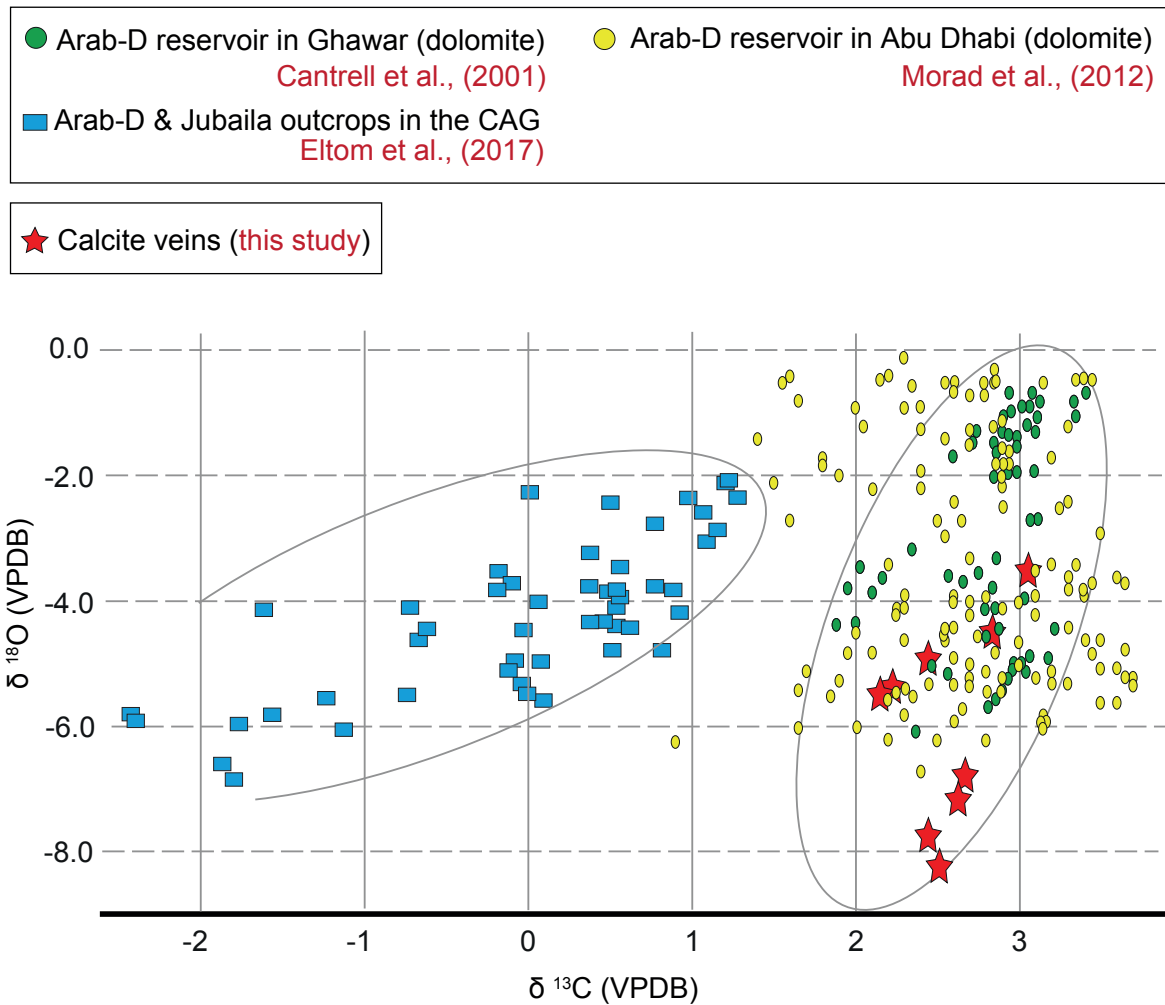


Fig. 4.25: Isotope measurements of calcite veins (plotted as red stars) display negative (light) oxygen isotope values and positive (heavy) carbon isotope values. The values are similar to the isotopic signatures of the Arab-D reservoirs in Ghawar and Abu Dhabi, and different to the Arab-D outcrops in Central Arabia.

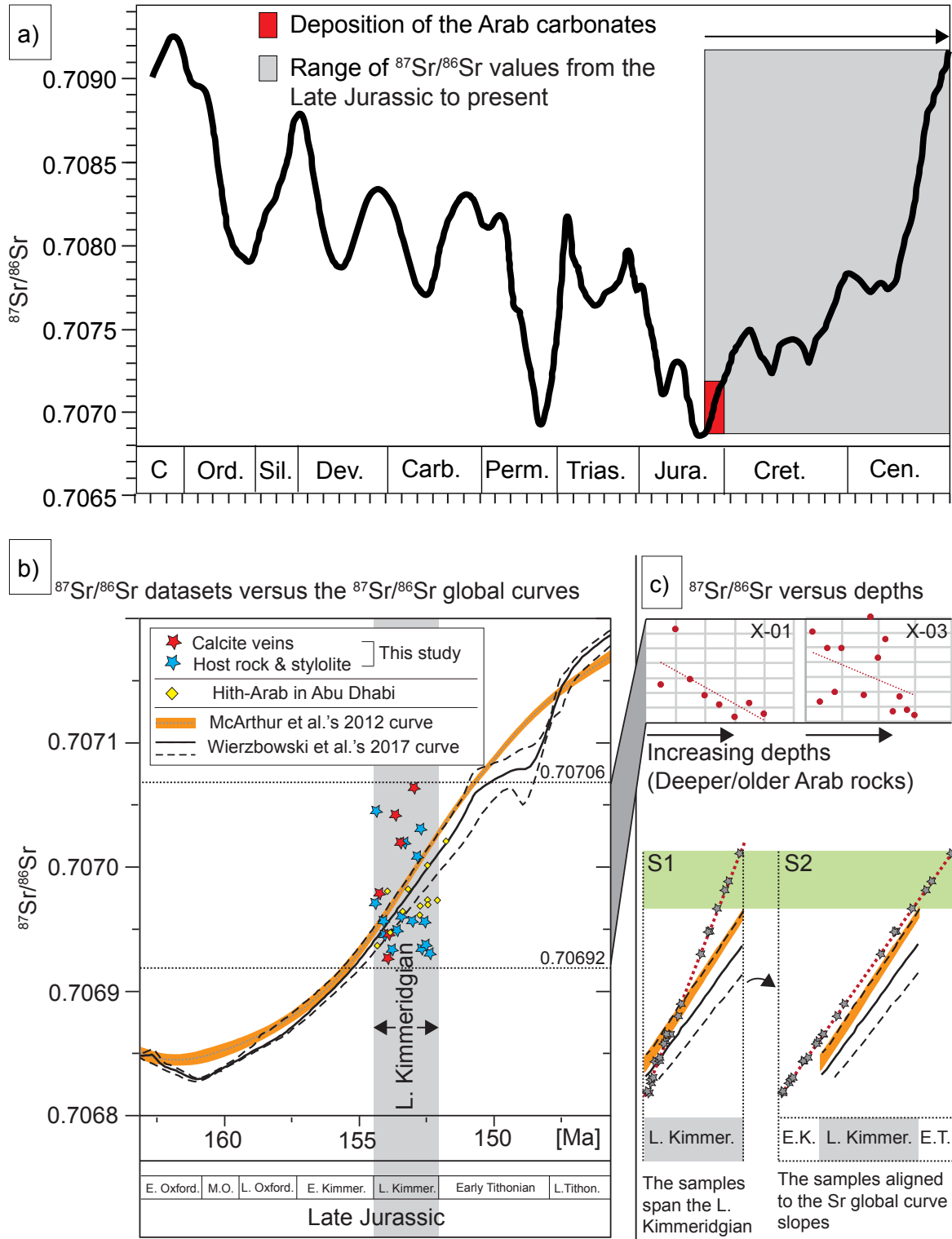


Fig. 4.26: a) Variations of the $^{87}\text{Sr}/^{86}\text{Sr}$ values through the Phanerozoic, modified from McArthur et al. (2012). b) Measured strontium isotopes of calcite veins, host rock, and stylolite zone materials. The $^{87}\text{Sr}/^{86}\text{Sr}$ values are not significantly different from the Late Kimmeridgian seawater $^{87}\text{Sr}/^{86}\text{Sr}$ curves, obtained with 95% confidence limits (McArthur et al., 2012; Wierzbowski et al., 2017) or the previously obtained measurements on the Hith and Arab (A, B, C, and D) reservoirs in Abu Dhabi (Azer and Peebles, 1998), c) the measured $^{87}\text{Sr}/^{86}\text{Sr}$ values relatively decrease with increasing depths of the reservoir samples. This depth relation is used in two hypothetical scenarios (S1, and S2); see the text.

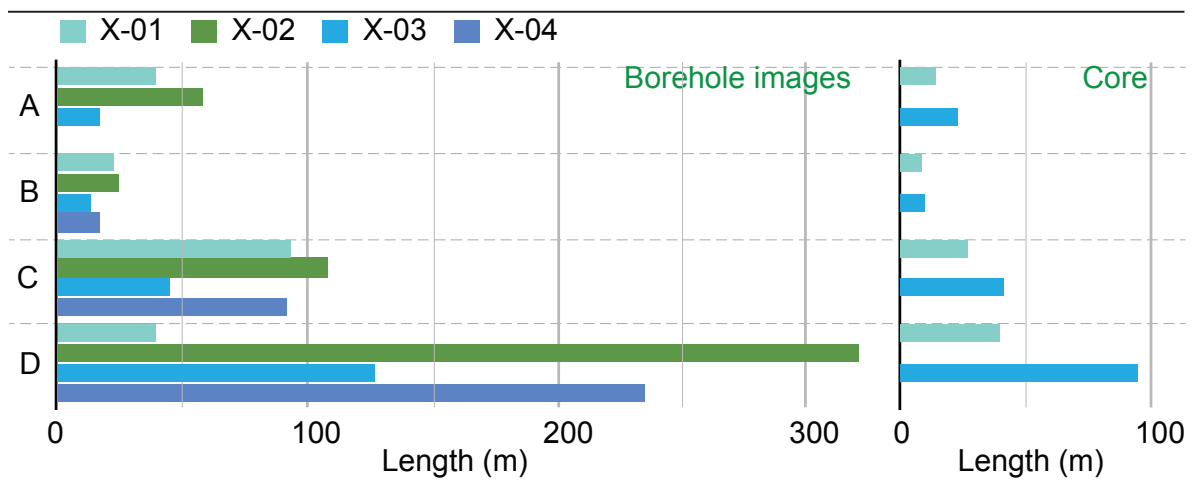


Fig. 4.27: Graphs demonstrate the lengths of the cored and imaged boreholes in the Arab reservoirs.

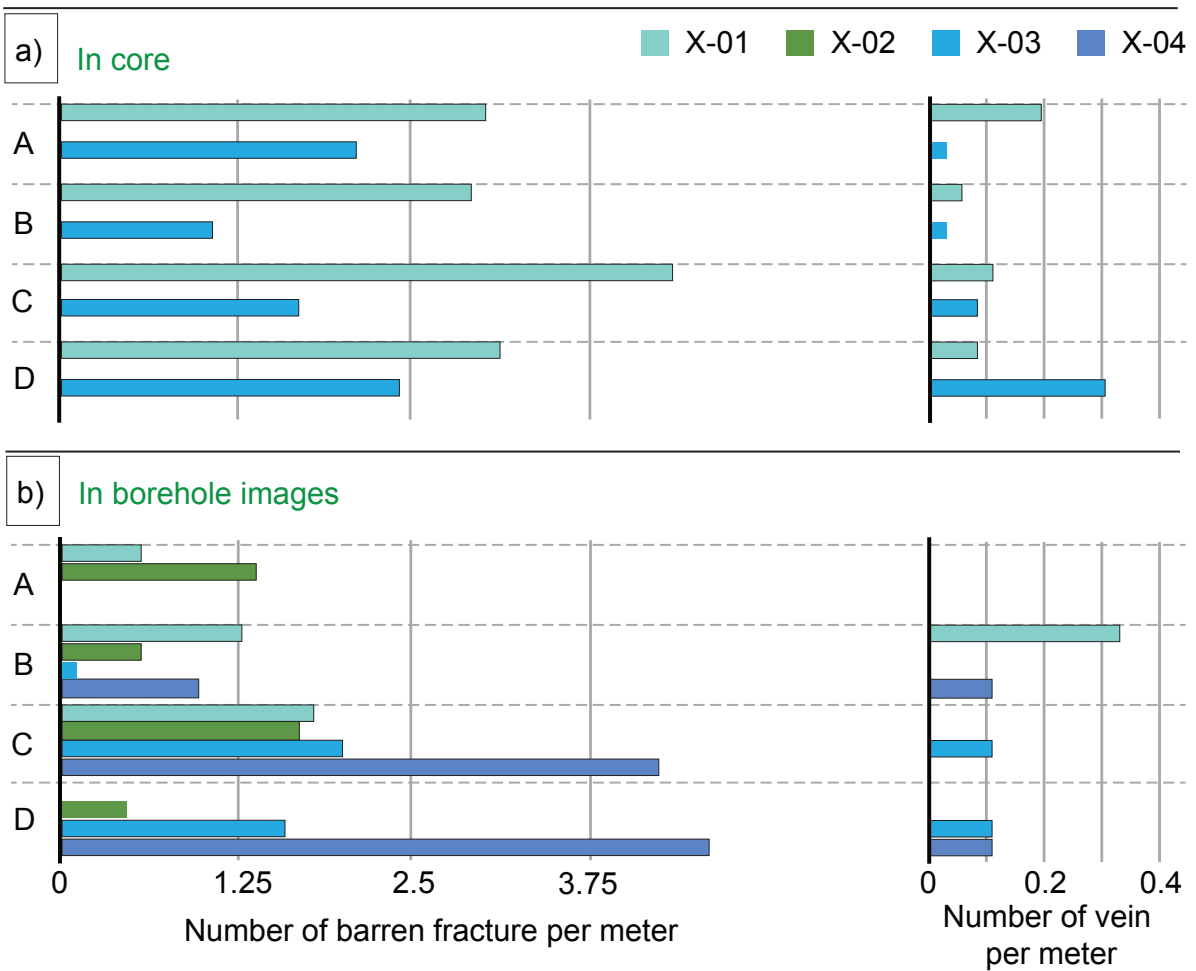


Fig. 4.28: a) Graphs demonstrate fracture abundance in a) core and b) borehole images, as number of fractures per length, or the inverse of fracture spacing, according to the reservoir, borehole, and fracture type (barren—left and veins—right).

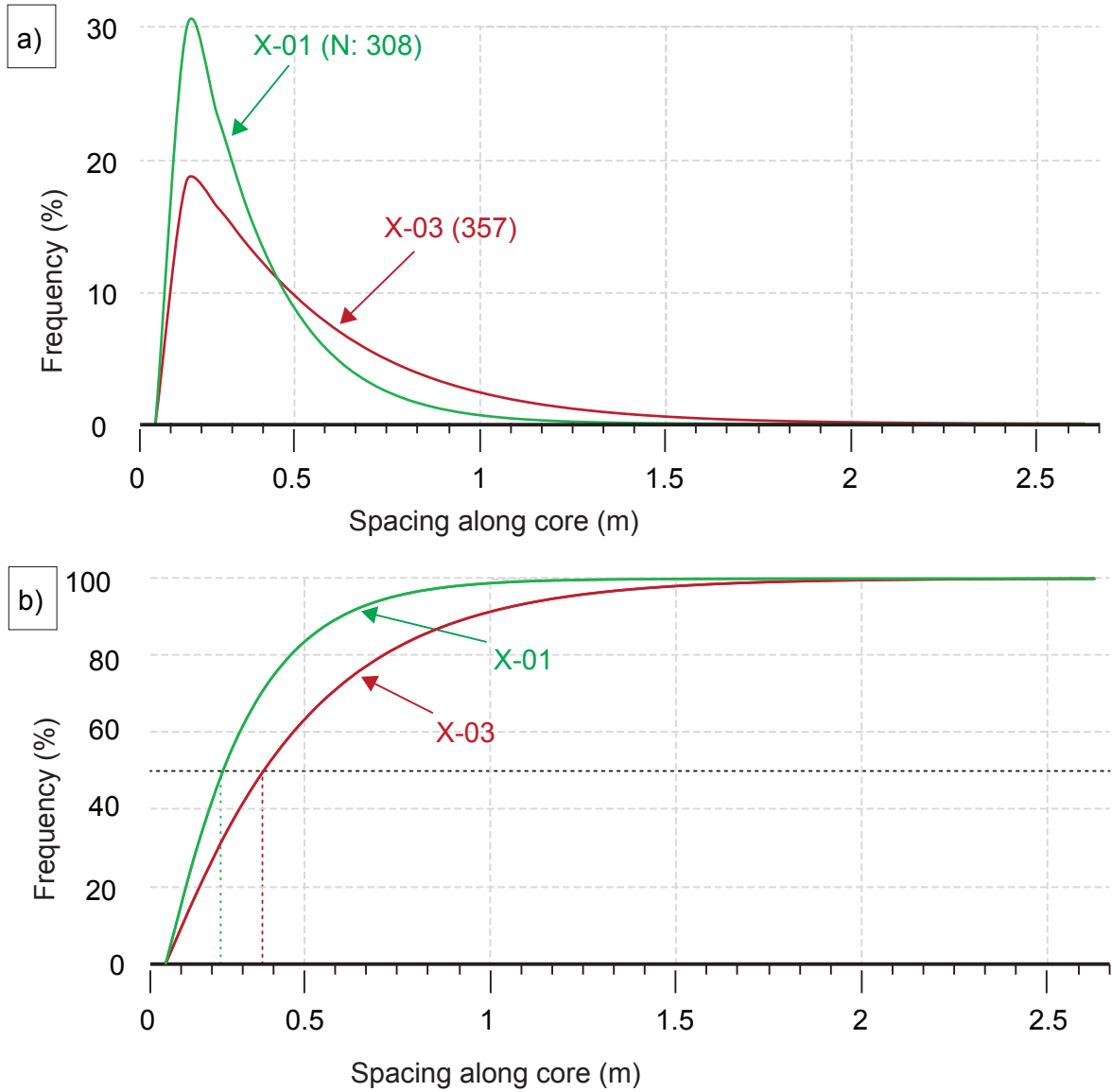


Fig. 4.29: Frequency distribution models of the barren fracture abundance based on the core interpretations of X-01 and X-03.

The two boreholes have different orientations and inclinations. The models display that fracture spacing along the core is dominantly less than 1m in the reservoirs. In the cumulative distribution in (b), 80% of the fracture spacing is less than 50 cm in X-01 and 70 cm in X-03. The mean value of fracture spacing from both boreholes is 35 cm. Model bins: 10 cm.

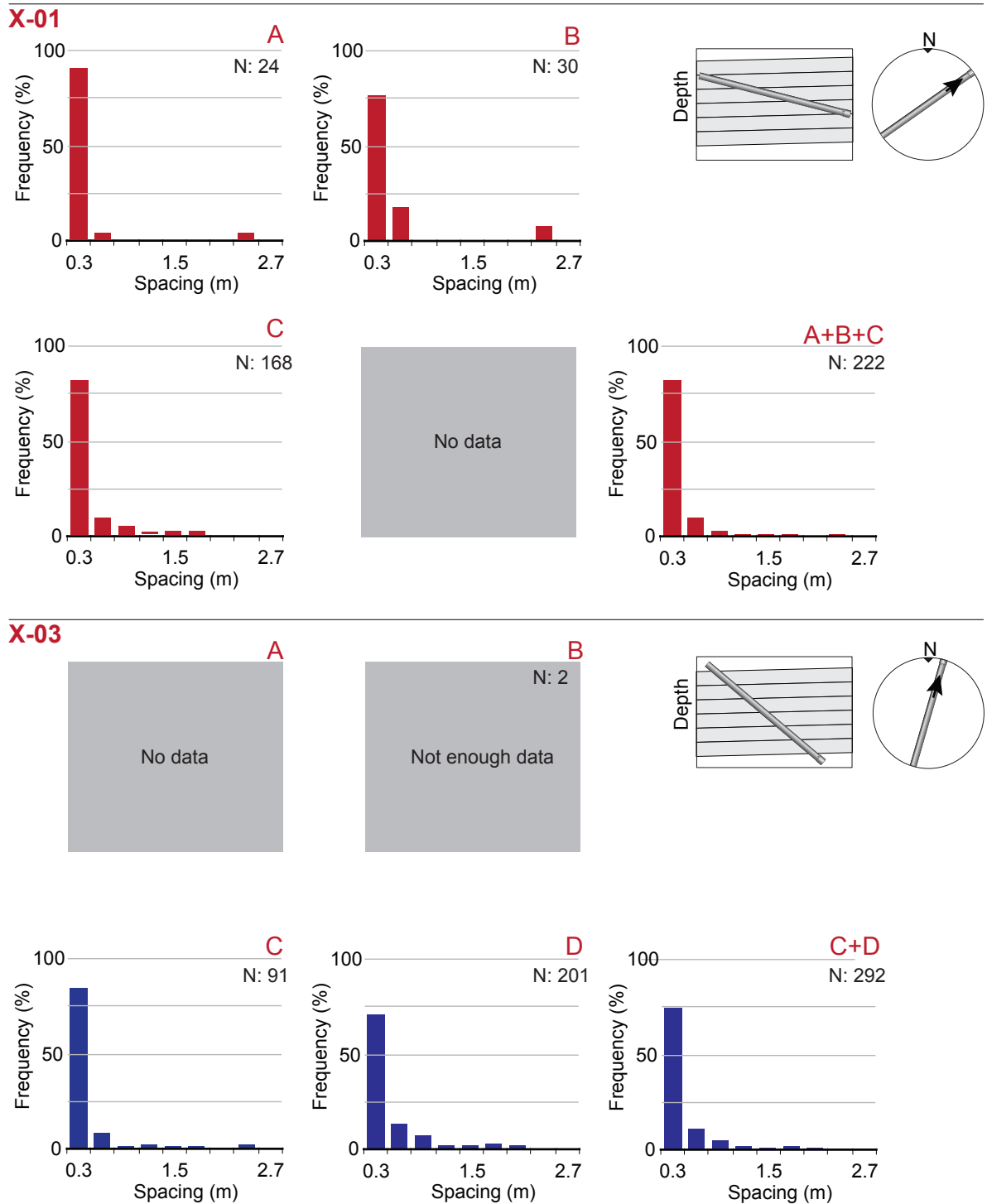


Fig. 4.30: Frequency distribution models of the barren fracture spacing along the boreholes from the borehole image interpretations of X-01 and X-03.

The two boreholes have different orientations and inclinations. The models display that fracture spacing is mostly less than 30 cm in the reservoirs. Note: Gray boxes are for the reservoirs that are not imaged or without enough measurements for statistical distributions. Model bins: 0.3 m.

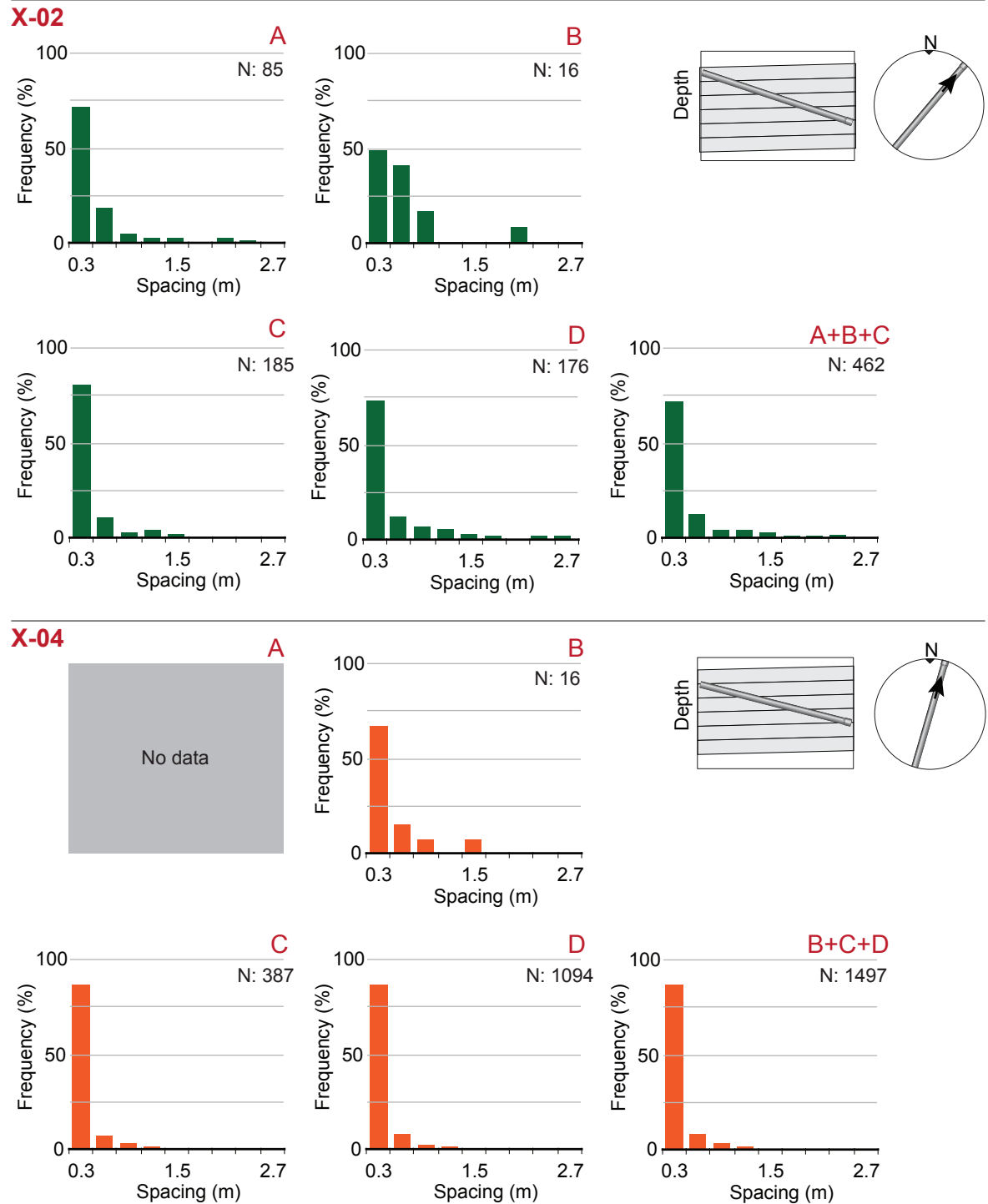


Fig. 4.31: Frequency distribution models of the barren fracture spacing along the boreholes from the borehole image interpretations of X-02 and X-04.

The two boreholes have different orientations and inclinations. The models display that fracture spacing is mostly less than 30 cm in all reservoirs. Note: Gray boxes are for the reservoirs that are not imaged or without enough measurements for statistical distributions. Model bins: 0.3 m.

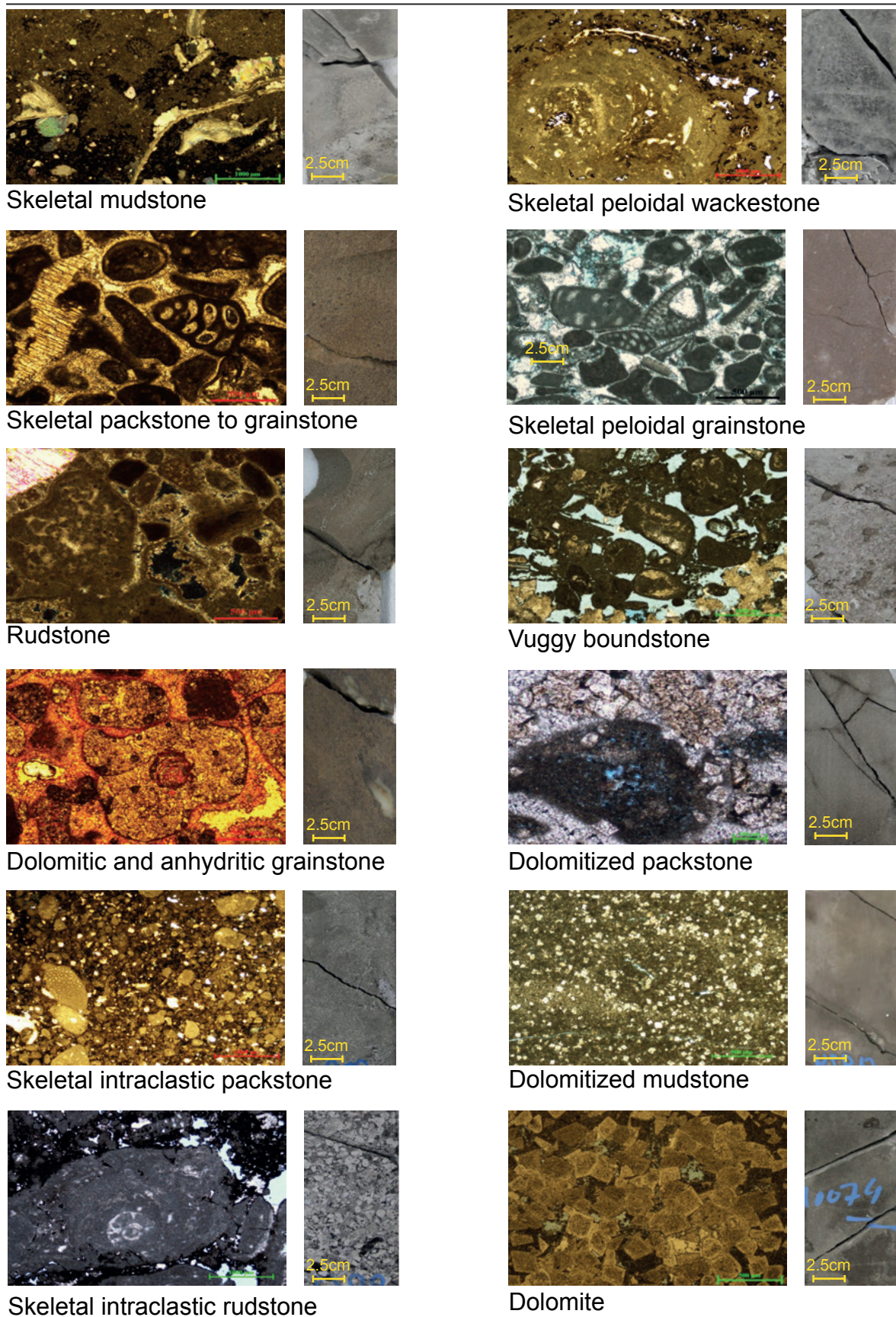


Fig. 4.32: Micrographs of the different carbonate lithofacies where barren fractures were found in the core (pictured at right of each micrograph).

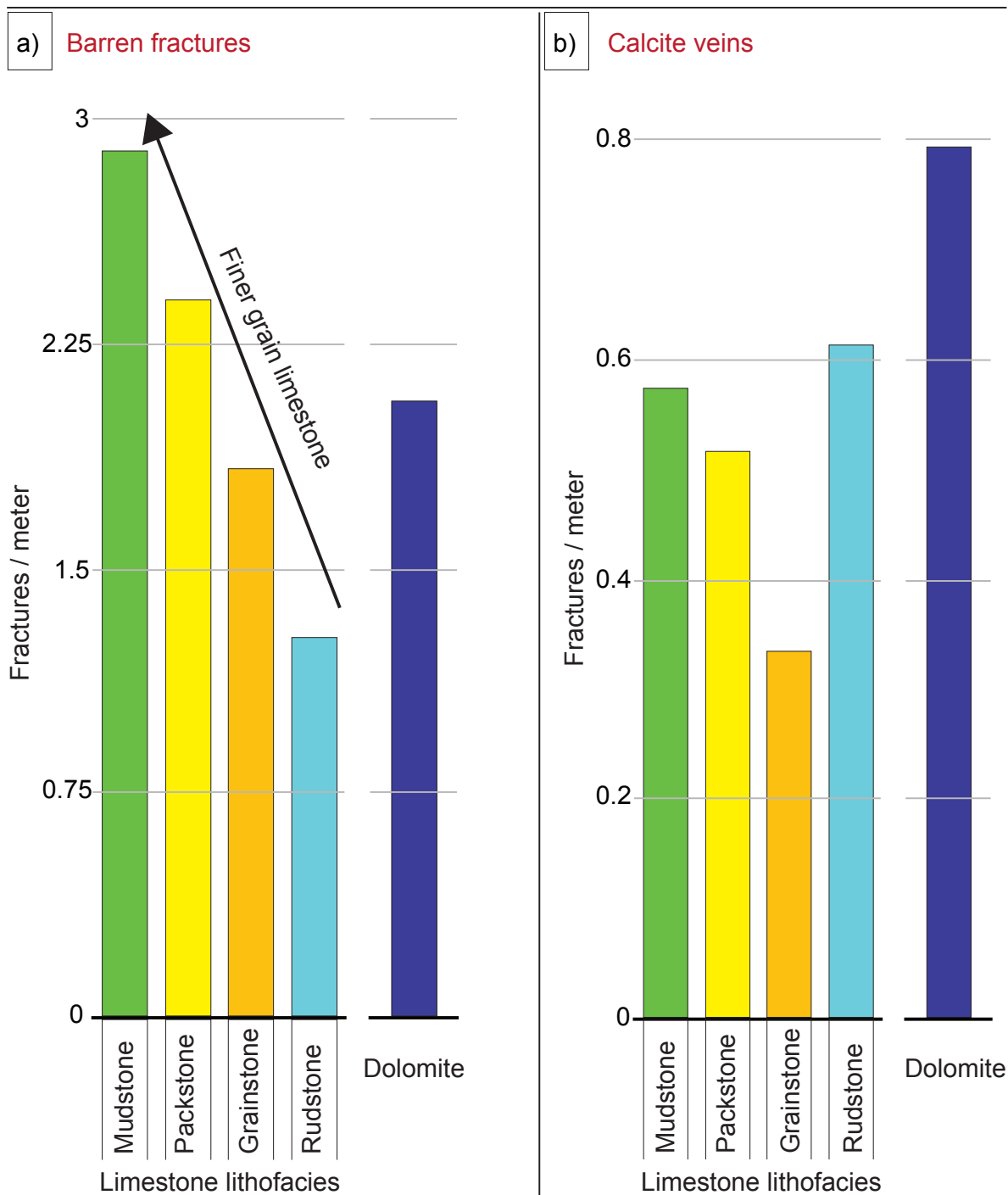


Fig. 4.33: Abundance of a) barren fractures and b) calcite veins in the different lithofacies of the Arab reservoirs based on the descriptions of the X-01 and X-03 cores.

The barren fractures are clearly more abundant in mud-supported limestone than in grain-supported limestone. The dolomite lithofacies displays an average value for the abundance of barren fractures. The abundance of calcite veins is low and does not seem to display an obvious relation to the reservoir lithofacies.

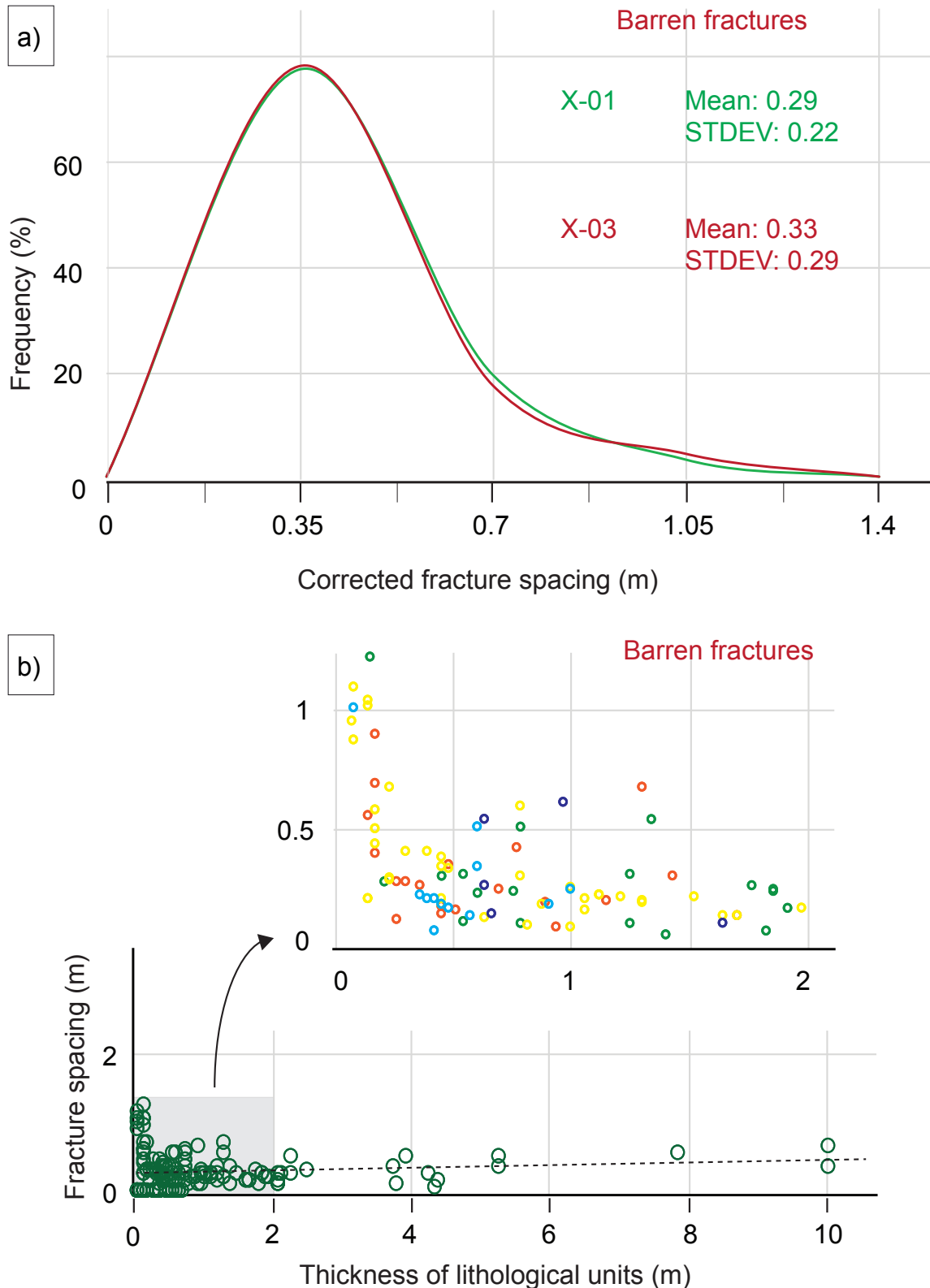
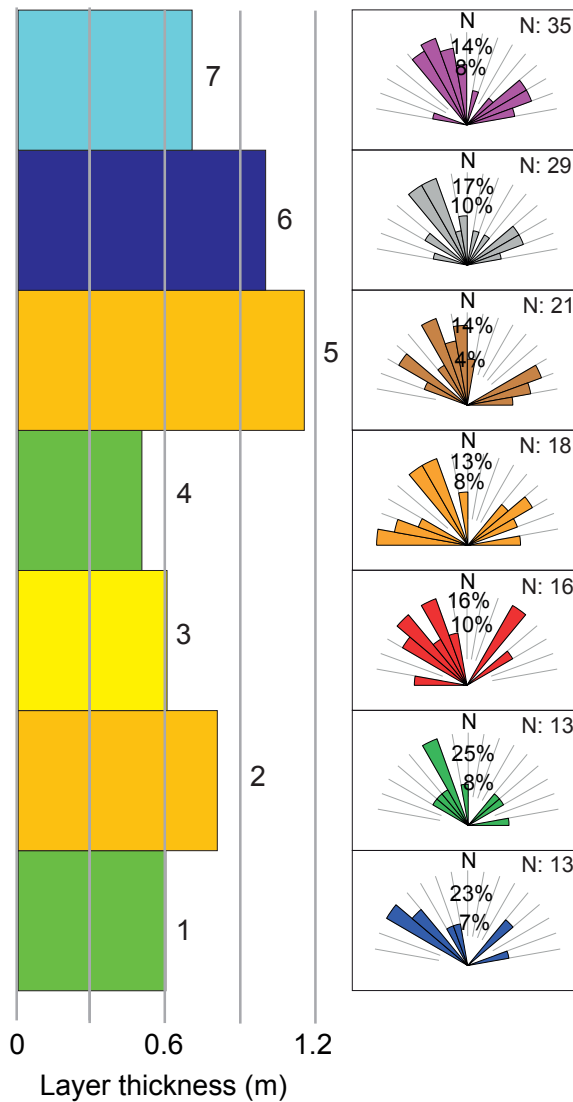
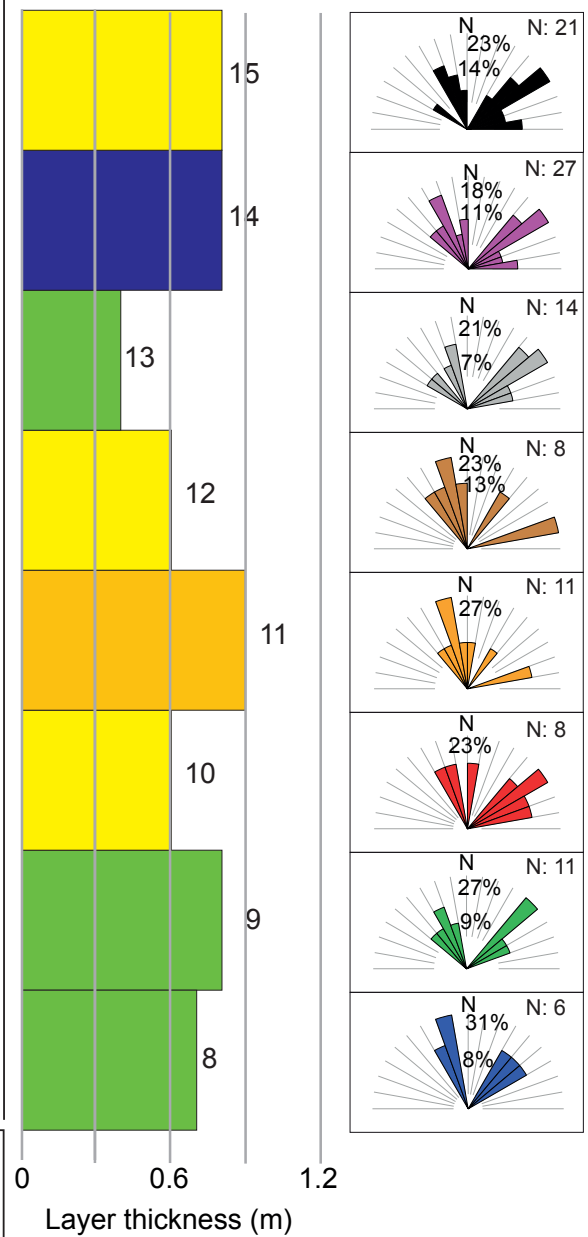


Fig. 4.34: a) The corrected spacing of the barren fractures in the modeled lithological units can be averaged to about 31 cm and with 24 cm standard deviations for the cores of X-01 and X-03. b) Plots of the corrected fracture spacing against thicknesses of the modeled lithological units for all measurements (green circles), and most measurements (colored circles designate the lithofacies). The results display no obvious linear relation to the thicknesses of lithological units.

Wadi Malham - Site 1



Wadi Malham - Site 2



Scanline ID (Rock unit ID)

Mudstone ■ Wackestone/Packstone ■ Grainstone ■ Rudstone ■ Dolomite ■

Fig. 4.35: The scanned units of the Arab-D outcrops in the northern limb of the homocline in Wadi Malham.

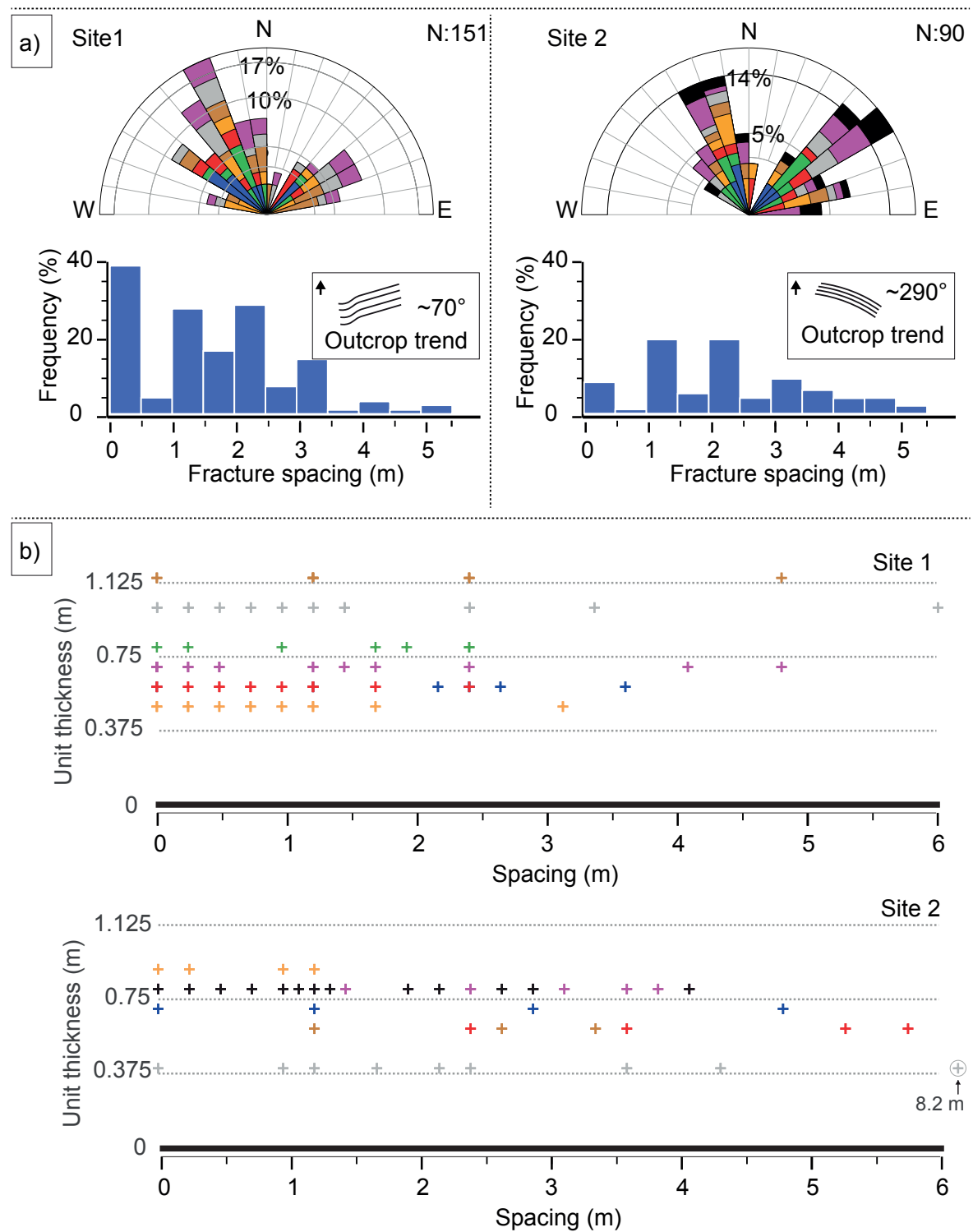


Fig. 4.36: a) Histograms of fracture strikes and spacing in the Arab-D outcrops in Wadi Malham, and b) fracture spacing versus the thickness of layers.
 Note: The statistical distributions of spacing are based on 0.5 m bin sizes. The various colors in the plots are for units at each site (see previous figure).

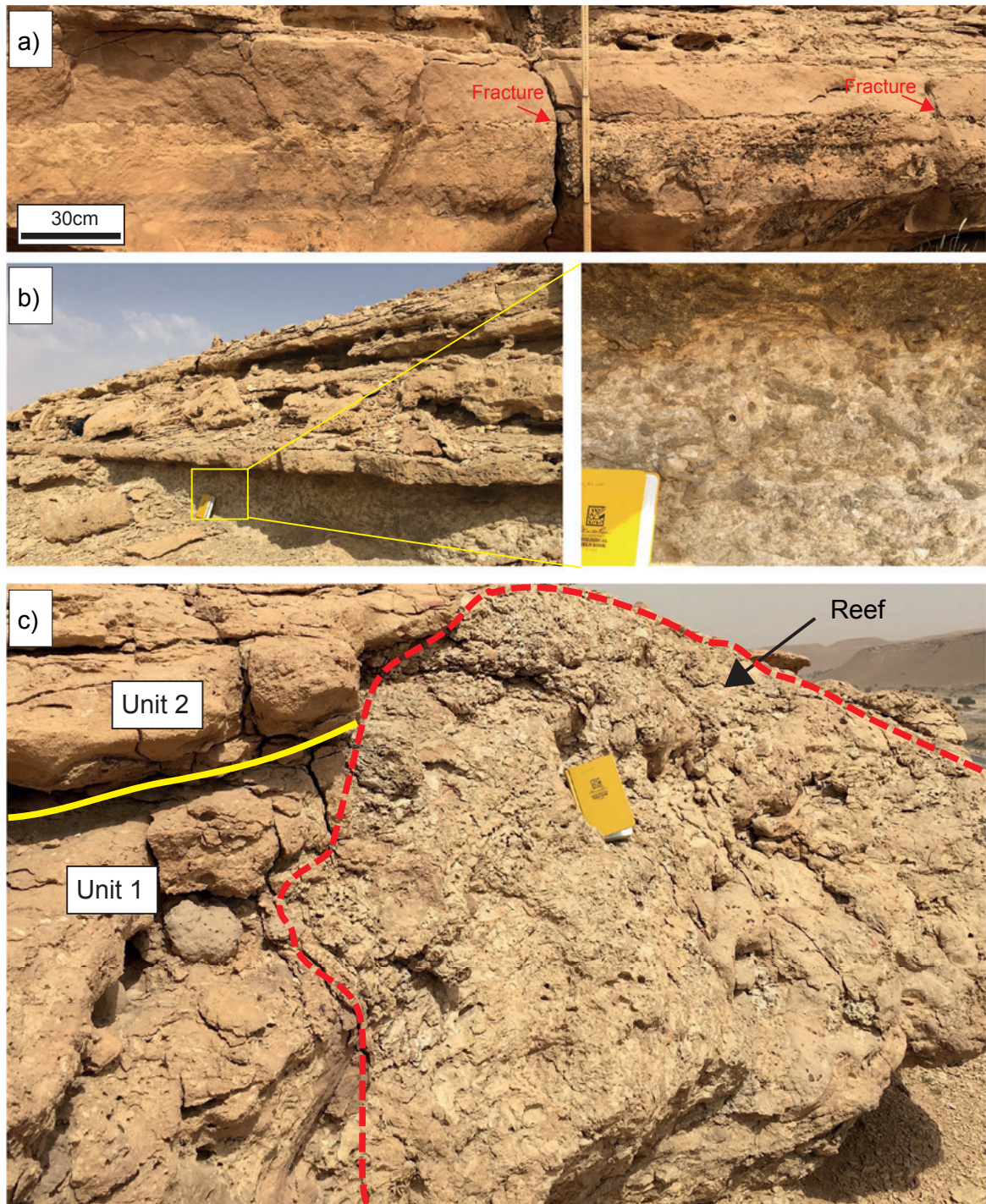
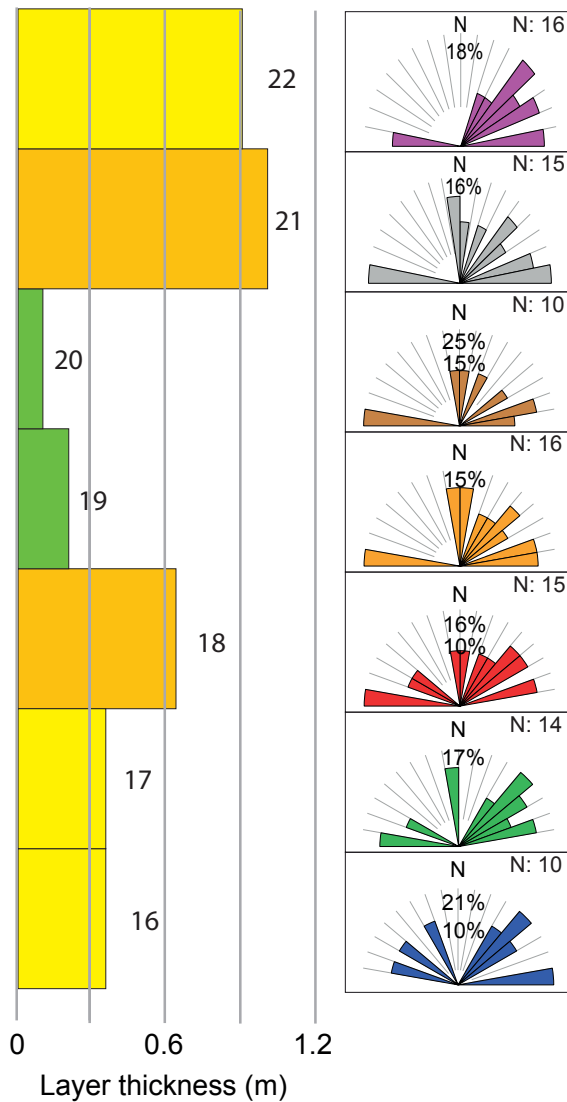


Fig. 4.37: Pictures show field examples of fractures and lateral changes in lithofacies in the Arab-D outcrops: a) a limestone unit (of about 1-m thickness) displays some barren vertical (normal to bedding) fractures, b) a limestone unit of lateral changes in lithofacies marked by presence of burrows and absence of fractures, and c) limestone units that are interrupted locally by a reef buildup.

Howtat Bani Tamim - Site 3



Howtat Bani Tamim - Site 4

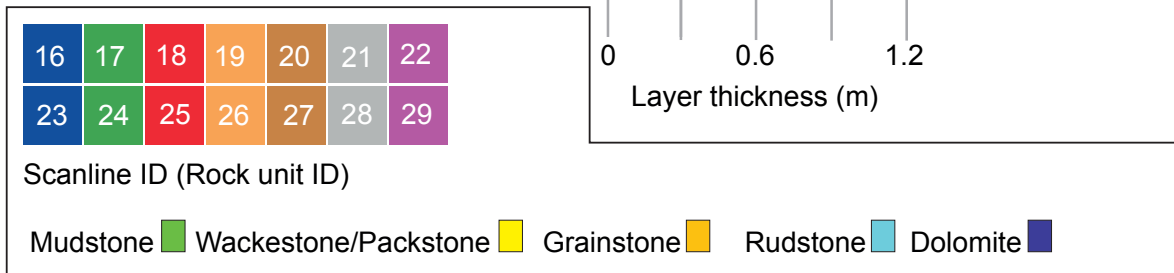
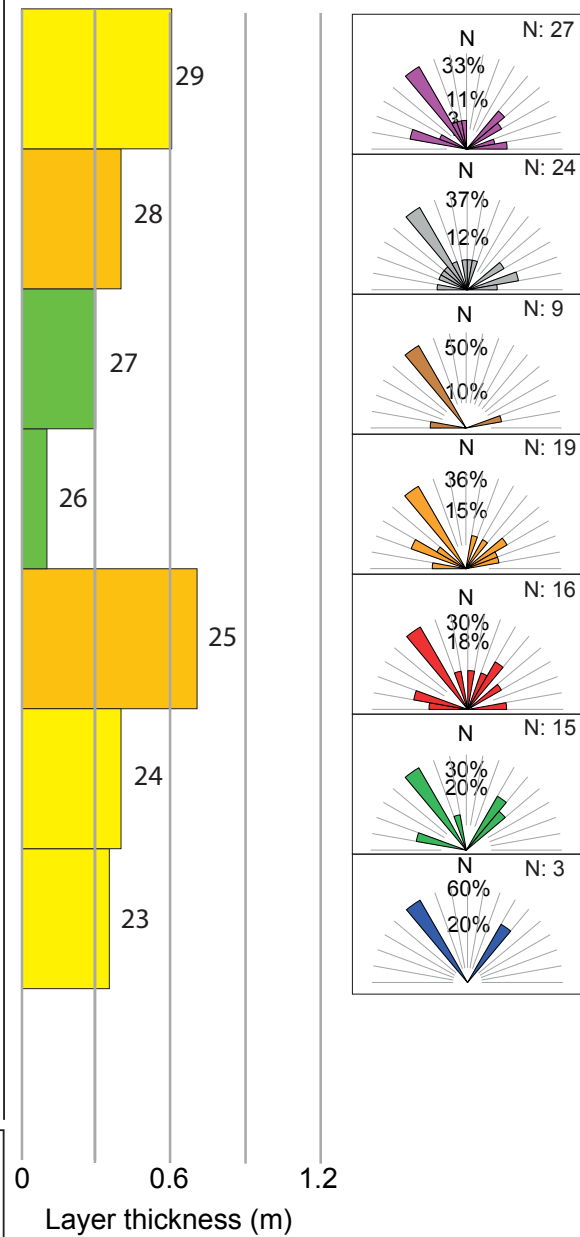


Fig. 4.38: The scanned units of the Arab D outcrops in the southern limb of the homocline in Howtat Bani Tamim.

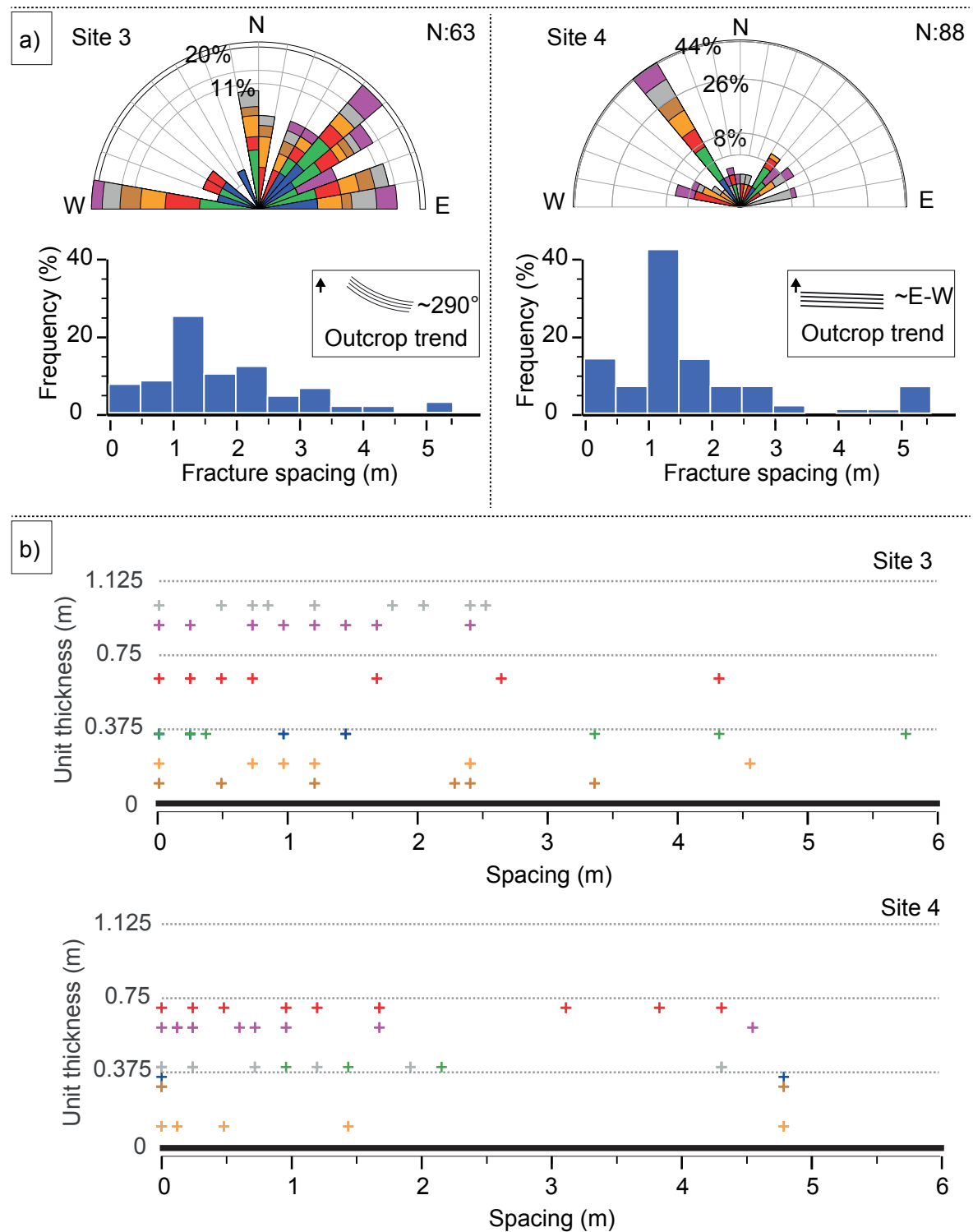


Fig. 4.39: a) Histograms of fracture strikes and spacing in the Arab-D outcrops in Howtat Bani Tamim, and b) fracture spacing versus the thickness of layers.
 Note: The statistical distributions of spacing are based on 0.5 m bin sizes. The various colors in the plots are for units at each site (see previous figure).

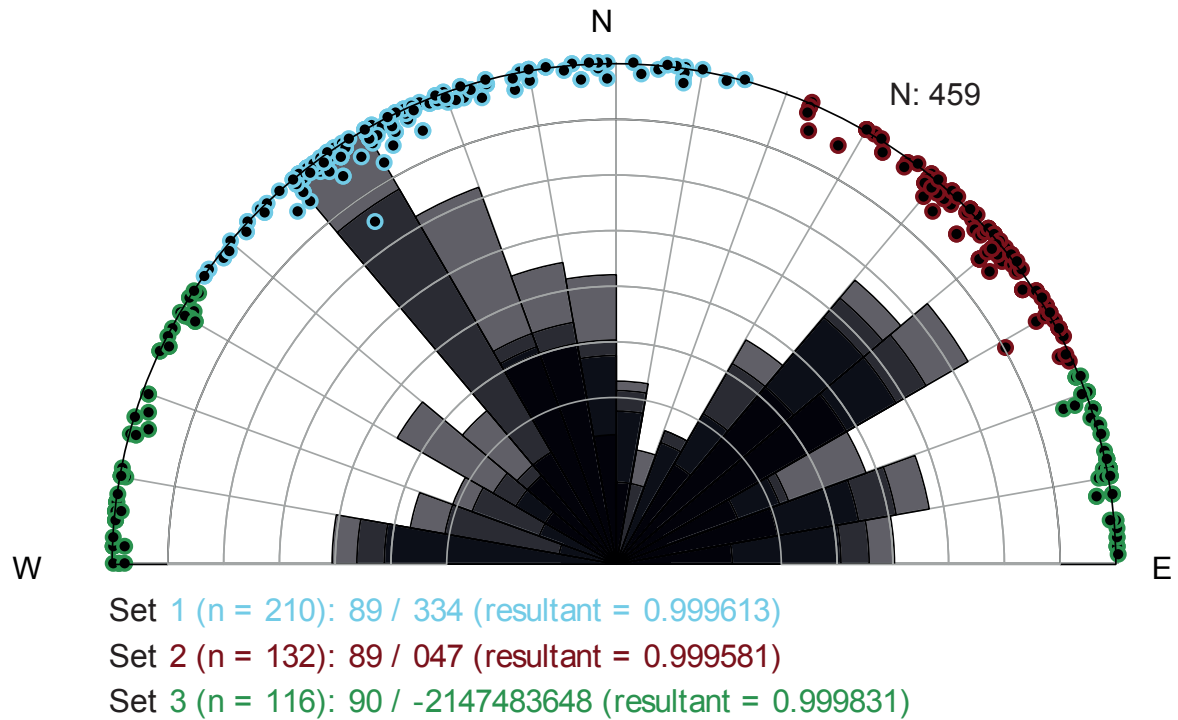


Fig. 4.40: Strike measurements of the Arab-D outcrop fractures in Wadi Malham and Howtat Bani Tamim. Fracture strikes display two primary sets of NE–SW and NW–SE fracture systems, in addition to a secondary E–W fracture system.

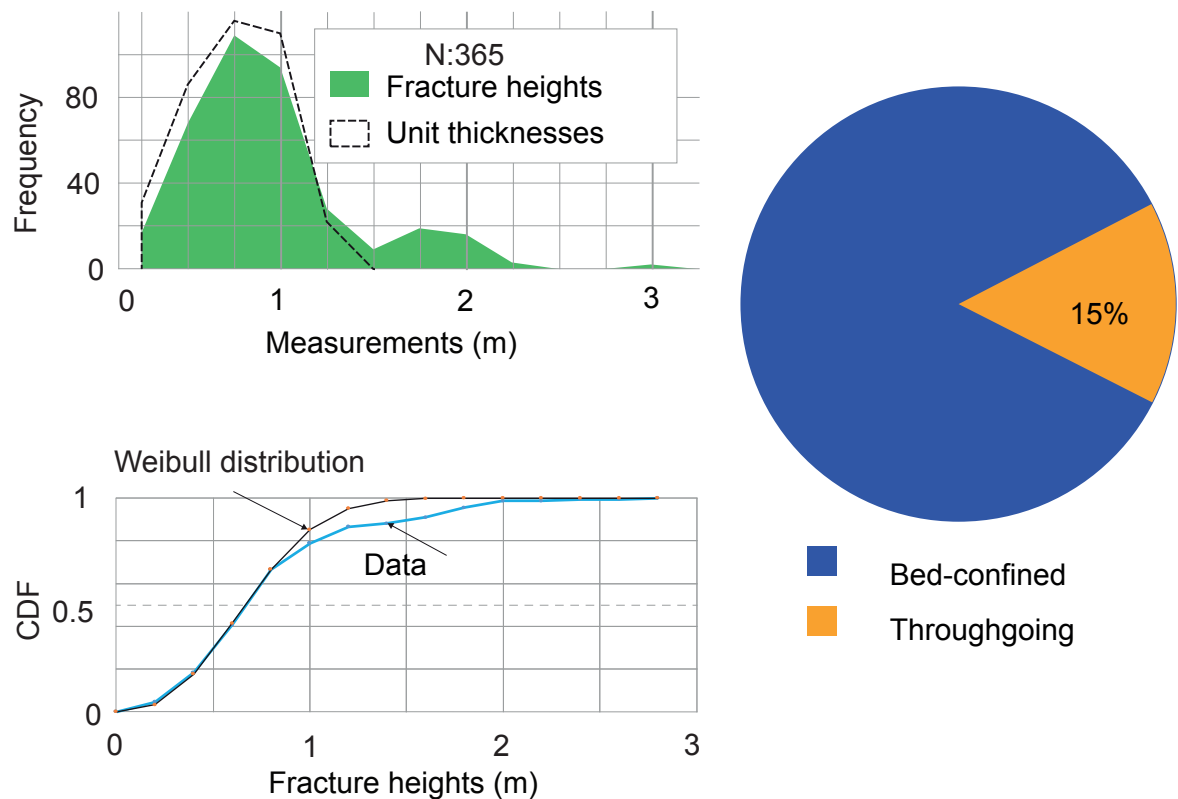


Fig. 4.41: Measurements of the fracture heights in the Arab-D outcrops in Wadi Malham and Howtat Bani Tamim. Most fractures (85%) are found to be layer-bounded fractures.

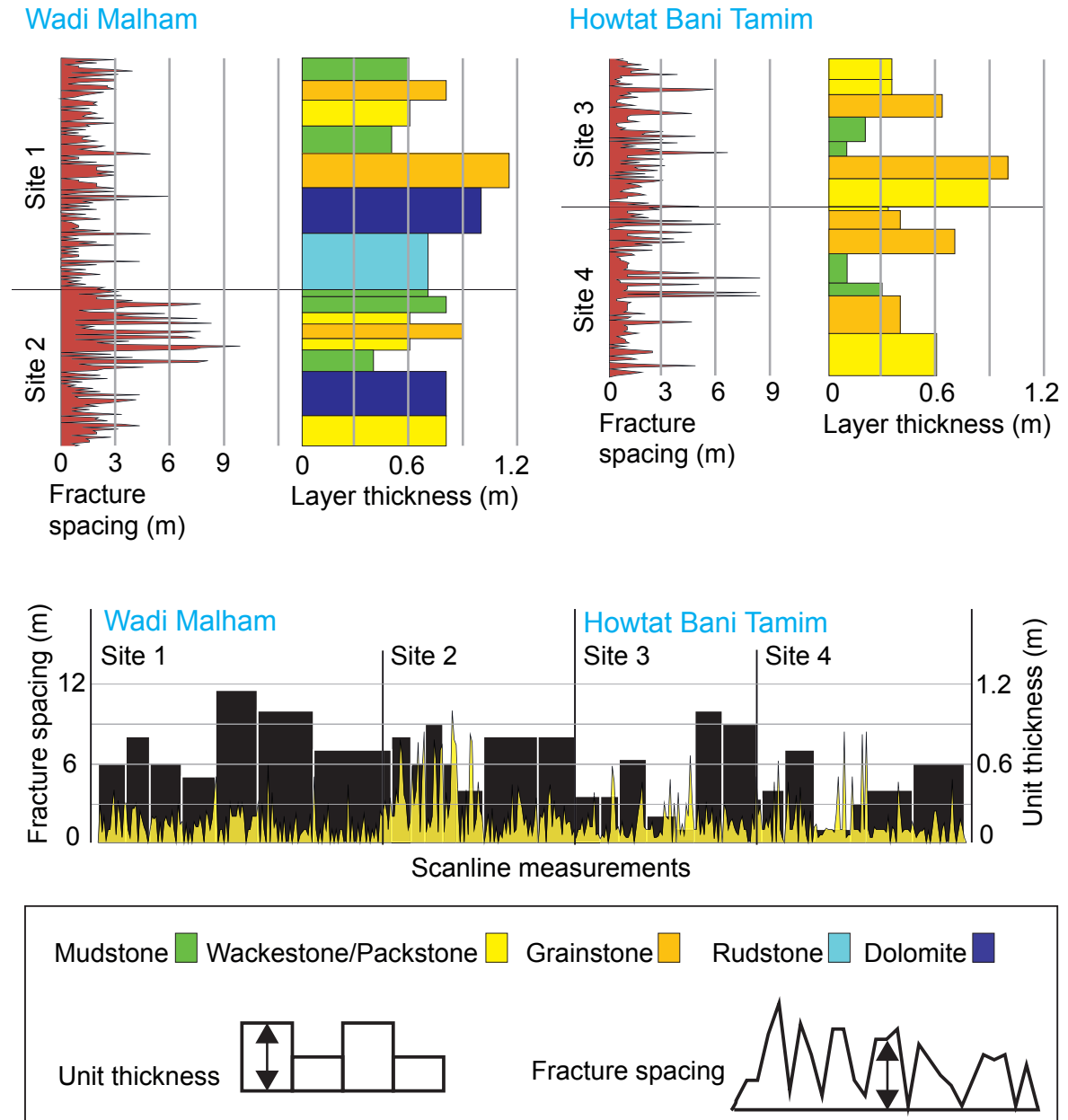


Fig. 4.42: Measurements of the fracture spacing in the Arab-D outcrop fractures in Wadi Malham and Howtat Bani Tamim.

Fracture spacing measurements are made along 29 scanlines that are plotted against the thickness and lithology of the surveyed layers. The plot displays that the fracture spacing fluctuates from small values of 0 (fracture intersection) to some large values (greater than 6 m). The spacing of fractures is mostly clearly larger than the thickness of the host layer, except for the thin mudstone units of less than 30 cm.

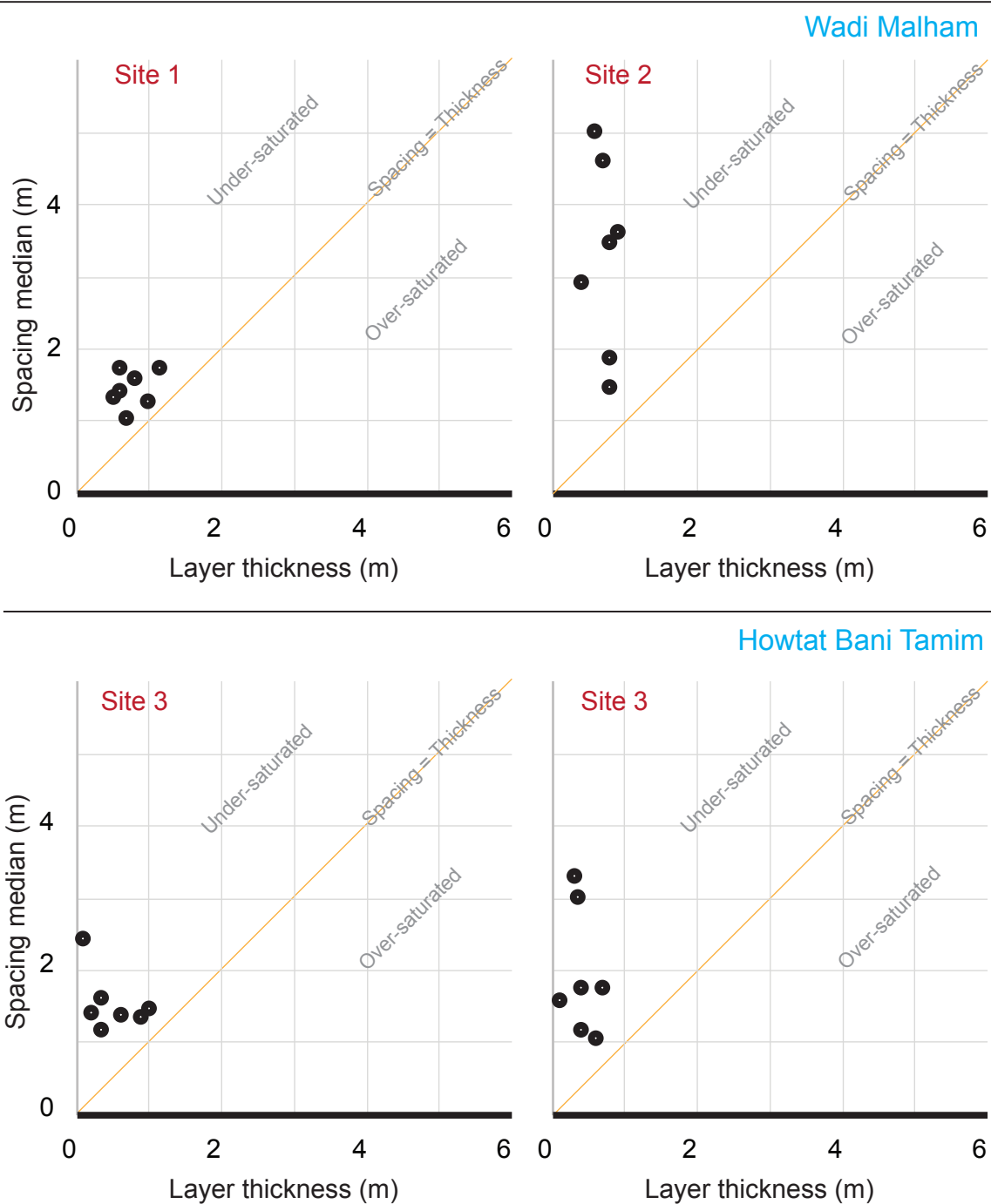


Fig. 4.43: Measurements of the fracture spacing in the Arab-D outcrop fractures in Wadi Malham and Howtat Bani Tamim.

There are no apparent linear relationships between the fracture spacing and lithology or thickness of the host layers. The fracture abundance is clearly undersaturated in these regions of the homocline.

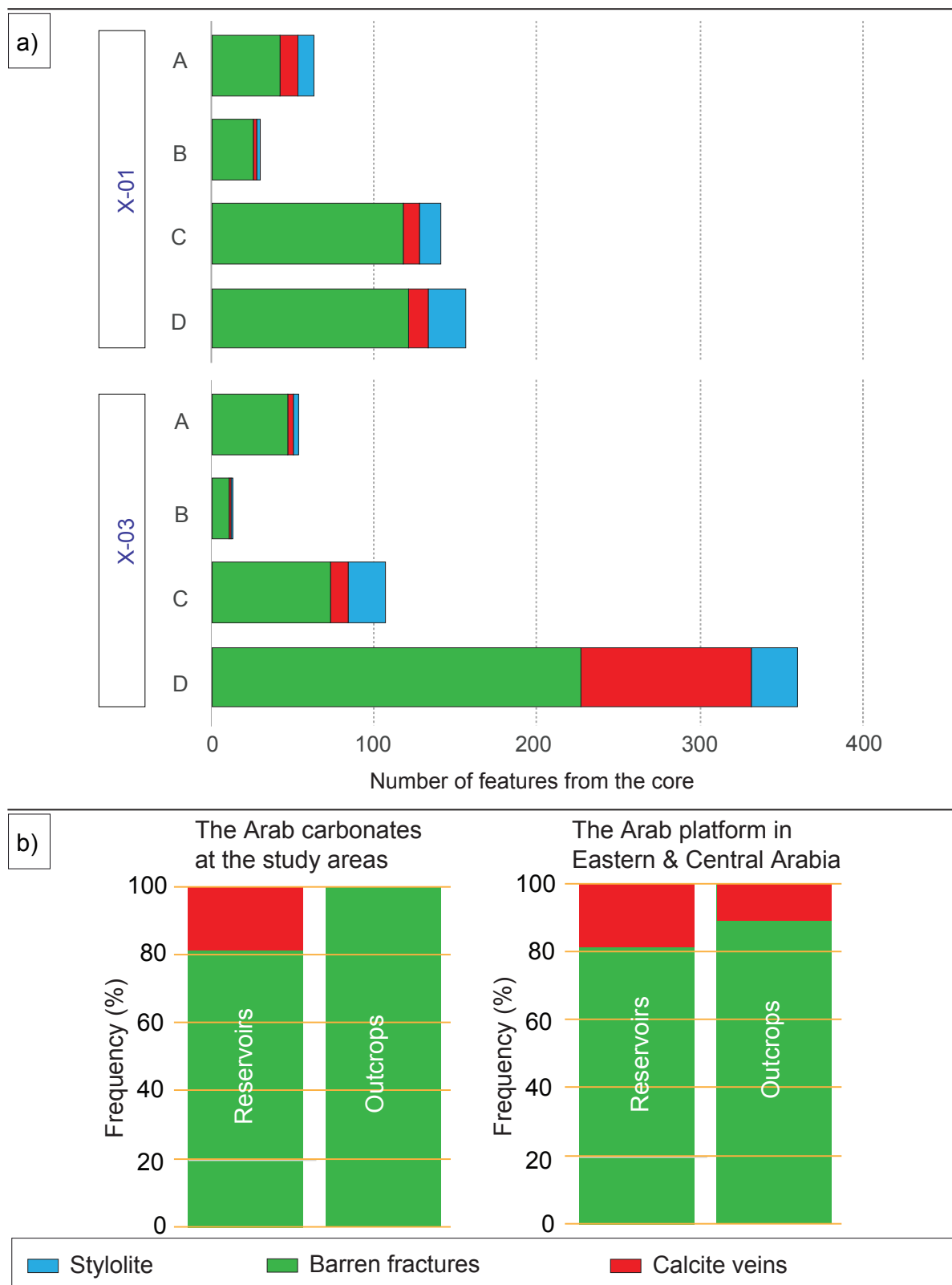


Fig. 4.44: a) Abundance of stylolites, barren fractures, and calcite veins described from the core of X-01 and X-03; b) models for possible ratios of barren fractures and calcite veins in the study areas and across the Arab carbonate platform based on this research and previous work (see the text).

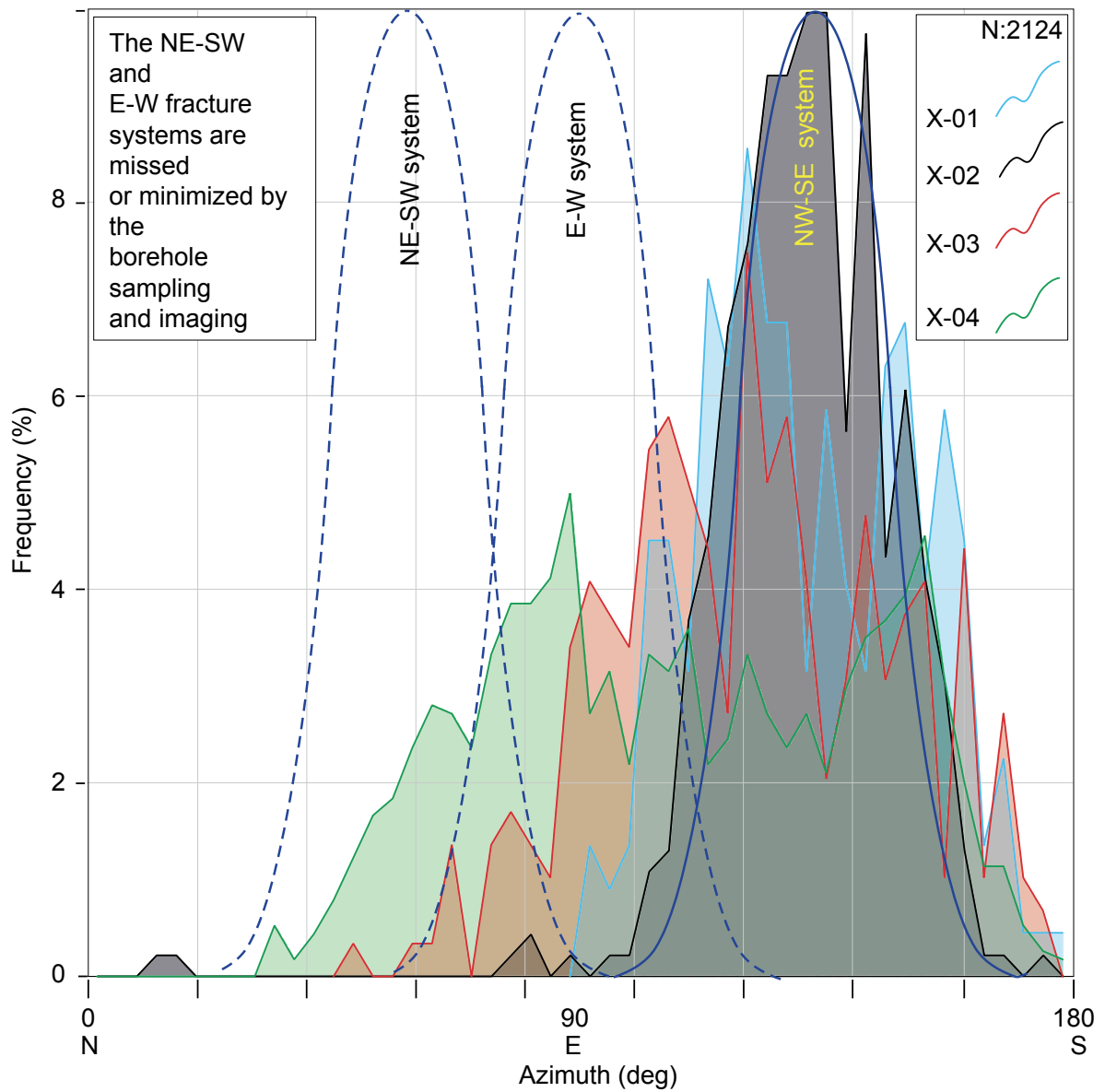


Fig. 4.45: Frequency distributions of the strikes of the reservoir barren fractures that are measured from the borehole images of X-01, X-02, X-03, and X-04.

The strike measurements are biased because fractures can be missed or undersampled by the parallel or nearly parallel boreholes. The boreholes of X-01 and X-02 missed the NE-SW and E-W fracture system, and the boreholes of X-03 and X-04 indicated the presence and abundance of these systems, despite the boreholes being not completely normal to the strikes of these fracture systems (between 60° and 80°).

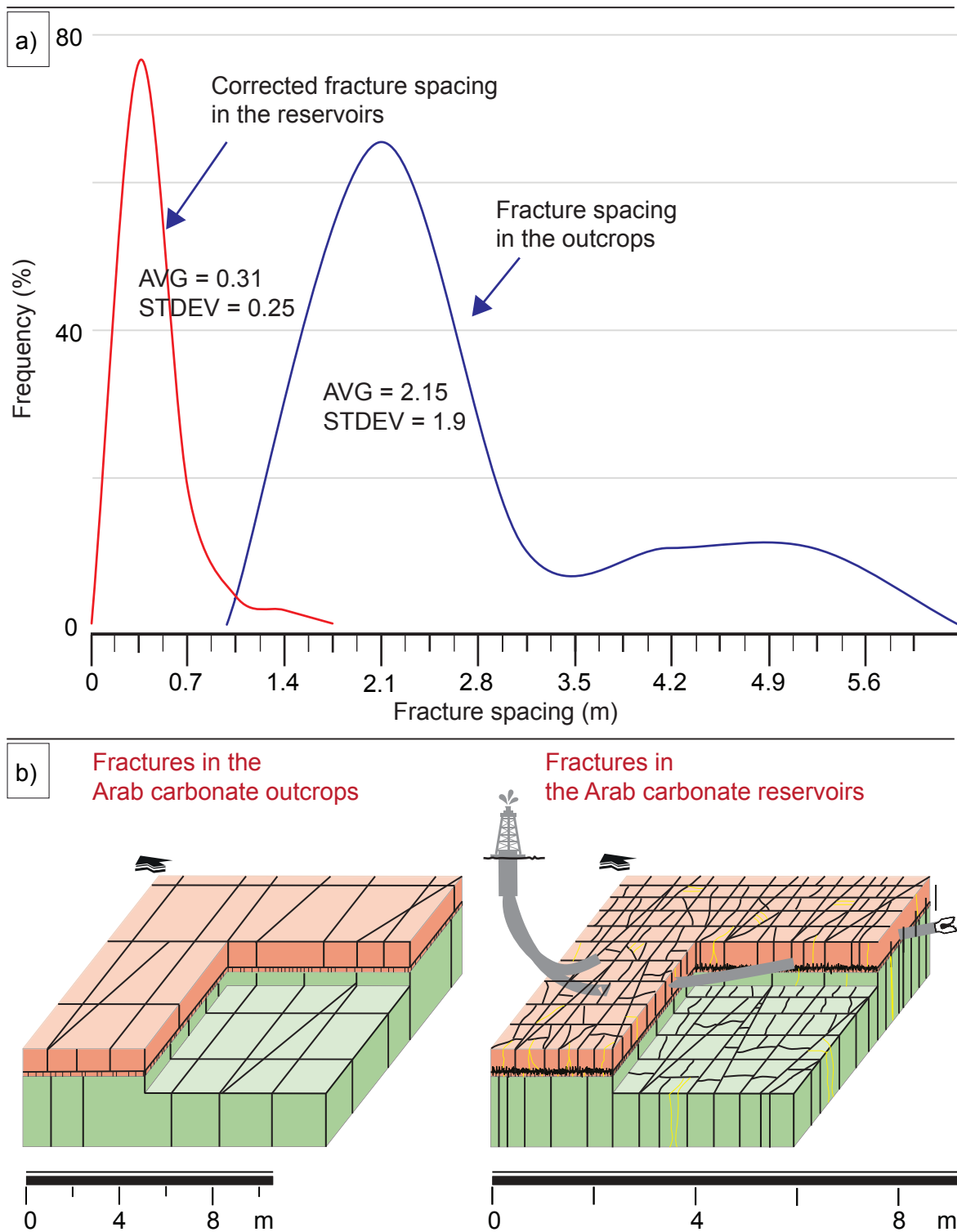


Fig. 4.46: a) Frequency distributions of the fracture spacing in the outcrops and the corrected fracture spacing in the reservoirs.

The abundance of the Arab reservoir fractures in the dome is much higher than the abundance of the Arab-D outcrop fractures. b) Schematic models display general abundance and trends of the fractures in the Arab carbonates (black lines for barren and yellow for calcite veins).

5 FRACTURE ABUNDANCE IN CORE AND BOREHOLE IMAGES

ABSTRACT

Several methods exist for collecting data about fractures in subsurface reservoir rocks. The datasets, with the exception of core data, are indirect and subject to limited resolution. This chapter presents new results on the detection of dilatant fractures in carbonate reservoirs by modern electrical borehole imagers. Barren and calcite-filled fractures (veins) were described and compared from core and borehole images. These datasets were obtained from directional drilling into the Arab reservoirs in Eastern Arabia. The comparison resulted in a significant mismatch in measurements of fracture abundance. Many core fractures could not be detected from corresponding borehole images. The mismatch can be generally related to fracture size (width of veins and aperture of barren fractures). Most calcite veins were undetected because they exhibit widths less than 2 mm. Exceptions include a few calcite veins of 0.5 mm that were detected because of the strong data resistivity contrast between these resistive veins and conductive host rocks. The barren fractures that are aligned subparallel to the present-day S_{Hmax} were detected more abundantly than other non-aligned fractures. Consistent with this finding was another important finding: aligned fractures exhibit relatively large apertures in the borehole images. The apertures diminish in size as fractures gradually deviate in orientation from S_{Hmax} . Most of the non-

aligned barren fractures were undetected, except the fractures with rough walls. This indicates that the walls of the non-aligned fractures are mechanically closed by the normal S_{Hmax} , and that the remaining apertures were dependent on the availability of roughness mismatches between the closed fracture walls. Electrical borehole imaging is generally limited in measuring fracture abundance, but indispensable to detect and measure the orientations and apertures of fractures. Deploying imaging tools can also help to filter out the large (i.e., more conductive) fractures in reservoir rocks.

5.1 INTRODUCTION

Diverse methods exist in the petroleum industry for describing some fracture properties in reservoir rocks (e.g., Nelson, 2001), but the datasets underpinning this effort are predominantly indirect and subject to limitations of data resolution, sampling dimension, and calibration (e.g., Nelson, 2011). The 3D seismic reflection survey provides the means to image large volumes of subsurface rocks (e.g., Cartwright and Huuse, 2005), but it is incapable of detecting fractures, leading to the labeling of fractures as “subseismic” in the scientific literature. Fracture detection methods derived from 3D seismic data are, nonetheless, increasingly being developed for possible indirect fracture signatures from anisotropy, curvature, and other attributes of seismic reflection datasets (e.g., Liu and Martinez, 2013).

The data from boreholes vary considerably, both in the quality of measurements and the length scale of detection of fractures relative to the borehole dimensions. Borehole datasets range in quality from well pressure tests that may merely hint at the influence of fracture aggregates (e.g., Tsang et al., 1990; Azeemuddin et al., 2002) to direct observations or measurements on core samples verifying a particular fracture property (e.g., Kulander et al., 1990). Whole core and borehole images provide the best data to observe fractures and describe some fracture properties along the borehole such as orientation, abundance (density), mineral fill, and width.

Borehole images are widely used to describe reservoir fractures, because core is expensive to acquire, non-oriented, or of poor quality for fracture characterization. Borehole images are commonly used to estimate fracture abundance (e.g., Wu and Pollard, 2002; Tokhmchi et al., 2010) and identify fracture corridors in subsurface reservoir rocks (e.g., Ozkaya, 2008). In addition,

borehole images were used to measure fracture aperture (Luthi and Souhailé, 1990) and fracture orientation (Genter et al., 1997; Lagraba et al., 2010). Fracture abundance, orientation, and aperture are important properties for modeling fracture driving stress and fluid flow paths in fractured reservoir rocks (e.g., Stearns and Friedman, 1972; Heffer and Lean, 1993).

Numerous studies have described fractures from borehole images, but relatively a few studies, from the petroleum industry and the Scientific Drilling Programs, have directly compared fractures from core and a corresponding interval of an electrical borehole image. These studies have provided important perspectives on the electrical borehole imaging of fractures in different reservoir and non-reservoir rocks. Nevertheless, the results were often limited by (i) the low core recovery from fractured intervals, (ii) the restricted extent of borehole coverage and resolution of old imaging tools, and (iii) the use of vertical boreholes, which miss vertical and subvertical fracture sets (see references given in Tab. 5-1).

Currently, there are many borehole imaging tools (e.g., Lagraba et al., 2010), chiefly based on the methods of ultrasonic formation logging (Zemanek et al., 1970) and formation electrical resistivity logging (Ekstrom et al., 1986). Electrical borehole imagers have improved since their early development in the 1980s (Ekstrom et al., 1986). The Formation Micro Imager (FMI) can provide better coverage and resolution of borehole walls than its predecessor, the Formation MicroScanner (FMS) (e.g., Pöppelreiter et al., 2010; Brown et al., 2013). For example, the FMI provides 80% coverage of a 20-cm borehole; it is more extensive than the 25–40% coverage of the FMS (e.g., Lagraba et al., 2010). Electrical borehole imagers can also provide higher resolution in discriminating barren fractures from mineralized fractures than is possible with acoustic borehole imagers such as the acoustic borehole viewer (BHTV) (e.g., Pezard and Luthi, 1988; Yu et al., 1998; Prensky, 1999).

In this chapter, borehole imaging of carbonate reservoir fractures is addressed from an unusually comprehensive database of core and borehole images (see Ch. 3.2). The core was obtained with excellent (98%) recovery. The borehole images are of excellent resolution and coverage of the borehole walls. The borehole images were acquired using modern electrical borehole imagers, which are described in some recent publications (e.g., Brown et al., 2013). The

drilling and coring were done by the same operator and the same service company during a short period of time between 2012 and 2014. The datasets were obtained during an extended reach drilling campaign from four boreholes drilled into the Arab carbonate reservoirs in a dome structure in Eastern Arabia (see Ch. 2.4). This is an area where the stress field is well documented (e.g., Ameen, 2014).

Compared fractures are from the core intervals C1, C2, and C3 of X-01, and from the core intervals C5, C6, C7, and C8 of X-03. There were no borehole images of the upper 6.7 m of C5 and entire C4 of X-01 (see Ch. 3.3). The intervals of missing core and the fractured core samples that could not be interpreted were excluded from the fracture abundance comparisons. Fractures with edges displaying signs of drilling and core handling damages were excluded in measurements of fracture size and roughness.

Further analyses were conducted to identify the effects that resulted in notable variations in the detection of fractures in the borehole images, and explain why some fractures were observed but others were missed. The results from comparing fractures reflect the number of considerations beyond counting the number of observed or missed fractures. All available information on borehole geometry, confining stress, drilling fluid pressure, reservoir depth, and reservoir fluid pressure were considered. In addition, described properties of fracture mineralization, orientation, size, roughness, wall mismatch, and host rock lithofacies were noted when comparing every fracture in the core with its actual equivalent (or, if undetected, supposed location) in the borehole image. The descriptions of fracture properties of mineralization and orientation can be found in Ch. 4. The descriptions of fracture sizes are included in this chapter. The measurements of roughness and wall mismatch are presented in Ch. 6.

The aims of this chapter are to (i) describe the abundance of fractures from core and corresponding intervals of borehole images, and (ii) identify and discuss the factors that possibly reduce or enhance detection of fractures in carbonate reservoirs by electrical borehole imaging. Given that electrical borehole imaging is an evolving technology that is cheaper than coring, it is important and timely to shed light on how fracture data from modern tools directly compare with the observations from an equivalent core.

5.2 RESULTS AND ANALYSES

5.2.1 Fracture Abundance in the Core and Equivalent Borehole Images

The results from comparing the number of fractures in the core and direct sections of the borehole images are presented as layouts of borehole sections in three figures (Fig. 5.1, Fig. 5.2, and Fig. 5.3). These figures demonstrate the occurrence of barren fractures and calcite veins in the same imaged borehole sections in the Arab reservoirs. The total number of barren fractures that were described from core is 544. The total number of core fractures that were detected in the equivalent borehole images is 222. The total number of veins that were described from core is 144 calcite veins and 1 anhydrite vein. The total number of core veins that were detected in the equivalent borehole images is 55.

5.2.2 Key Observations

The notable observations from the comparison of fractures between core and borehole images are as follows, see also (Tab. 10-5). Firstly, the total number of barren fractures and veins in the core is 688, from which only 277 fractures and veins were detected in corresponding borehole images (Fig. 5.1, Fig. 5.2, Fig. 5.3). The fractures observed in cores considerably outnumber those observed in borehole images, which provided only 40% of the fractures in the core. Secondly, the comparison of fractures shown in Fig. 5.1, Fig. 5.2, and Fig. 5.3 shows that borehole imaging detection levels vary along the borehole image sections; the level of sampling accuracy ranges from 0% to 100% of what is reported from the core intervals.

Further analyses were performed on the detection of fractures in the borehole images to interpret why some fractures were observed and others were missed. The results are organized here under subheadings to reflect the considerations given to the properties of the imaged fractures and their host lithofacies. These were additional to the available information about the drilling and the Arab reservoir conditions.

5.2.2.1 Presence and Absence of Mineralization

Fractures were found to be occurring in two systems: barren fractures and calcite veins (see Ch. 4). The barren fractures detected in borehole images are visible as dark linear traces, which

reflect apertures of higher conductivity (or lower resistivity) values in the images (Fig. 5.4). This figure shows examples of two barren fractures that were identified in a core section and equivalent borehole images. Although these borehole images display many features, the barren fractures display the following: (i) aperture for drilling fluid infiltration, (ii) shape of sine curves that indicate a rock discontinuity plane intersected by the borehole, and (iii) high dips that are consistent with the observations in the core (Fig. 5.4). The other dark linear traces in the borehole images that parallel the borehole axis were interpreted as tensile-wall fractures (TWFs) (see Ch. 3.3.2.1). TWFs were not observed in the equivalent core samples.

The mineralized fractures that were detected in the borehole images are visible as light linear traces, reflecting planar discontinuities of higher resistivity values in the images (Fig. 5.5). The figure shows a mineralized fracture (calcite vein) that was identified in a core section and the equivalent borehole images. The mineralized fractures can be identified in the borehole images on the basis of their (i) resistivity values reflecting their lack of porosity for drilling fluid infiltration, (ii) shape of sine curves that indicate a rock discontinuity plane intersected by the borehole, and (iii) use of dip and strike measurements. The other light sine waves (planar features) were identified as bedding planes of high resistivity. The case when some calcite veins and barren fractures were present in a core section but could not be detected in the borehole is presented in Fig. 5.6.

5.2.2.2 Size and Roughness of Fractures

The fractures in the core show subtle variations in magnitude of width of mineral fills, aperture, roughness, and wall mismatch (Fig. 5.7).

The fractures were first described qualitatively according to these observations and divided into two end members: rough-wide fractures and smooth-narrow fractures from the core samples (Fig. 5.7). Rough and smooth fractures were compared with their detection levels, and signatures, in equivalent borehole images. Observing rough-wide fractures in the corresponding borehole images was more frequent than the fractures of smooth and narrow apertures. But occurrences of rough barren fractures in the borehole images were not systematic. Many fractures were missing in the borehole images. Furthermore, it was not possible to establish consistent observations for the

detected fractures and their traces in the borehole images. The barren fractures in the borehole images vary considerably from the signatures of relatively narrow and partially open fractures (i.e., partial traces of apertures) to the signatures of fractures with strong conductive (dark) and relatively wide apertures. Similarly, the signatures of mineralized fractures vary in the borehole images from the signatures of fractures with partial traces, or a mere abrupt change in lithology, to the signatures of fractures with strong resistive (light) and relatively wide thickness.

Furthermore, the quantitative measurements of fracture size and roughness demonstrate some relations to the detection levels of fractures in the borehole images. The barren fractures in the core vary in sizes of their apertures (Fig. 5.8). About 90% of the measured apertures of barren fractures in the core are less than 6 mm, for the typical widths, which were averaged between two parallel walls using the digital fracture profiles described in Ch. 3.3. The veins are dominantly thin. About 90% of the veins are less than 2 mm, for the typical widths. The variations in width along large fractures and veins partly reflect their roughness and wall mismatch. The rough fractures in the core have apertures exceeding 5 mm, and the smooth fractures have closely matching walls with apertures of less than 3 mm.

The statistical distributions in Fig. 5.8 show that the fractures of large apertures in the core are more likely to be observed in the borehole images than are the fractures of smaller apertures. The fractures that were measured from the core exhibit matching walls and mismatching walls (Fig. 5.9). The degrees of fracture wall mismatching (i.e., difference between top and base wall) in barren fractures were correlated with their observations in borehole images in Fig. 5.9. The results indicate that detected fractures are of mismatching rough walls (Fig. 5.9). These observations were complemented by measurements of fracture apertures in borehole images. The aperture sizes are mostly less than 1 mm (Fig. 5.10). These aperture measurements show an obvious separation between sizes of the mechanical and hydraulic apertures. Individual fractures in the borehole images display lateral changes in their aperture sizes, which are clear indication of wall mismatches, as described in Ch. 3.3.

The qualitative and quantitative descriptions on width, aperture, roughness, and wall mismatch strongly indicate that rough-wide fractures have greater probability to be observed more

frequently than are smooth-narrow fractures. However, the comparisons resulted in some exceptional observations for both barren and mineralized fractures. A core barren fracture of a relatively large width (5 mm) was difficult to detect in the borehole image because the vuggy nature of the host rock masks the fracture, which has a “rough” texture similar in rugosity to the vugs (Fig. 5.11). Furthermore, some 0.5-mm-wide calcite veins were detected in the borehole images (Fig. 5.11). These images of thin calcite veins also show how the layers of the resistive anhydrite nodules partially mask the calcite veins.

5.2.2.3 Orientations of Fractures and Boreholes

The comparisons show that the borehole images of X-03 had better sampling of fracture abundance than borehole images of X-01 for barren fractures (Fig. 5.12). The total number of barren fractures described from the core of X-01 is 187, and 37 of these fractures were observed from the borehole images. The total number of barren fractures described from the core of X-03 is 340, and 188 of those fractures were observed in the borehole images. The barren fractures missed by the borehole images account for 83% from X-01 and 45% from X-03. The two boreholes are different in their orientations and the orientations of the fractures intersecting them in the Arab reservoirs (Fig. 5.13).

The X-01 and X-03 boreholes intersected NW–SE fractures, but X-03 additionally intersected E–W and NW–SE fractures. Measurements of fracture apertures from the borehole images of X-01 and X-03 were correlated with their measurements of strikes in Fig. 5.14. The obtained profiles of averaged apertures have a consistent trend from the two borehole images. The sizes of the mean apertures (both hydraulic and mechanical) are greater in the fractures of $\sim 60\text{--}100^\circ$ (NE–SW) orientations than in the fractures of $\sim 120\text{--}180^\circ$ NW–SE orientations. The orientations of the NE–SW fractures are closely parallel to the present-day S_{Hmax} in Eastern Arabia. The NE–SW, E–W, and NW–SE fractures were interpreted to be part of the regional system previously documented in the Arab, Hanifa, and Khuff reservoirs.

5.2.2.4 Types of Borehole Imaging Tools and Drilling Fluid Pressure

The detection levels of geological features in the borehole images from wireline tools

(FMI-HD) look generally better than those of the borehole images from the LDW imagers obtained from X-02 and X-04. The two boreholes have no core against which to compare the fractures interpreted from their borehole images. But the most notable features of the images of X-02 are that the barren (conductive) fractures have unusual large apertures when qualitatively compared with the fracture apertures from the wireline borehole images (see Ch. 3.3.2).

While many open-barren fractures with wide apertures were observed on the LDW images of X-02, some open-barren fractures were also observed with narrower apertures similar to those in the wireline images of X-1 and X-03. The LDW images are inferior in imaging quality to the wireline images.

5.3 FACTORS CONTROLLING BOREHOLE IMAGING OF FRACTURES

5.3.1 Fracture Size

The majority of the calcite veins in the core were not identifiable in the corresponding borehole images because they are less than 2 mm wide. Nevertheless, some 0.5-mm-wide calcite veins were detected, but their detection is related to the high data resistivity contrast. These calcite veins are resistive in the images, while their host rocks are very conductive. This observation is consistent with previous reports that rock features with a high resistivity contrast can be detected in borehole images even if they seem smaller than the imaging sampling intervals (e.g., Brown et al., 2013). Nevertheless, the vein widths are finite, and can accordingly indicate the quality of borehole imaging.

The barren fractures with larger mean apertures in the core exhibit a higher probability to be visible in the corresponding borehole images (Fig. 5.14). The aperture measurements from the core were interpreted qualitatively, as they may not characterize the apertures under the confining subsurface conditions. The rock samples are elastically unloaded by core retrieval. The range of aperture sizes from borehole images seems representative, although there is no independent method to confirm if these apertures are exact in the subsurface. The apertures seem small, but recent lab experiments (Ponziani et al., 2015) validated measuring such small apertures of less than 1 mm.

Nonetheless, it is reasonable to infer that the detected barren fractures are open for the infiltrating drilling fluid. Accordingly, the water-based drilling fluid makes the fractures visible as highly conductive traces (sine curves) in electrical borehole images. In contrast, it is conceivable that the undetected barren fractures were mechanically closed; the drilling fluid did not infiltrate into parts of these fractures to make tracing them possible in the borehole images.

5.3.2 Present-day Stress Field

The borehole images of X-03 provided significantly better detection for the abundance of barren fractures than did the borehole images of X-01 (Fig. 5.12). Furthermore, the profiles of the mean apertures measured from the images of both boreholes (X-01 and X-03) are clearly increasing toward the fractures striking E–W and NE–SW ($\sim 60\text{--}100^\circ$), and decreasing toward the fractures striking NW–SE ($\sim 120\text{--}180^\circ$). These results indicate that the borehole imaging of barren fractures depends on the fracture behavior under the present-day stress field. It is, therefore, suggested here that the aperture size depends on the present-day $S_{H\max}$ in Eastern Arabia. The two boreholes were drilled under similar borehole conditions and imaged by the same imaging tool, but they differ in their orientations and therefore they intersected barren fractures of different orientations. Both boreholes intersected the NW–SE (non-aligned) fractures, but X-03 additionally intersected the E–W and NE–SW (aligned) fractures. The aligned fractures exhibit larger apertures, and hence were more easily detected by the borehole imaging. The non-aligned fractures were mostly undetected as they are presumably closed under the present-day $S_{H\max}$. The present-day stress is apparently the strongest factor in enhancing and limiting the detection of barren fractures in borehole images in the study area. The stress field did not seem to influence the borehole imaging of mineralized fractures. The measurements indicate that aperture size is dynamic under the stress field in the subsurface. This can be explained by the mechanical concept that fractures are free surfaces, in which the tensile strength of rocks is very low (i.e., zero).

It seems that the stress field played a major part in the mismatch in measuring the abundance of barren fractures between core and borehole images. Therefore, it can be suggested that the stress field has influenced previous studies that used dominant fracture trends from interpretation of borehole images. The observations in this research may explain why the NE–SW

fractures in Eastern Arabia represent the dominant (i.e., more abundant) system in the Arab, Hanifa, and Khuff reservoirs (e.g., Ameen et al., 2010; Ameen, 2014; and internal Aramco reports). It is suggested here that the dominance of the aligned barren fractures was biased by their relatively larger apertures, which were easy to detect by the imaging tools. It is possible that the NW–SE system is as abundant as, if not more abundant than, the NE–SW system, but most apertures of the NW–SE system are mechanically closed by the stress field for imaging tools (see Ch. 6).

Nonetheless, this bias of borehole imaging seems very useful for modeling the fluid flow in subsurface reservoir rocks. The fractures in the Arab reservoir are abundantly barren with mostly matching walls, and their apertures depend on S_{Hmax} in Eastern Arabia. The fractures can be modeled with gradual increase or decrease in aperture size according to the direction of the stress field.

5.3.3 Fracture Roughness and Wall Mismatch

Wall mismatch, especially of rough fractures, seems to increase the mean size of fracture width (Fig. 5.14), and therefore influenced the borehole imaging of fractures. Wall-mismatching fractures are generally found with larger mean apertures than those of wall-matching fractures (Fig. 5.14). Furthermore, the fractures detected from the borehole images of X-01 and X-03 exhibit wall mismatch along fracture profiles. The aperture measurements of mean aperture demonstrate clear separation between mechanical apertures and hydraulic apertures (Fig. 5.14). All these observations demonstrate the role of roughness and wall mismatch in the detection of barren fractures. Most of these barren fractures were found to be wall matching, but a minority (~20%) of fractures have noticeable wall mismatch (see Ch. 6). This is consistent with the borehole imaging of a small percentage of the NW–SE barren fractures from X-01. The S_{Hmax} apparently reduced or closed the apertures of the NW–SE fracture system, except where wall mismatch prevented complete contacts of fracture walls, and therefore allowed drilling fluids to partially permeate the fractures.

5.3.4 Resistivity of Fractures and Host Rock

Fracture comparison indicates that a few fractures are either unexpectedly undetected or detected (such as the small calcite veins) from corresponding borehole images. It is known that

fracture detection by borehole imaging is reduced if fractures are of low data (resistivity or conductivity) contrast against their host rocks (e.g., Ponziani et al., 2015). The data contrast may be improved by image processing techniques (Ekstrom et al., 1987); however, these techniques cannot help distinguish the fractures from the host rocks if their electrical properties are similar or moderated by the drilling fluid types (e.g., Tehrani et al., 2002; Khoshbakht et al., 2012). The water-based mud was optimal in this case study for the detection of open fractures. The issue of resistivity contrast is noted for a limited number of detected fractures. It is not possible, however, to relate if some fractures are undetected, because of their low resistivity contrast. They may be limited in number as well, as fractures generally differ in their resistivity, or conductivity, properties from their host rocks.

5.3.5 Drilling Fluid Pressure

The relatively large apertures of the fractures observed from the LWD images of X-2 (Fig. 5.15) are interpreted to be the product of drilling with high fluid pressure. The LWD images are inferior in quality to wireline images, so the observed large apertures in X-02 must have been increased greatly for electrical imaging by the conductive mud infiltrate. This observation of large apertures could not be related to the pixelation of the processed images, as there are other open fractures in the same LDW images with narrower apertures matching the ones observed from the wireline images (Fig. 5.15). This is an exceptional case of the drilled boreholes, although it provided important insight on how the LWD images gave instant (LWD) measurements for the behavior of barren fractures under high pressure of drilling fluid infiltrations. This view remains qualitative; the quantitative techniques are not yet available to measure fracture apertures from the LWD borehole images. It seems from this observation that borehole imaging with overbalance drilling (i.e., with drilling-fluid pressure higher than the reservoir fluid pressure, such as the case of X-02) may improve the signature and detection level for barren fractures. It is well known that the detection of open fractures is dependent on the conductive mud (e.g., Spies, 1996). The ability of the conductive drilling fluid to permeate fractures, and locally displace the non-conductive hydrocarbons, may depend on the fluid equilibrium between the borehole pressure and the reservoir pressure.

5.4 DISCUSSION

5.4.1 Potential and Limitations of Datasets

The carbonate reservoir fractures described and compared from core and equivalent borehole images highlight the values of obtaining core with high-resolution borehole images from deviated boreholes with different trajectories. The two methods are limited to provide a full picture of the fractures in the subsurface; their limitations are inherently those of the sizes and orientations of the boreholes.

Nevertheless, borehole imaging provides generally limited detection for fractures intersected by boreholes, and hence lower fracture abundance for fractures along boreholes. Estimating fractures along boreholes is important for modeling drainage areas around boreholes and consequently entire reservoirs. But borehole imaging provides very useful information about most likely effective reservoir fractures, as borehole imaging preferentially detects the mostly permeable and large fractures. For example, measuring the size of apertures using borehole images seems more reasonable than using core, given that binging core from reservoirs is associated with unloading of confining stresses.

The quality of the datasets used in this study for fracture observations is exceptional. The data derive from long sections of boreholes and excellent recovery of core, which was optimally deviated to intersect subvertical fractures in the gently dipping strata of the Arab carbonate reservoirs. The identification of barren fractures from the core was facilitated by the geometry of the borehole, which was neither perpendicular to the reservoir rock bedding nor to fracture planes.

5.4.2 Potential and Limitations of Borehole Imaging

Electrical borehole imaging is widely used in the oil industry as a reliable method of reservoir fracture measurements and a cost-effective replacement to cutting core samples. However, the comparisons show that borehole imaging is limited and inconsistent to accurately and comprehensively sample fractures. The results may not be surprising for old imaging tools. The datasets of this research, however, were obtained using new-generation borehole imagers. Although the new tools were not previously used to address fracture sampling in the light of core

sampling, the images may have been expected to provide results that are equivalent to core observations, given that these tools were substantially improved over the past two decades (Ch. 3.3).

The borehole images provided by the new tools can be of poor quality if they were acquired in limiting borehole conditions (Tab. 5-1). Examples of limiting physical conditions include borehole irregularities for measuring tools, unsuitable mud chemistry of oil-based mud, high temperature, and lack of previous field testing on rocks, as in previous cases of the Scientific Drilling Programs. The limiting physical factors were not encountered, except in the case of the LWD images used while drilling the X-02 borehole, which was drilled with mud pressure higher than reservoir pressure (see Ch. 3.3). But other boreholes were normal to the FMI-HD acquisition, which is common practice for the operating company of the Arab reservoirs.

The datasets seem ideal to critically assess the capacity of borehole electrical imaging to detect and estimate the abundance of fractures in the carbonate reservoirs. The fracture sampling mismatch between core and borehole images seems to be related to certain factors that were identified based on the results from direct comparison.

5.4.3 Implications of Borehole Imaging

The data and analysis show how borehole-imaging technology can influence fracture studies, particularly in areas of measuring and predicting static and dynamic fracture properties such as trends, abundance, and permeability (e.g., Ozkaya and Mattner, 2003). These static and dynamic properties commonly make up the building blocks of geomodeling and flow simulation of fractured reservoirs.

5.4.3.1 Fracture Abundance

Borehole images are commonly used to compute fracture abundance (e.g., Wu and Pollard, 2002; Tokhmchi et al., 2010) and identify fracture corridors in subsurface reservoirs (e.g., Ozkaya, 2008). This study suggests that borehole images can lead to erroneous estimates of fracture abundance. Comparison of the results clearly indicates that the borehole images misrepresent the abundance of open and calcite-filled fractures in certain reservoirs and

stratigraphic sections (Fig. 5.12).

In the absence of rock core, the results from borehole images would be insufficient by themselves to estimate fracture abundance in subsurface rocks. Fracture abundance is often estimated when building reservoir fracture models with consideration to borehole sampling bias (e.g., Wu and Pollard, 2002) and fracture spacing models (e.g., Narr, 1991; Massiot et al., 2015).

5.4.3.2 Fracture Trends

Core is not oriented in most cases, and borehole images are the best available and reliable logging tool that provides measurements of fracture trends in the subsurface. Fracture trends are critical for the identification of fracture types and their past driving stresses. Fracture trends are indicators of past stress trends (e.g., Nemat-Nasser and Horii, 1982), and have long been treated as trajectories of paleostresses of folding structures (e.g., Stearns and Friedman, 1972; Cosgrove and Ameen, 2000) and far-field regional tectonics (e.g., Engelder and Geiser, 1980). In addition, trends of open fractures are critical for modeling the preferred fluid flow paths in subsurface reservoirs (e.g., Heffer and Lean, 1993; Carrera and Martinez-Landa, 2000).

Studies from the Arabian carbonate reservoirs used borehole images to indicate that the dominant trend of naturally open fractures strikes NE–SW (refer to the region defined as Domain B in Ameen et al., 2010). The data from these reservoirs also show a secondary system of NW–SE striking open fractures (e.g., Ameen et al., 2010; Ameen, 2014). The NW–SE fracture system is abundantly described in this study because of the borehole orientations. The NE–SW and E–W fracture systems that are aligned or closely aligned with the regional in situ stress are greatly minimized or missed due to the orientations of X-1 and X-02. But X-03 and X-04 intersected many of the NE–SW and E–W fracture systems, and, therefore, the detection of these fractures from the borehole images of X-03 was outstanding when compared with the core observations.

The electrical borehole imaging tools seem to detect the open fractures aligned with S_{Hmax} more frequently than other non-aligned open fractures. Accordingly, this study attributes the dominance of the NE–SW system in the region to the easy detection of the fractures by the borehole images because of their relatively larger apertures or higher permeability for conductive drilling fluids. In essence, the borehole images are limited in resolution and only detect the mostly

permeable and wide fractures. But this is particularly useful for the modeling of the preferred fluid flow in fractured reservoirs. As these abundant fractures are open, barren of cement, and without shear displacement, their conductive signatures from borehole images support the conventional wisdom that the S_{Hmax} -aligned, open fractures are preferred for fluid flow because of the lowest of normal stresses across their planes (e.g., Heffer and Lean, 1993).

5.5 CONCLUSIONS

Borehole imaging is the common method used in the oil industry to collect data on reservoir rocks, because it is efficient and cheaper than core sampling. In this chapter, new results are demonstrated on the detection of carbonate reservoir fractures by electrical borehole imagers. The reservoir fractures, existing as barren and calcite-filled, were described and directly compared between cores and corresponding intervals of borehole images. The descriptions were based on high-quality datasets that were obtained from boreholes optimally deviated to intersect subvertical fractures in the Arab carbonate reservoirs.

The comparison resulted in a significant mismatch in measuring fracture abundance. The borehole imaging provides generally limited detection of fractures, and hence significantly lower fracture abundance from the reservoirs. In general, fractures were detected by borehole imaging because they exhibit sizes greater than about 2 mm. The borehole imaging, however, detected much smaller fractures, of 0.5 mm finite width. This is attributed to the contrast between the resistivity data of these fractures and the host rock intervals.

The borehole images revealed that the sizes of fracture apertures depend on the present-day stress field, specifically S_{Hmax} , in Eastern Arabia. The results indicate that the barren fractures that are aligned with S_{Hmax} are (partially or completely) open. Their apertures are large enough to be easily detected by the borehole imaging. The non-aligned barren fractures are completely closed under the same stress field, except the fractures with remaining apertures preserved by rough-wall mismatches, which were further investigated in Ch. 6.

The imaging detection of barren fractures can be further influenced by the pressure of drilling fluid. Similar to the effect of tectonic stresses, drilling with high-pressure fluids seems to open mechanically closed fractures or increase the sizes of existing apertures. The observations

from this research are summarized in Fig. 5.16.

The study results have direct implications on the characterization of subsurface rock fractures. In particular, the biased borehole imaging results on fracture abundance lead to erroneous use of the fracture dominant trends as paleostress trajectories in the structural and tectonic analyses of sedimentary basins. However, the same biased results toward detecting large and open fractures are rather useful for modeling the preferred fluid flow directions in reservoir rocks.

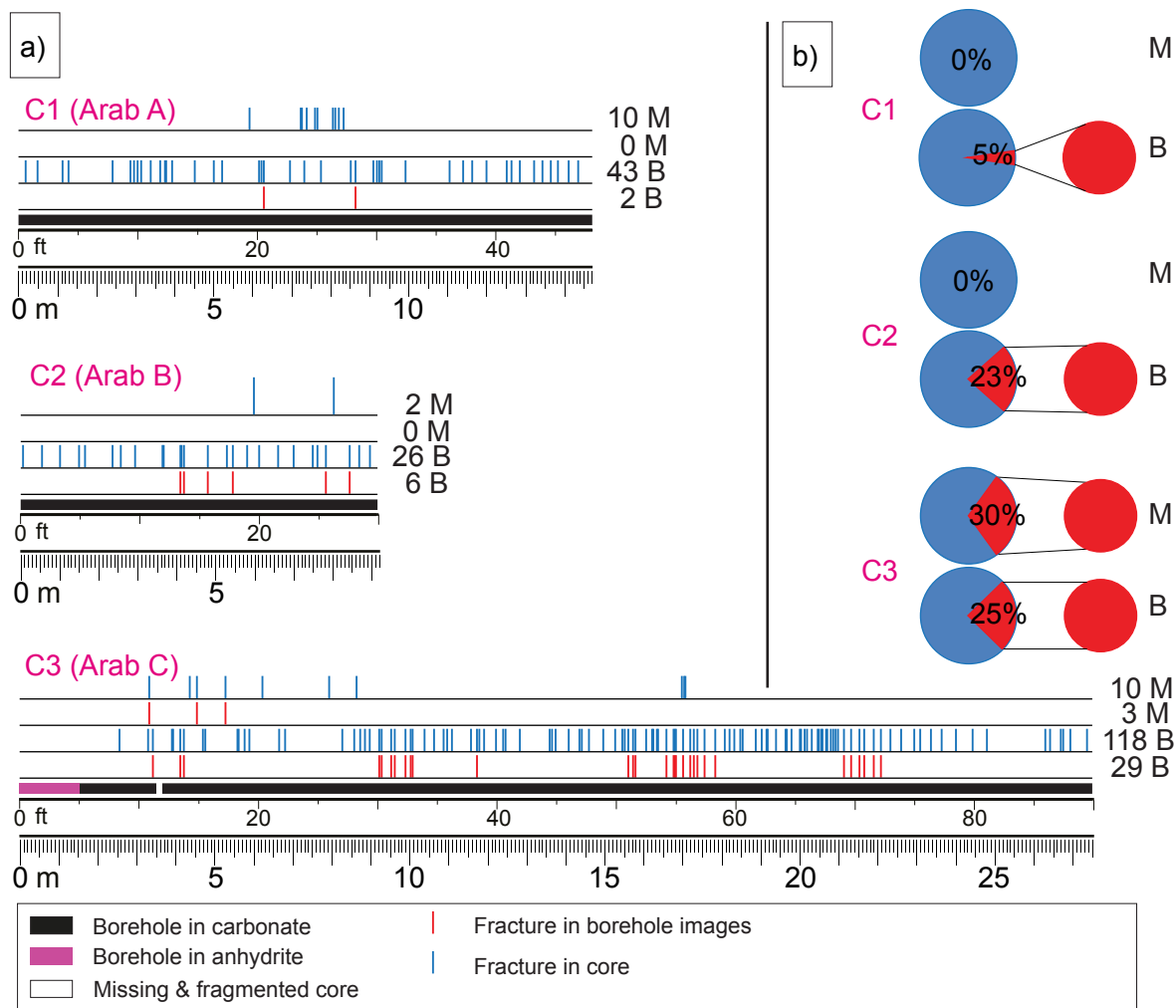


Fig. 5.1: A layout of fracture abundance from core and corresponding borehole images of X-01.

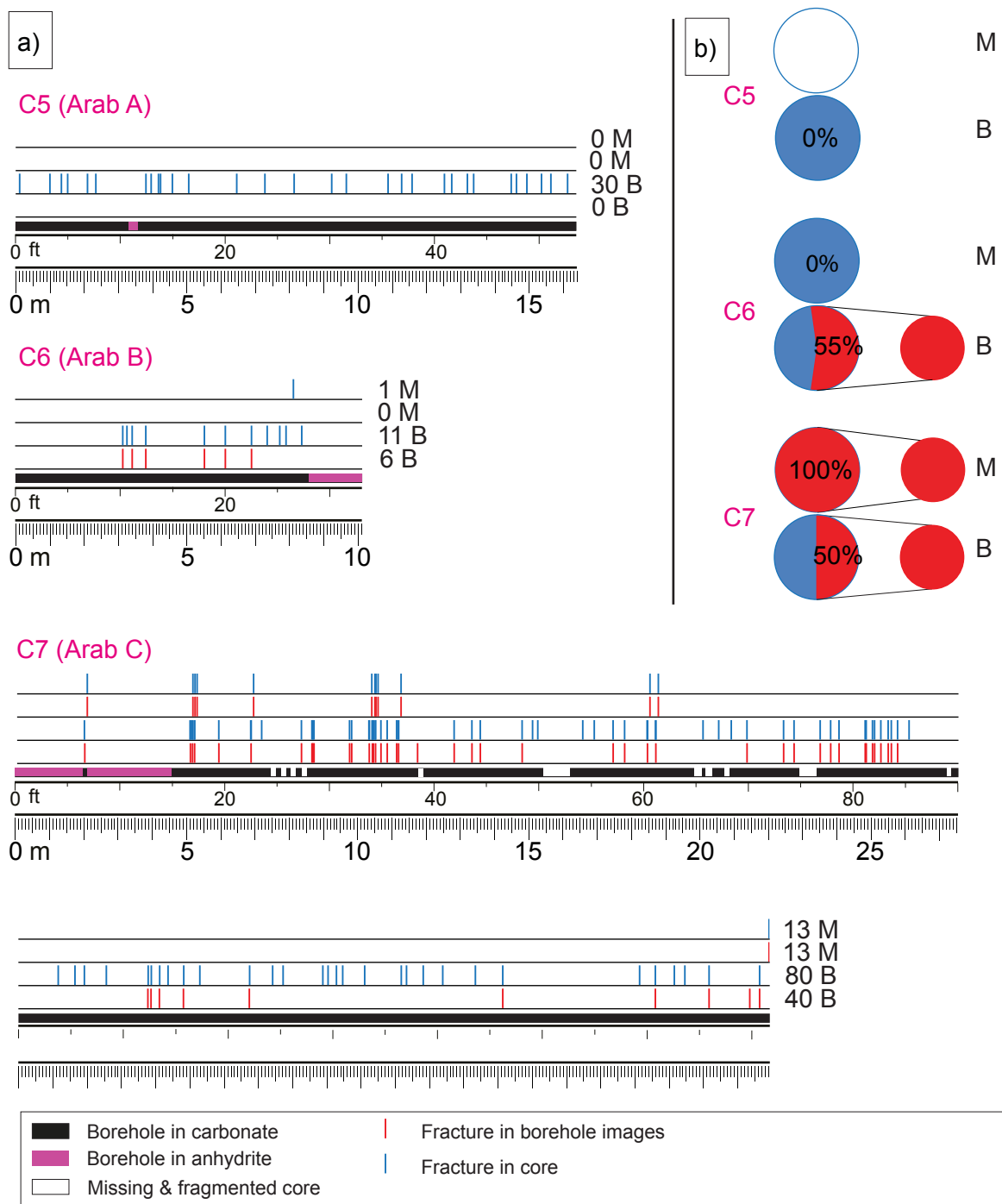


Fig. 5.2: A layout of fracture abundance from core and corresponding borehole images of X-03.

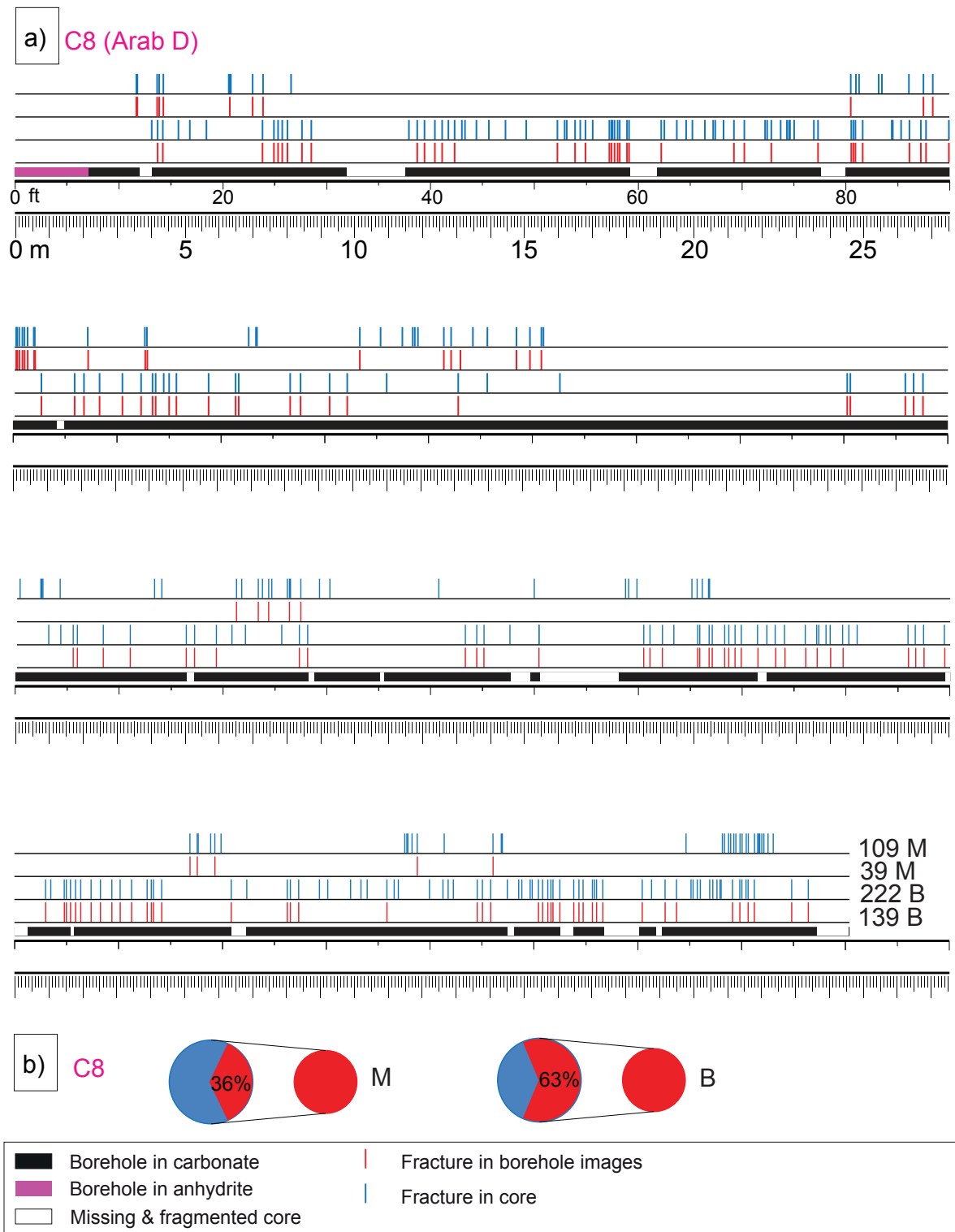


Fig. 5.3: A layout of fracture abundance from core and corresponding borehole images of X-03.

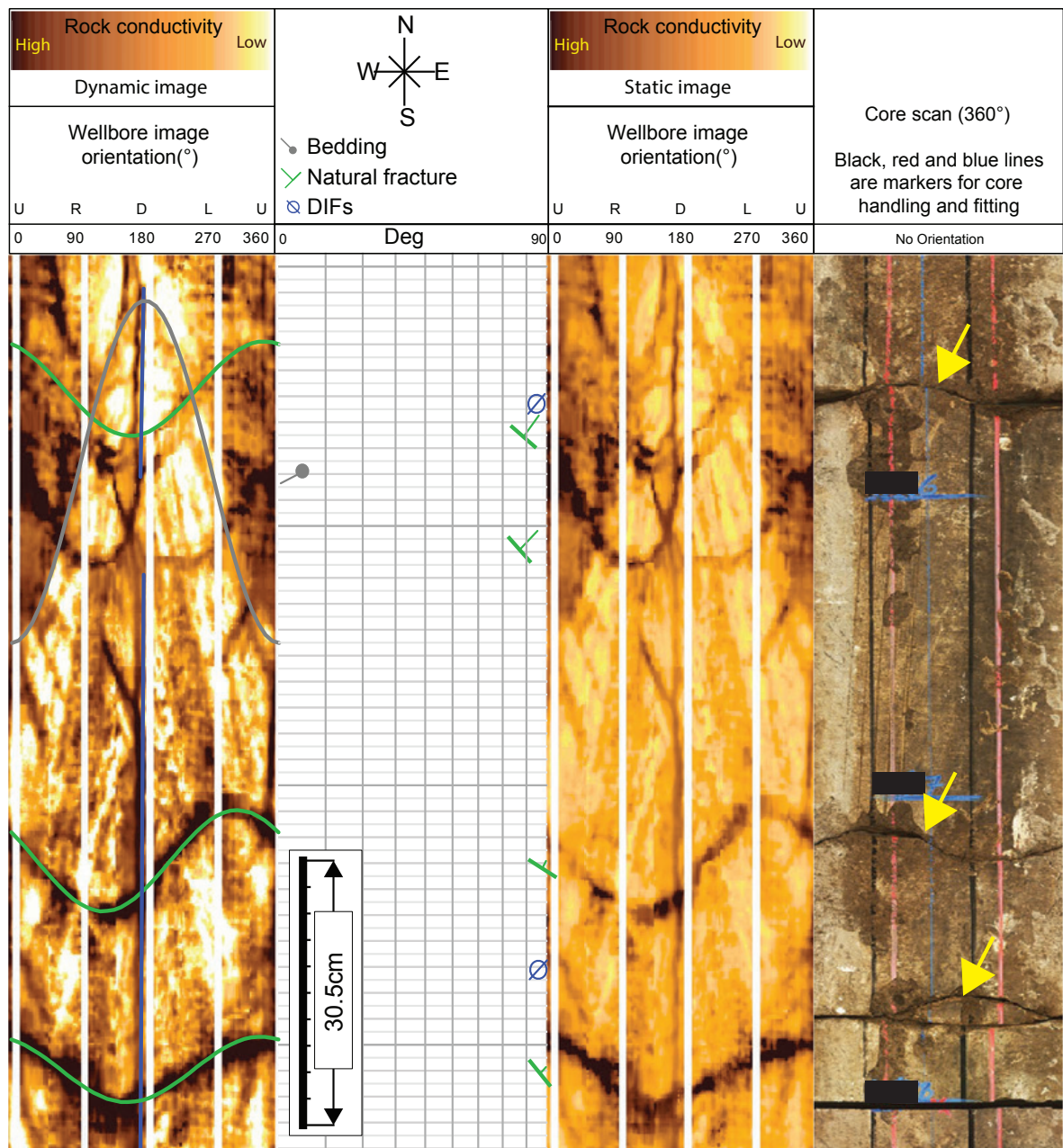


Fig. 5.4: Barren fractures (sine curves) in the borehole images and the corresponding core.

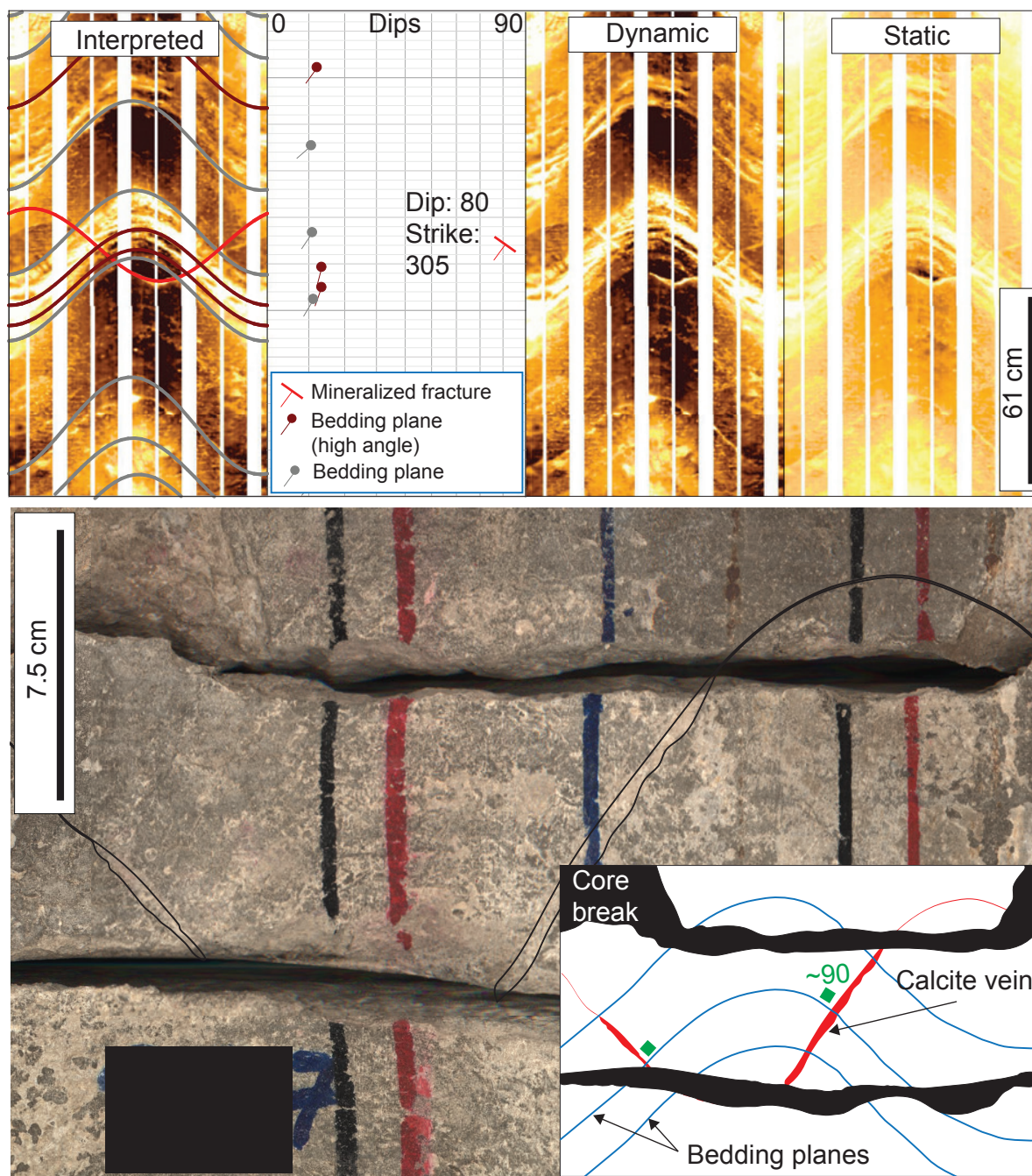


Fig. 5.5: Calcite vein in the borehole images (above) and the corresponding core (below). The vein is normal to the planes.

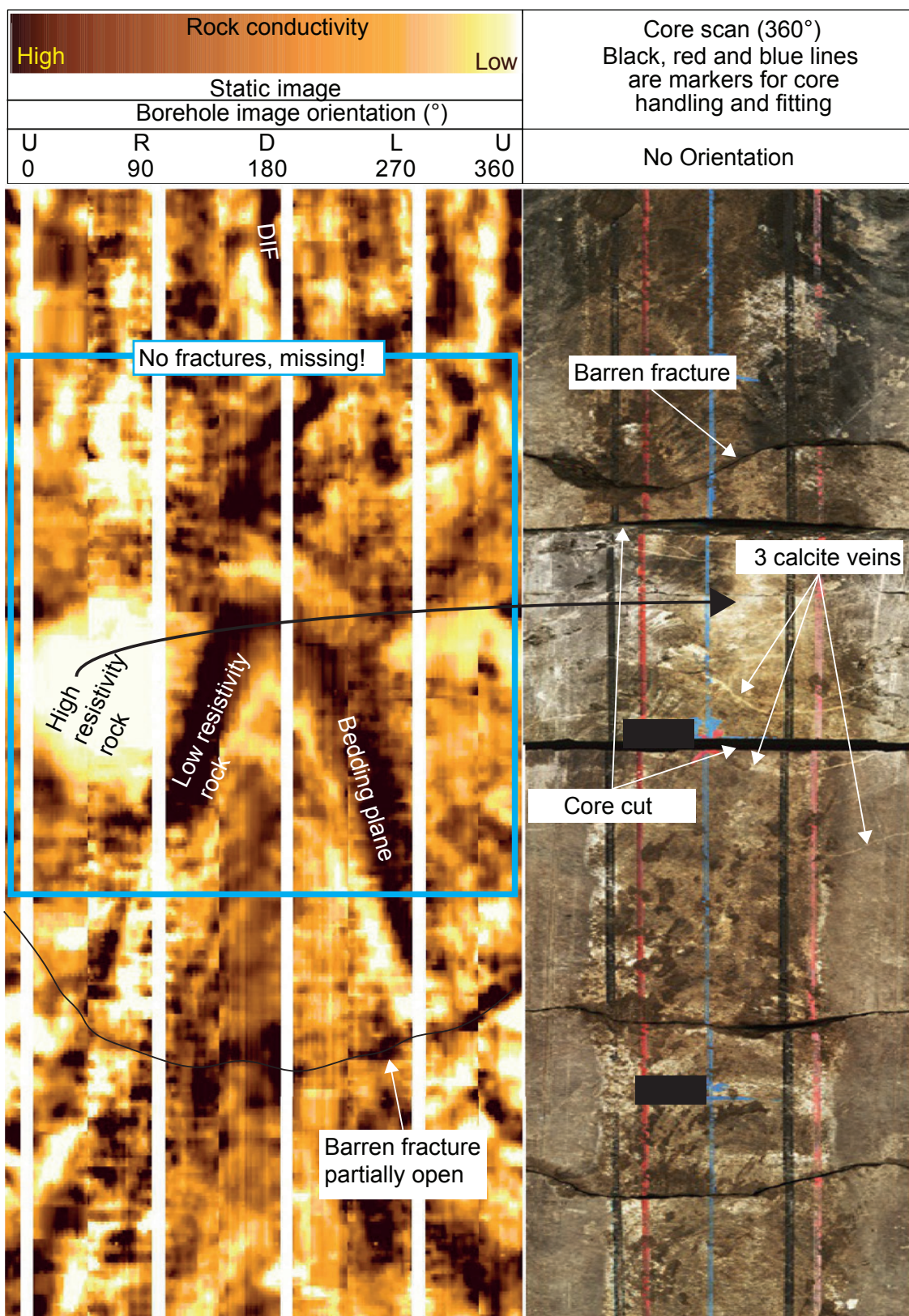
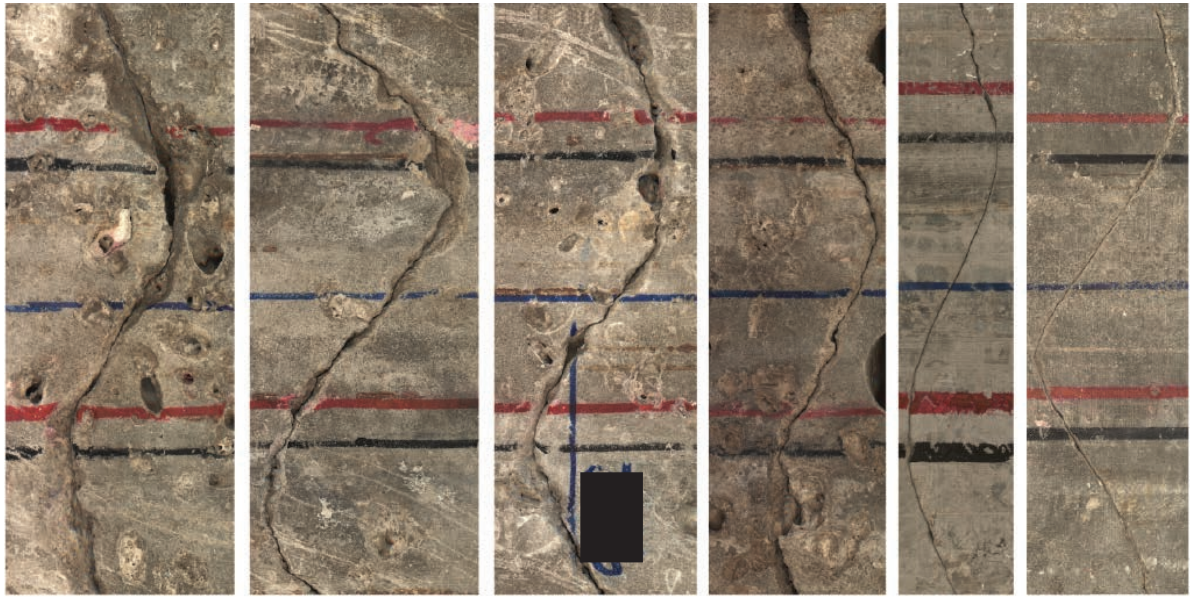


Fig. 5.6: Example of fractures in the core that are missing from the equivalent borehole images.

Barren fractures in core



Calcite-filled fractures in core

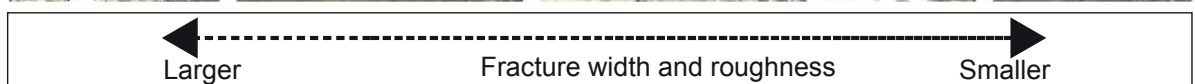
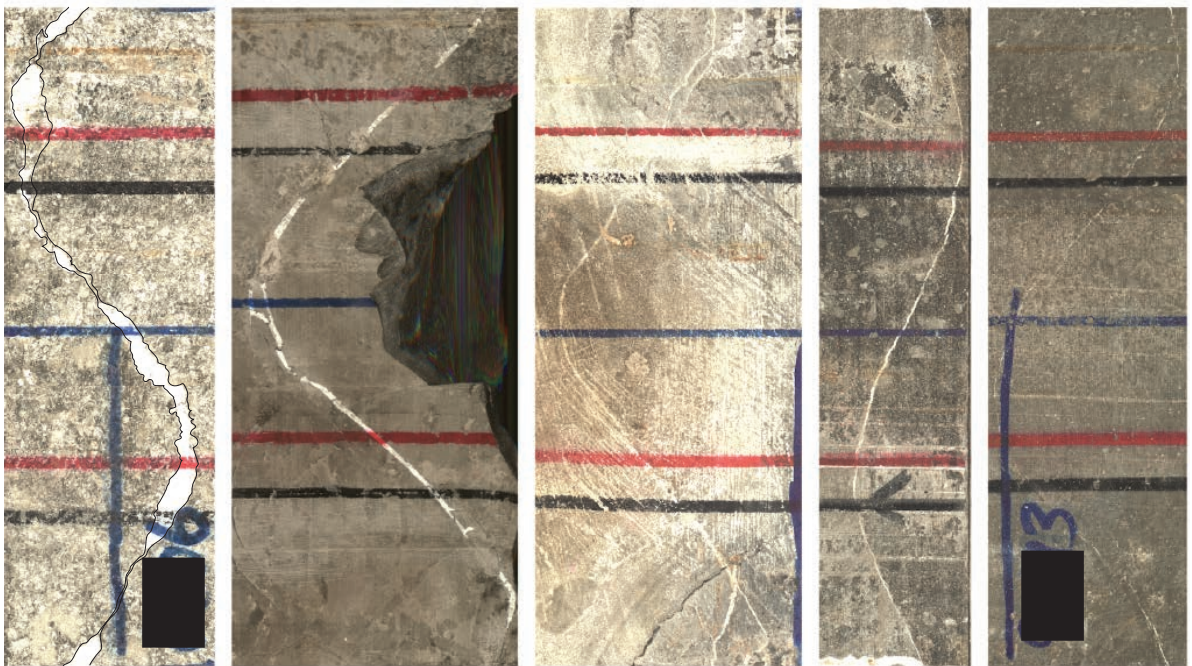


Fig. 5.7: Photographs from the core optical scans display variations in sizes of fracture widths. Sizes range from small (0.5 mm) at right to large (5 mm) at left of the core photographs. The core photographs also display the dependence of fracture sizes on roughness and wall mismatch, which are product of the primary and diagenetic fabrics in host carbonates.

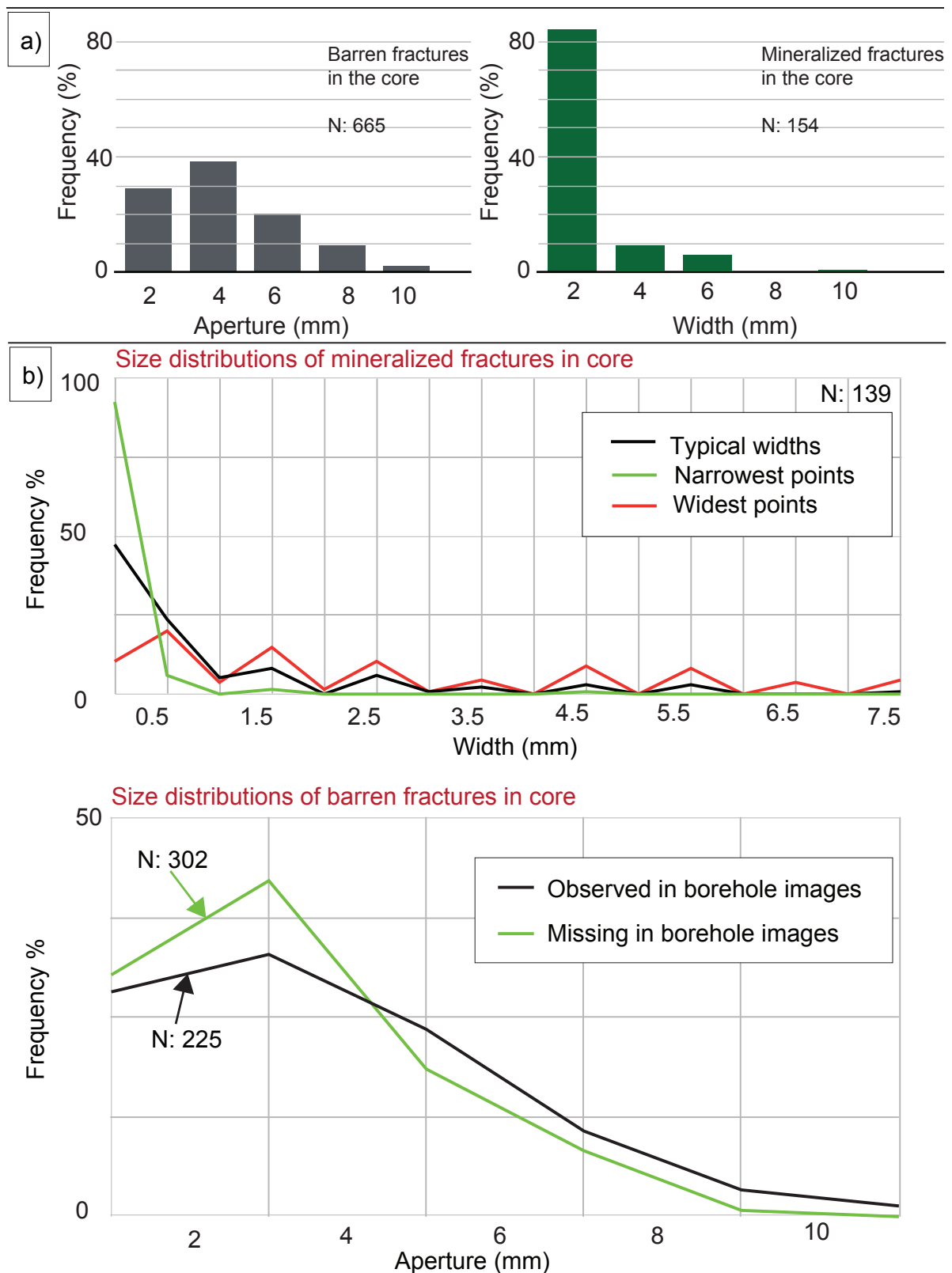


Fig. 5.8: a) Frequency distributions for sizes of the widths of mineralized and barren fractures in the core. b) Above, the frequency distributions for width variations of calcite veins, and below, two frequency distributions, separated for the observed and missed fractures in borehole images.

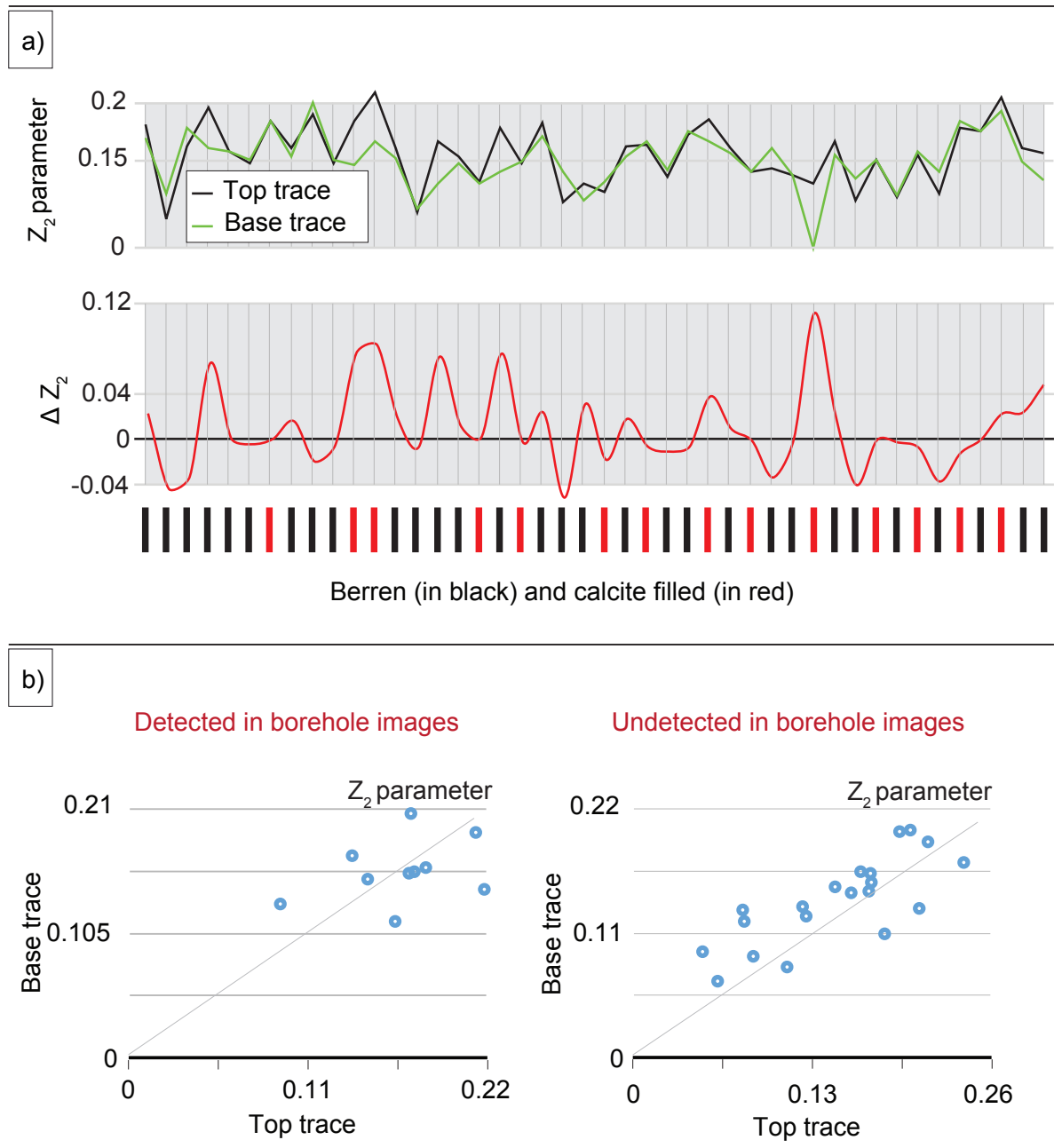


Fig. 5.9: a) Measurements of the Z_2 parameter for fracture roughness and wall mismatch for a sample of barren fractures and calcite veins. b) Correlation between roughness of fracture walls (top and base traces) and their detection in borehole images indicates that detected fractures are of mismatching rough walls.

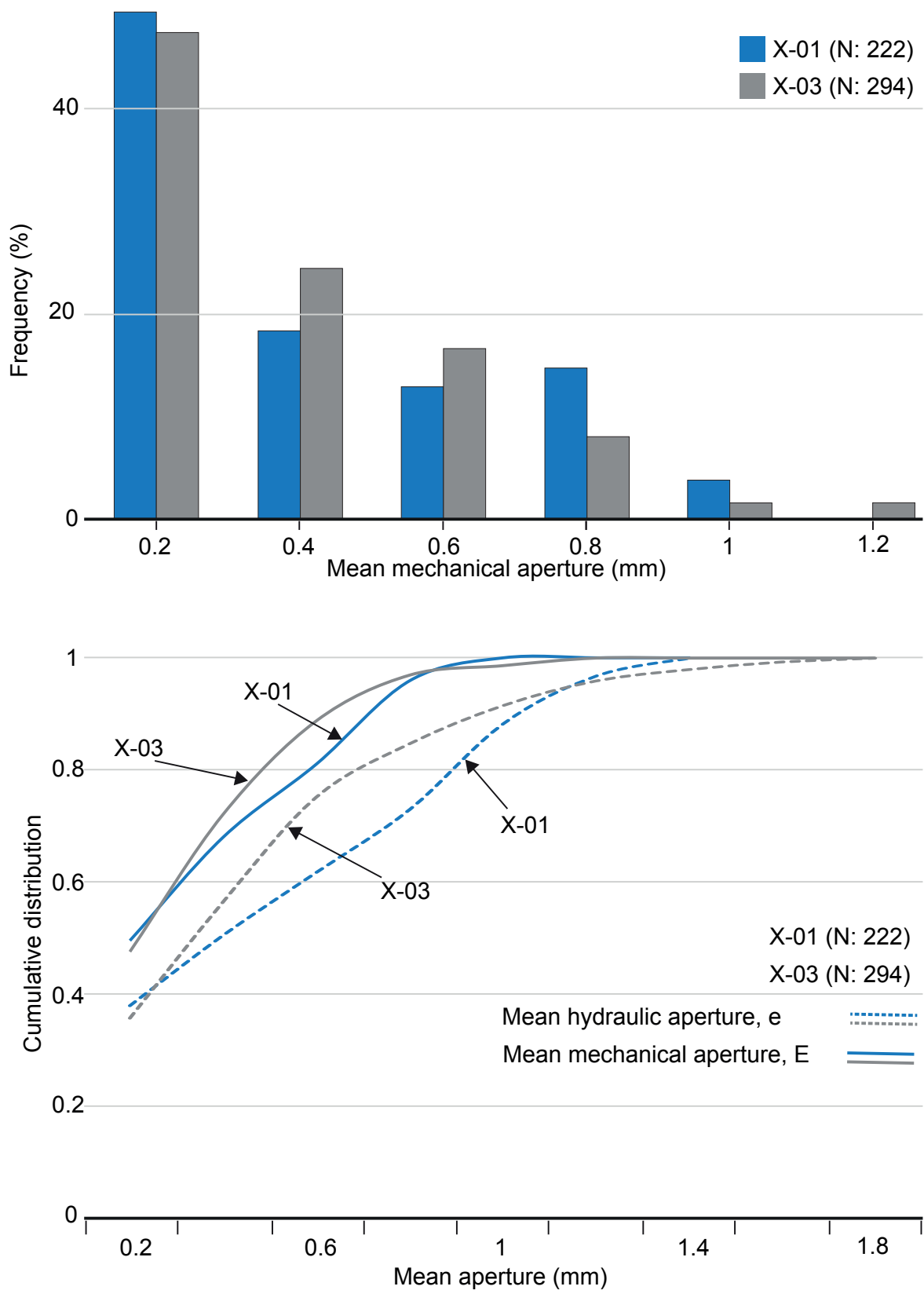


Fig. 5.10: Measurements of barren fracture apertures from the borehole images of X-01 and X-03.

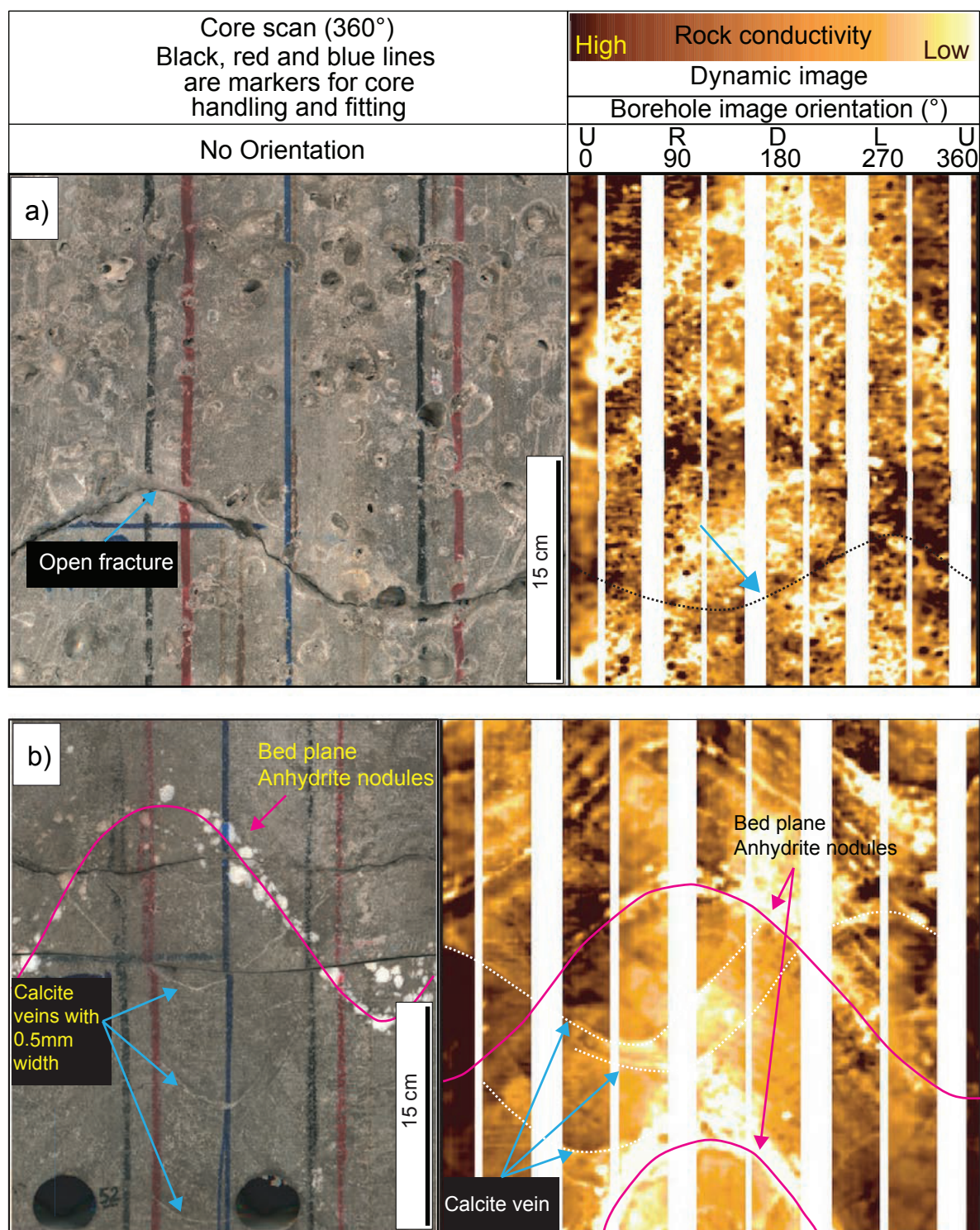


Fig. 5.11: Examples displaying how the detectability of fractures is reduced if fractures weakly contrast the host rock in resistivity measurements such as in the case of a) a barren rough “conductive” fracture in highly porous “conductive” host rock, and improved such as in the case of b) calcite “resistive” fractures within porous “conductive” host rock. These calcite veins are 0.5 mm wide.

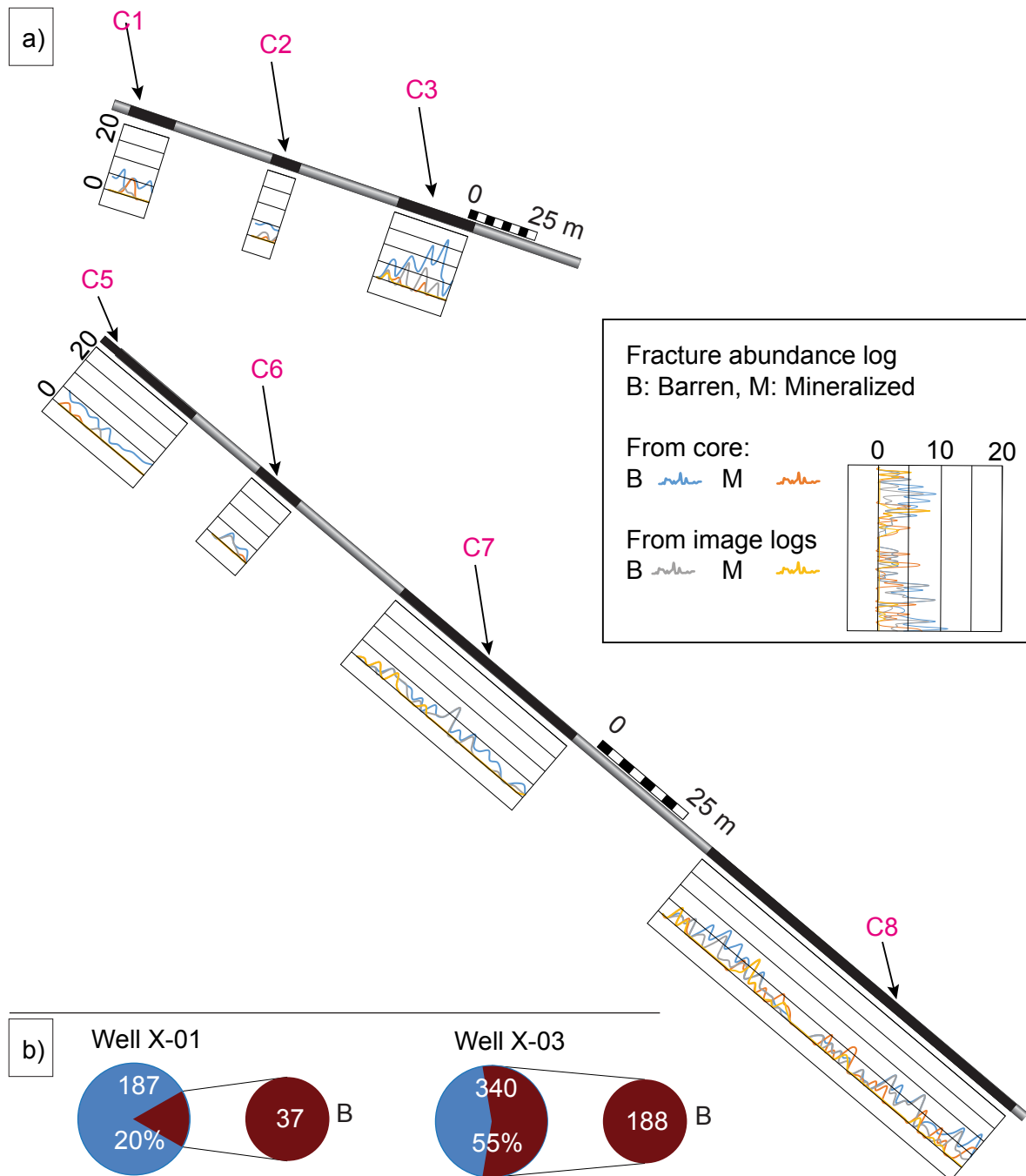


Fig. 5.12: a) Logs of fracture abundance from core and borehole images plotted against the borehole geometry; and b) number of fractures in core and borehole images and percentages of detection levels of borehole images.

The borehole images of X-03 provided better detection for barren fractures than the borehole images of X-01.

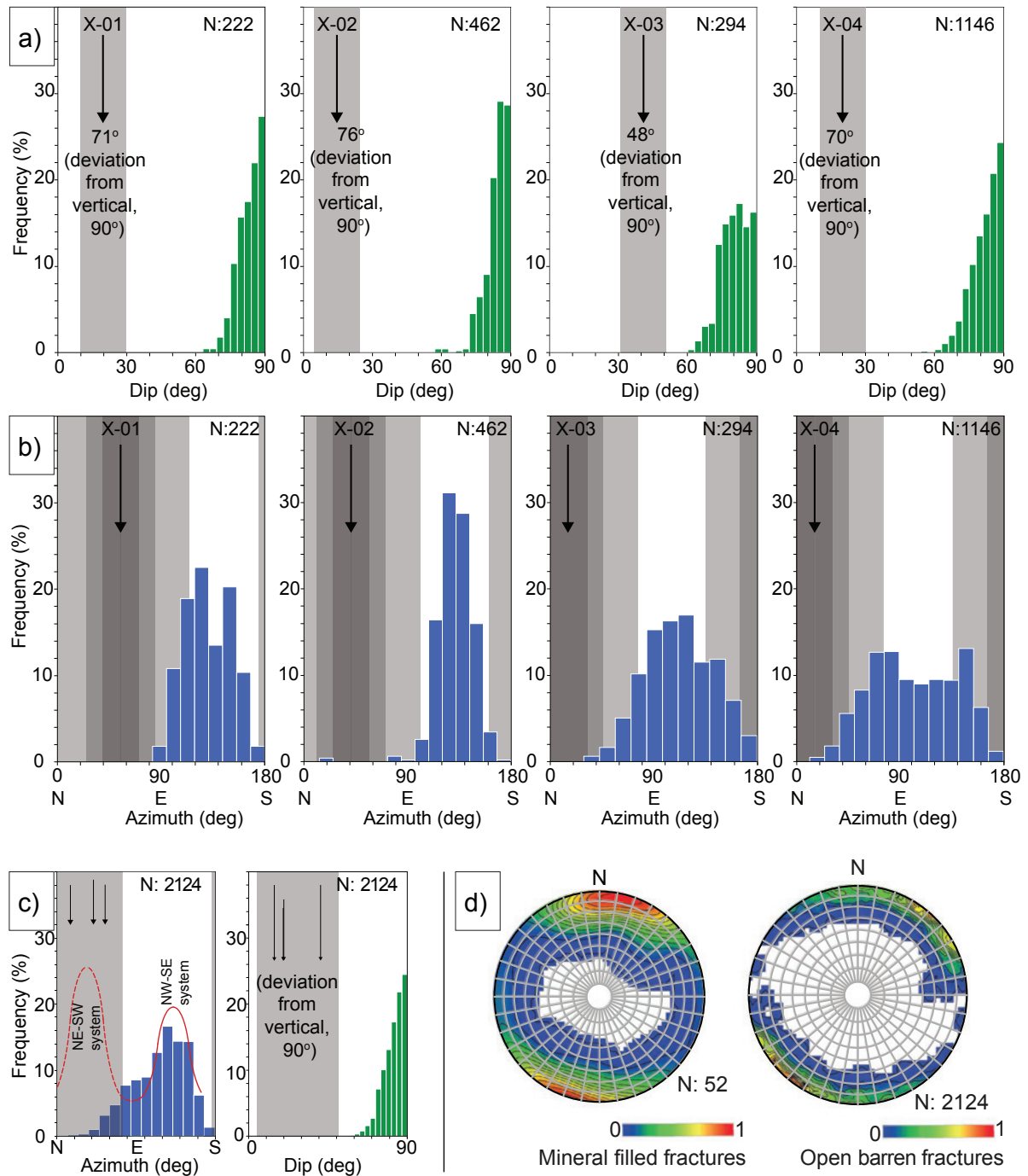


Fig. 5.13: Orientation measurements of open barren fractures from borehole images for a) dips; b) strikes; c) combined dips and strikes from the four boreholes; and d) stereonets (Schmidt pole and plane lower hemisphere) displaying dips and strikes of the mineralized and barren fractures.

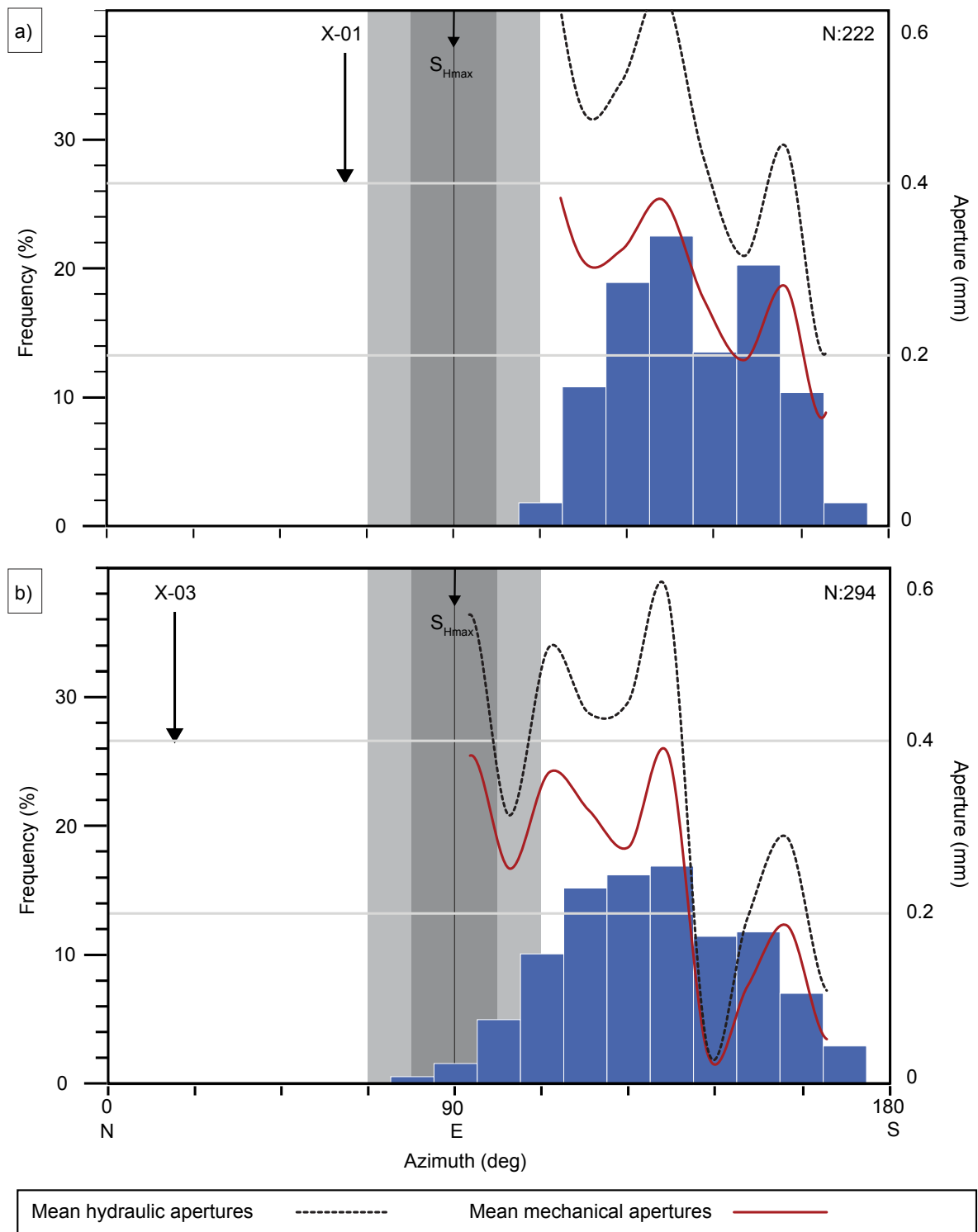


Fig. 5.14: Frequency distributions of the strikes of the barren open fractures interpreted from the borehole images of X-01 and X-03 plotted against their mean aperture measurements.

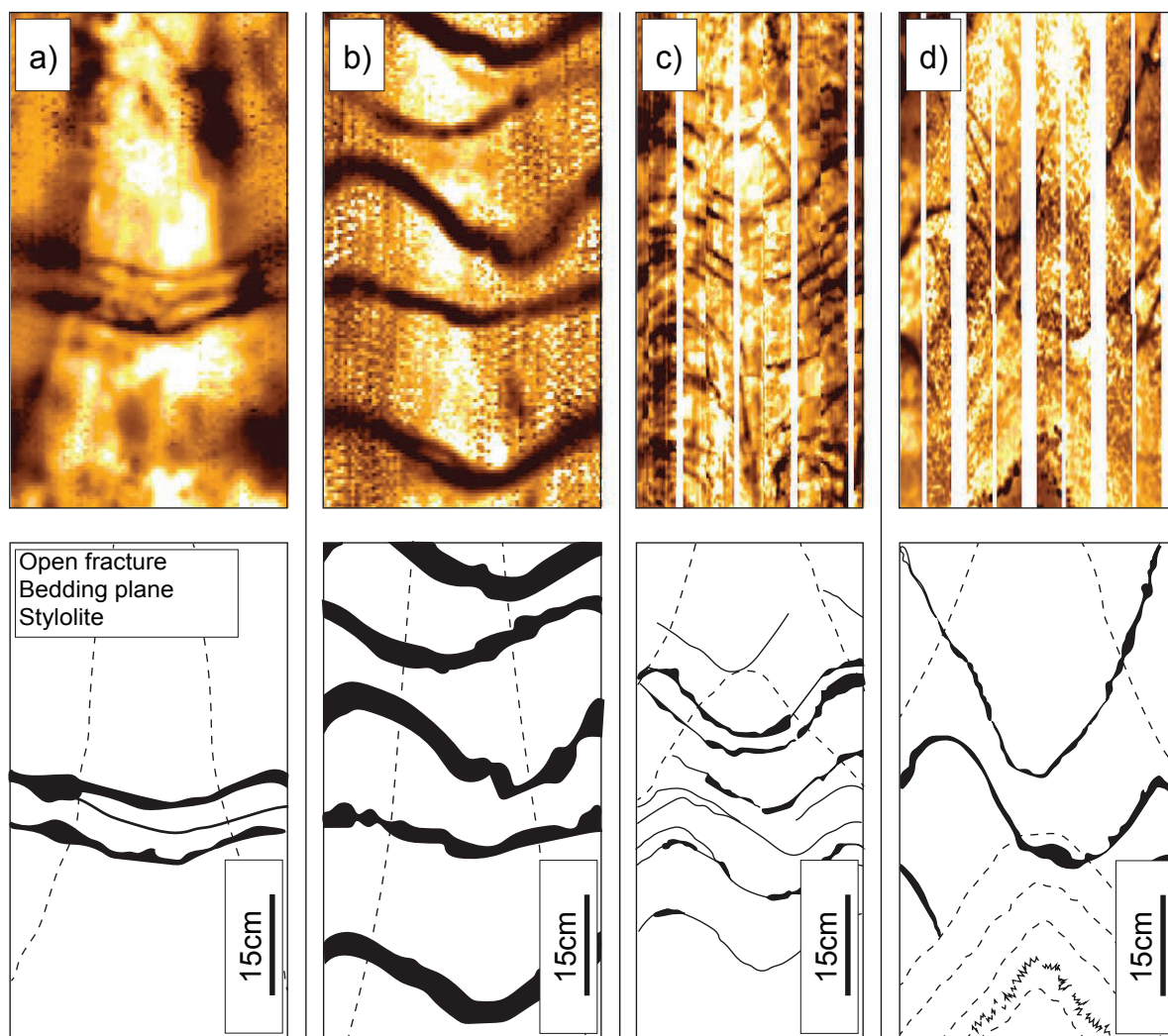


Fig. 5.15: Comparison of the open barren fractures described from a, b) the LWD images of X-02, c) wireline images of X-01, and d) wireline images of X-03. The large apertures in (b) were apparently enhanced for the LWD imaging despite the inferior resolution of the tool compared to that of the wireline tools. This is not due to the pixelation of the LWD images, because they show narrower fractures in (a).

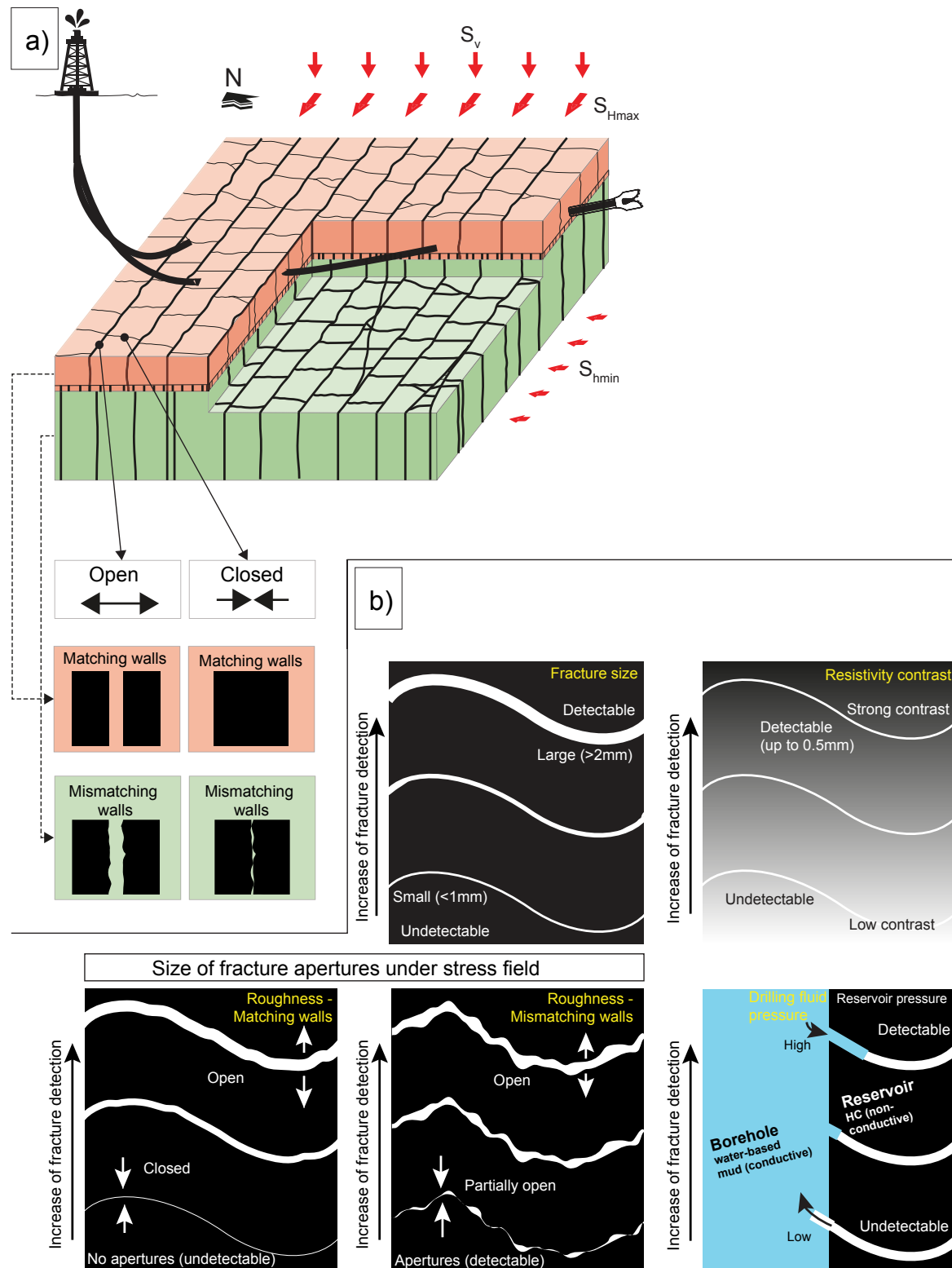


Fig. 5.16: a) An idealized model demonstrating (open) aligned and (closed) non-aligned barren fractures in Eastern Arabia. Fracture apertures depend on the present-day S_{Hmax} and the mismatching walls preventing complete fracture closure under S_{Hmax} . b) Factors governing or influencing the fracture detection by modern borehole imagers (FMI-HD) in carbonate reservoirs.

Fractures are detected if they have relatively larger size, greater than 0.08 (~2 mm). Other factors include resistivity contrast improving or reducing signatures of fractures, and aperture fluid intake under the balance of the fluid pressure between borehole and reservoir.

Study	Borehole images and core	Borehole drilling	Reservoir rock and location	Some findings from comparing fractures
Laubach et al., 1988	FMS images were acquired from Howell No. 5, and prototype FMS images from Mast No. 1-A. Core was acquired from Howell No. 5, Mast No. 1-A, and SFE No. 2 (359 ft). Core recovery: N/A.	Vertical	Gas reservoir, tight sandstone and shale, Lower Cretaceous, Travis Peak Formation, Texas, USA	The FMS detected some of the natural fracture in the core, but natural and drilling-induced fractures could not be distinguished from the images. The FMS did not provide enough coverage to determine fracture abundance or orientation.
Pezard et al., 1992; Ayadi et al., 1996; Lovell et al., 1998; C��lerier et al., 2002; ODP, IODP archives (BGS, 2003)	FMS images were acquired from a total of 33 basement boreholes. Boreholes: 504B, 794D, 793B, and 792E. Core recovery: Generally poor.	Vertical	Varied lithologies of sediments and crystalline rocks, between ODP Leg 126 and IODP Expedition 324 (1989–2010)	Fractures were often visible on the FMS. Where core was available, the FMS provided limited fracture sampling. The FMS images acquired in the ODP are often of an inferior quality than those acquired by the industry, because of borehole conditions, limited coverage (20–40%) of borehole, operational constraints, and the broad range of lithologies.
Kubik and Lowry, 1993	FMS images were acquired from boreholes: COOP No. 1 and ED. Core recovery: 99% from COOP No. 1, and 85% from ED with poor conditions.	Vertical	Gas reservoir, Devonian shale, Kentucky, USA	No fracture sampling was provided, but the advantages and disadvantages of each tool were presented with guidelines for applications.
Azer et al., 2003	FMI images were acquired from borehole OAD-1. Some 42 m of oriented core were recovered. Core recovery: N/A.	Deviated (38 degrees from vertical)	Oil reservoir carbonates, Upper Jurassic Arab-D, offshore Abu Dhabi, UAE	Comparison shows good agreement in fracture geometry between core geometry and FMI images, where some core fractures were observed in images.
Lin et al., 2007 Wu et al., 2008	FMS images were acquired from the upper section of TCDP hole-A, and FMI from the borehole lower section. FMS covers 55% of the borehole, and FMI covers 90% of the borehole. Core recovery: 92%, and low recovery from fractured intervals.	Vertical	Sandstone and shale, Miocene-Pleistocene stratigraphy, Taiwan Chelungpu-fault Drilling Project	Comparison shows discrepancies between core and borehole images. Thick, steep fractures can be better resolved in borehole images, whereas core can show small, low-angle dipping fractures. Core provides better coverage of fracture abundance than do images, but neither technique is perfect.

Khoshbakht et al., 2012	FMS images and core were acquired from well (A). Core recovery: 94%. The core was not recovered from highly fractured zones.	Vertical	Oil reservoir, carbonates, Asmari Formation, Southwest of Iran	Comparison indicates that the number of open fractures in the FMS is more than in the core because the core was not recovered from highly fractured zones. Anhydrite and dolomite veins couldn't be detected due to the low data contrast and low coverage of the FMS.
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Tab. 5-1: Studies directly interpreted and compared fractures from core and equivalent borehole intervals imaged by electrical imaging tools.

6 ROUGHNESS AND WALL MISMATCH OF CARBONATE RESERVOIR FRACTURES

ABSTRACT

Roughness and mismatch of fracture surfaces (walls) are key hydromechanical rock properties, but exceptionally difficult to detect and describe from subsurface reservoir rocks. This chapter includes new insights about roughness and wall mismatch of opening-mode fractures in carbonate reservoir rocks using a combination of new measuring techniques (described in Ch. 3). The fractures were described from core and modern electrical borehole imaging datasets from extended-reach drilling into the Arab carbonate reservoirs in Eastern Arabia. The fractures, existing as calcite veins and barren, exhibit roughness ranging between 5 and 14 on the joint roughness coefficient (JRC) scale. The majority of fractures exhibit matching walls, permitting use of the cubic law for fluid flow modeling. A minority of barren fractures exhibit mismatching walls that preserve their apertures under compression of the current stress field in Eastern Arabia. Roughness and mismatch of fracture walls were found to reflect the fabrics of host carbonates and, hence, are potentially predictable from analyses of carbonate lithofacies.

6.1 INTRODUCTION

Roughness and mismatch of fracture walls are key hydromechanical properties of shear strength and hydraulic conductivity (permeability) of rock masses (e.g., Barton et al., 1985; Olsson and Barton, 2001) (see Ch. 3). Measuring rock shear strength and permeability is an important topic for a wide range of scientific research and industrial applications. Relevant fields include geotechnical, hydrological, and petroleum reservoir sciences, as well as geophysical imaging of subsurface fractures.

Roughness measurements have been extensively and almost exclusively reported from numerical simulations, laboratory experiments on artificial fractures, and fractures in near-surface rocks (e.g., Barton and Choubey, 1977; Brown, 1987; Maerz et al., 1990; Tatone and Grasselli, 2010). Roughness measurements on deep reservoir fractures are rare, possibly due to inadequacy of direct data on roughness, lack of efficient measuring techniques, or both. Rationally, direct roughness measurements are unattainable from using various subsurface data sources other than core—assuming it is of good quality and from boreholes that were geometrically ideal to intersect fractures in subsurface rocks.

Nevertheless, fracture roughness is a central element in some models estimating fluid flow in subsurface reservoir rocks. Using borehole data, Barton et al. (1995) demonstrated a correlation between high permeability and fractures with planes (optimally oriented) parallel to S_{Hmax} . The correlation source was related to fracture roughness, citing the empirical findings of Brown (1987). Earlier, Heffer and Lean (1993) proposed that optimally oriented fractures in reservoir rocks have the least resistance to closure, and, hence, they are the most permeable. These different interpretations, on an obviously similar and general correlation, carried out different implications for fracture roughness.

Subsequently, Barton et al. (1995) introduced the hypothesis of critically stressed fractures (CSF), whose ratios of shear to normal stresses exceed their frictional strengths. The CSF hypothesis has since been advanced to applications of reservoir geomechanics (Rogers, 2003; Zoback, 2010). Rogers (2003) emphasized that dilations due to shear of CSF are the source for high permeability. This embeds the assumption that original walls of fractures are both perfectly matching and rough. The slips of walls, therefore, mechanically produces roughness anisotropy and apertures between fracture walls (e.g., Brown, 1987; Thompson and Brown, 1991). It is still uncertain if the high flow in subsurface fractures

was related to fracture roughness, since it was not measured, because of data resolution limits on individual fracture characteristics (Barton et al., 1995).

Fracture roughness is also relevant to borehole geomechanics (g.e., Plumb et al., 2000). This is a field of application in the petroleum industry that is considered imperative for drilling operations to rule out possible problems of borehole instability (e.g., Moos et al., 2003; Kang et al., 2009a). Borehole problems range from a stuck pipe, and consequently loss of costly bottom hole assembly, to a total hole collapse and loss of a multimillion-dollar project (e.g., Kang et al., 2009b). Despite roughness being often overlooked, a few theoretical studies (Chen et al., 2003; Younessi and Rasouli, 2010) promoted the potential risk of sliding failure along the fractures intersecting a borehole. This failure is similar to the slope instabilities described in geotechnical studies (Barton and Choubey, 1977). The shear strength of a fracture is correlated with the rock sliding potential on the fracture; the rougher the fracture surface, the lower the sliding potential (e.g., Barton and Choubey, 1977; Younessi and Rasouli, 2010).

This chapter includes measurements and insights on the nature of roughness and wall mismatch of carbonate reservoir fractures. The fractures were described from outstanding datasets of directional core combined with high-resolution electrical borehole imaging (Fig. 6.1). Roughness was found to be among the major factors that control the detection of fractures using electrical borehole images (see Ch. 5). Observations of roughness and wall mismatch were noticeable from comparing fractures in the core to the detected fractures in the borehole images. The observations on roughness were initially visual, and qualitative, and were simply based on correlations of different fracture profiles (Fig. 6.2). It was, however, necessary to develop novel methods to quantitatively measure roughness and wall mismatch of the observed fractures in core.

The measurements were obtained from applying new quantitative nondestructive techniques on fracture profiles digitized from high-definition optical scans of the core of X-01 and X-03 (Ch. 3). The results from the core data were correlated with the detection levels of fractures and aperture measurements from the corresponding borehole images. The results bear general implications to the modeling of fracture permeability and sliding potential in subsurface carbonate reservoirs.

6.2 RESULTS

6.2.1 ROUGHNESS OF FRACTURES

The roughness magnitudes for all measured fractures (calcite veins and barren fractures) range between 0 and 0.27 for the Z_2 parameter (Fig. 6.3, and Tab. 10-6 in the appendix). About 95% of the Z_2 measured values range between 0.08 and 0.24. The values demonstrate a semi-normal statistical distribution, which permits to define certain ranges and mean values to relate roughness magnitudes to the nature of measured fractures.

The Z_2 values were converted to the JRC scale, using the relationship introduced in Ch. 3.3.3.4. The conversions resulted in values ranging between 0 and 14 on the JRC scale (Fig. 6.4). About 90% of the JRC values are greater than 4 and less than 15, for both mineralized and barren fractures.

6.2.1.1 *Roughness of Barren Fractures*

The roughness of the barren fractures ranges between 0 and 14 on the JRC scale. About 85% of the JRC values are between 4 and 13 (Fig. 6.3). The mean value of the JRCs for barren fractures is 7.5, with a standard deviation of 3. The average of the roughness values can be represented by the typical profile 6–8 on the JRC scale (Fig. 6.4).

The range and average of measured values indicate that the barren fractures range from smooth to moderately rough fractures. The very smooth fractures (< 4 JRC) seem anomalous in the measurements.

6.2.1.2 *Mineralized Fractures*

The roughness of the calcite veins ranges between 0 and 14 on the JRC scale. About 85% of their JRC values are between 5 and 12 (Fig. 6.3). The mean value of the JRCs of the veins is 7.5, with a standard deviation of 3. The average of the roughness values can be represented by the typical profile 6–8 on the JRC scale (Fig. 6.4).

The range and average of measured values indicate that the barren fractures range from smooth to moderately rough fractures.

6.2.2 MATCHING OF FRACTURE WALLS

6.2.2.1 *Barren Fractures*

Most fractures exhibit mismatch coefficients less than 0.1 (Tab. 10-7 in the appendix). A small number of fractures have noticeable degrees of mismatch. The results from calculating the standard deviation of apertures display that about two-thirds of fractures have less than 0.15 units, and the remaining one-third range between 0.15 and 0.4 units. The limited occurrences of wall mismatch resulted in weak relationships between the JRCs and correlation coefficients as well as the standard deviations of apertures.

6.2.2.2 *Mineralized Fractures*

Most fractures exhibit mismatch coefficients less than 0.1. A small number of fractures have noticeable degrees of mismatch. The results from calculating the standard deviation of apertures display that about two-thirds of fractures have less than 0.15 units. The remaining one-third ranges between 0.15 and 0.4 units. The limited occurrences of wall mismatch resulted in weak relationships between the JRCs and correlation coefficients as well as the standard deviations of apertures.

6.2.3 ROUGHNESS AND WALL MISMATCH VS. LITHOLOGY

6.2.3.1 *Barren Fractures*

The barren fractures in coarse-grained lithofacies exhibit profiles rougher than those of the fractures in fine-grained lithofacies (Fig. 6.2 and Fig. 6.5). These observations are similar for the calcite veins (Fig. 6.2). This relationship between roughness and lithology is more obvious from the limestone fractures than it is from the dolomite fractures (Fig. 6.5).

6.2.3.2 *Calcite Veins*

The roughness generally increases with increasing grain sizes of the host limestone. The probability of finding wall mismatch, although limited, seems to increase with increasing grain and pore sizes of the host limestone rocks.

6.2.4 APERTURE MEASUREMENTS

The aperture measurements from borehole images display separation between mechanical and

hydraulic apertures (Fig. 6.1b, Fig. 6.6, and Fig. 6.7). The size of apertures varies along the profiles of barren fractures in borehole images (Fig. 6.6 and Fig. 6.7). In addition, the mean apertures display comparable trends from both boreholes, with increasing apertures toward the fractures striking E–W and NE–SW ($\sim 60\text{--}100^\circ$), and decreasing toward the fractures striking NW–SE ($\sim 120\text{--}180^\circ$) (Fig. 6.1b).

6.3 DISCUSSION AND IMPLICATIONS

6.3.1 Nature of Roughness and Predictions

The fractures exhibit a moderate to high range of roughness magnitudes on the JRC scale, between 5 and 14. The roughness values above 10 JRC are high, although they can still be considered moderate in the context of carbonate lithology (N. Barton, personal communication).

The range of roughness measurements is comparable for barren and calcite veins, despite that the two fracture systems differ in their diagenesis history. The roughness is apparently independent of the fracture mineralization process. Mineral fills are well-preserved casts for paleo fracture roughness of fracture walls. The fractures (smooth and rough) have generally matching walls, and only a minority of the rough fractures exhibit an obvious wall mismatch. Applying the parallel-plate approach (the cubic law) is practical for estimating fluid flow in these reservoir fractures.

The roughness and mismatch of fracture walls are clearly products of the variations in sizes and shapes of the matrix, grains, crystals, and pores of host carbonates (Fig. 6.8). The limestones and dolomites of the Arab carbonate reservoirs exhibit both primary and diagenetic fabrics (e.g., Mitchell et al., 1988). The statistical distributions of roughness reveal the probability of sampling different lithological beds from fine-grained to coarse-grained beds. High values of roughness and wall mismatch are more common from coarse-grained rock than from fine-grained rock with small pore sizes. The observed wall mismatch can be noted here as *fabric-dependent* to make a distinction from the wall mismatch occurring due to wall slips in sheared fractures (faults) (Barton et al., 1995). Fabric-dependent roughness and wall mismatch are potentially predictable from limestone lithological descriptions. The Arab reservoir rocks exhibit a wide range of limestone lithofacies, such as mudstone, wackestone, packstone, grainstone, floatstone, and rudstone (e.g., Mitchell et al., 1988). Some, if not all, of these lithofacies types exist in other carbonate reservoirs.

Nonetheless, the prediction of roughness magnitude from lithological fabrics involves some

assumptions about fracture height. The prediction is possible for multi-lithofacies carbonates whose mechanical stratigraphy typically bounds fracture height. The throughgoing fractures (i.e., fractures that cut through various lithological layers) are expected to display roughness stratification (i.e., roughness anisotropy, with the vertical direction normal to the strata horizontal planes) (Fig. 6.8). The measured magnitudes of fracture roughness are considered static, which means that the core-based measurements are representative for the magnitudes of reservoir fracture roughness. Two reasons can be listed here to support this consideration. First, the texture, porosity, mineralogy, and mechanical properties of the Arab reservoir rocks are not stress-sensitive (i.e., these properties do not change under the reservoir stress conditions) (Ameen et al., 2009). Second, the core did not exhibit distortions in the pore scale architecture, such as breakages of grain bonds or cracks that can be considered signs for confining stress removal (unloading).

6.3.2 Roughness Effects on Fracture Apertures

The effects of fracture roughness and wall mismatch on the aperture of barren fractures are apparent from analyses of borehole images. There are two important results supporting these interrelated effects on apertures. First, wall mismatches of fractures are obvious from the aperture sizes varying along the profiles of detected fractures in borehole images. The sum of these aperture variations is visible from the separations between the mean mechanical and mean hydraulic apertures (Fig. 6.1b). Second, the mean apertures (hydraulic and mechanical) are generally increasing toward the fractures optimally oriented to S_{Hmax} ($\sim 60\text{--}100^\circ$), and decreasing toward the fractures striking NW–SE ($\sim 120\text{--}180^\circ$), because their walls (subnormal to S_{Hmax}) are closed under the compressive stress in Eastern Arabia.

The fracture apertures are dynamic under the stress field because the tensile strength of barren fractures is typically zero (i.e., the fracture walls are not bonded by minerals) (Fig. 6.9a). Because of S_{Hmax} and the dominant wall matching walls, about 80% of the core barren fractures could not be detected from the corresponding borehole images of X-01. The majority of these NW–SE fractures are closed under the compressive stress. A minority of fractures (about 20%) that are detected from X-01 have wall mismatches preserving apertures between fracture walls under this compressive tectonic regime. The barren fractures are detected because of their apertures (and hence permeability) to the infiltrated

drilling mud. Calcite veins exhibit high resistivity in borehole images, indicating they are impermeable to the infiltrating drilling fluid. These observations indicate that in situ permeability of fractures is ineffective if fractures are mechanically closed with complete (matching) wall contacts, or sealed completely with impermeable minerals such as calcite cements. However, dissolving calcite by acid fracturing can potentially make the calcite veins with wall mismatch as permeable as barren fractures (Fig. 6.9b).

6.3.3 Roughness Effects on Rock Strength

The effects of fracture roughness on reservoir rock strength (i.e., the strength of the intact rock blocks and freedom of block movement) are not possible to describe for deeply buried rocks. In the absence of observations, we can only relate the possible effects of roughness from previous empirical studies (Fig. 6.9a). Rock strength is an important factor in planning, drilling, and completing boreholes, especially the directional drilling boreholes that cost millions of dollars. In general, lower JRCs bear the highest potential of sliding (e.g., Barton, 2013) and, hence, may risk stability of directional boreholes. The sliding potential can be correlated to slope instability; the rougher the fracture surface, the lower the sliding potential (e.g., Younessi and Rasouli, 2010). The drilled boreholes (X-01 and X-03) did not have any signs of instability issues such as collapse or tight hole. But some fractures may slip in critically stressed environments and under the dynamics of reservoir production and injection (e.g., Zoback, 2010) (Fig. 6.9).

Some considerations must be given, besides roughness, to the shapes and sizes of fractured rocks (blocks). It is suggested here that fractured blocks that are smaller than borehole sizes can slide and fall into the boreholes (Fig. 6.10). The large blocks are not expected to be displaced, unless driven by large-scale faulting. Some considerations must also be given to internal friction angles, bonding strengths of calcite filling, and the setting in relation to the effective stress field and borehole geometry (Fig. 6.10).

6.3.4 Roughness Effects on Fracture Detection and Abundance

The effect of fracture roughness and wall mismatch on geophysical detection methods of subsurface fractures can be estimated from borehole images. Borehole imaging is the most commonly used geophysical method for measuring fracture orientation, abundance, and aperture in subsurface

reservoir rocks. Fracture roughness and wall mismatch are among the major factors influencing the capability of borehole imaging to detect or miss carbonate reservoir fractures (Ch. 5).

The sizes of barren fracture apertures are dynamic, depending on the roughness and wall mismatch of fracture walls as well as the compressive stress field in Eastern Arabia. The wall mismatch, especially of rough fractures, contributed to relatively large fracture sizes and preserved apertures in the fractures that were closed under the tectonic compression. Accordingly, these fractures are easily detected and measured in borehole images. Wall-matching fractures that were closed under the compressive stress field (i.e., lack of apertures for infiltrating drilling mud) are undetected in borehole images. This situation contributed to an inconsistency and reduction in estimating fracture abundance using borehole images. The variations in fracture aperture sizes due to wall mismatch and stress field contribute to the reservoir rock anisotropy, which must affect geophysical measurements for electrical, seismic, and fluid flow properties of the reservoir.

6.4 CONCLUSIONS

This chapter includes insights on the properties of roughness and wall mismatch of the fractures in the Arab carbonate reservoirs using a combination of new measuring techniques. The fractures, existing as barren and calcite filled, were found to exhibit moderate to high roughness, between 5 and 14 on the JRC scale.

The majority of the smooth and rough fractures have matching walls, indicating that the degree of wall matching is not related to the magnitude of fracture roughness. The roughness and mismatch of the fracture walls reflect the lithology of the host carbonates. Therefore, the fracture roughness is labeled in the text as “fabric-dependent”, to distinguish it from the roughness that can result under rock sliding and friction typical of faults. The roughness magnitudes are higher in coarse-grained rocks and lower in fine-grained rocks, and can accordingly be predicted from describing the lithofacies of carbonates, such as mudstones, packstones, grainstones, and rudstones.

The role of wall mismatch is considered significant, despite it being limited to a minority of fractures. Those barren fractures of mismatching walls were detected in the borehole images, while most barren fractures, of wall-matching walls, were missing. Given that the fractures are normal to S_{Hmax} , the NW–SE fractures are considered closed under the tectonic compression in Eastern Arabia. The drilling

fluids could not enter these closed fractures for lack of aperture. It can be seen from the observations that mismatching walls preserve some apertures of mechanically closed fractures. This finding of a minority of barren fractures with wall mismatches is significant for fracture detection, which directly affects measurements of fracture abundance in subsurface reservoirs. The roles that roughness and the stress field play in changing sizes of fracture apertures in reservoir rocks affect geophysical measurements of fractures using indirect methods that are dependent on electrical, seismic, and fluid flow properties.

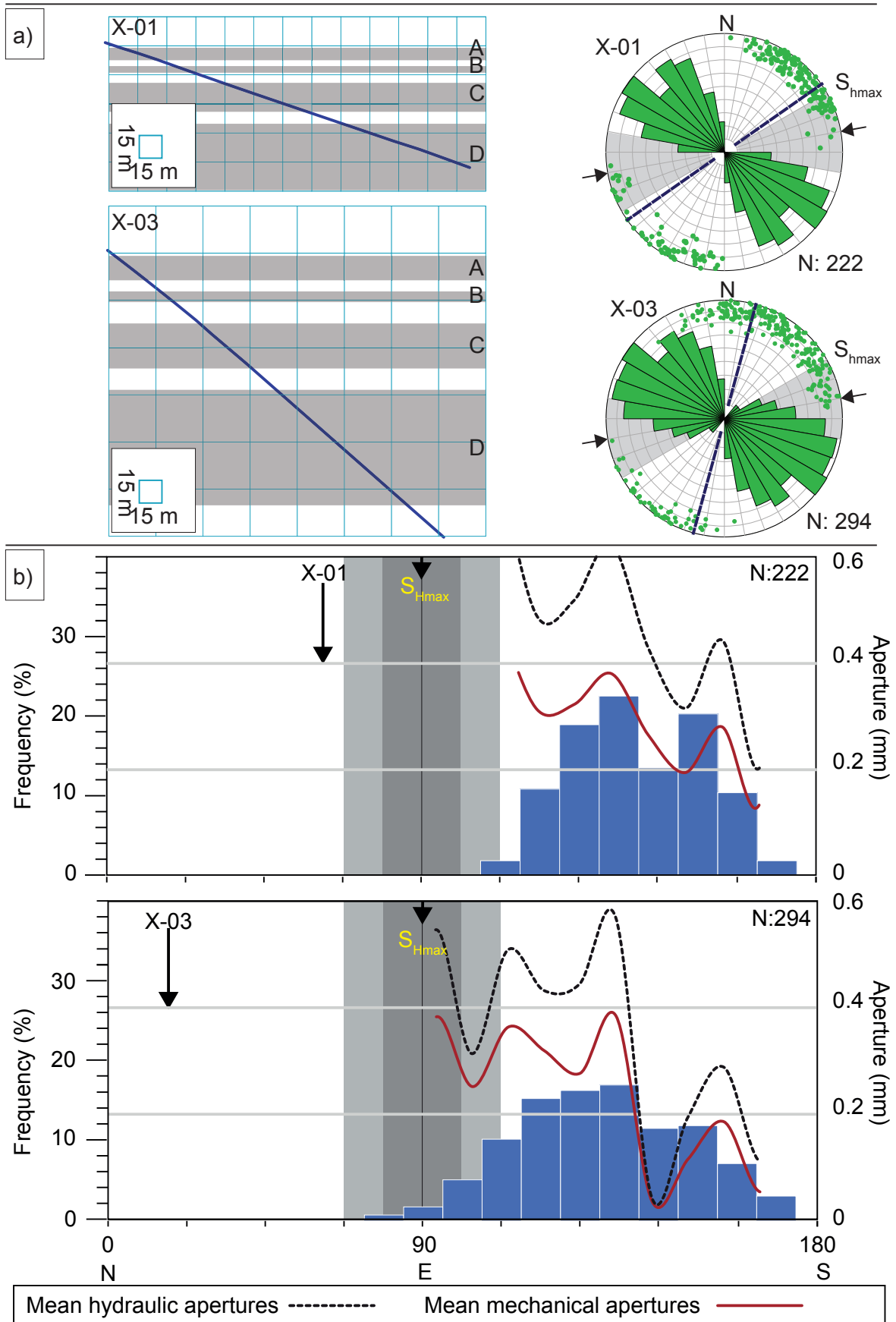


Fig. 6.1: a) Fracture strikes measured from the borehole images of X-01 and X-03. b) Plots for correlations of fracture strikes, fracture apertures, borehole orientations, and the present S_{Hmax} .

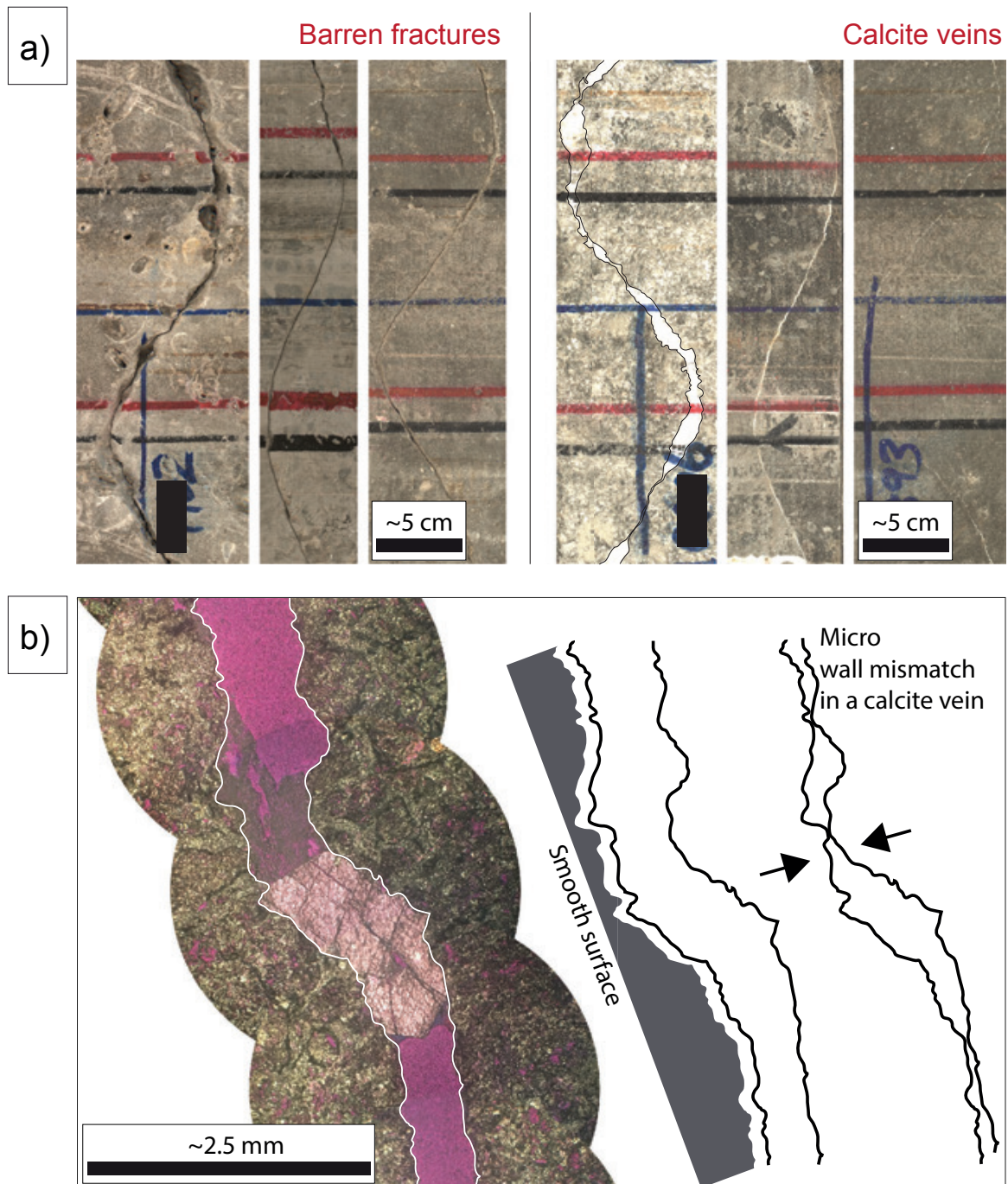


Fig. 6.2: Core photographic scans of mineralized and barren fractures of walls ranging from mismatching rough to matching smooth; b) measurements from the borehole images demonstrate the mean mechanical apertures (red curve) and mean hydraulic apertures (dashed curve) of the barren fractures. See the text for further details.

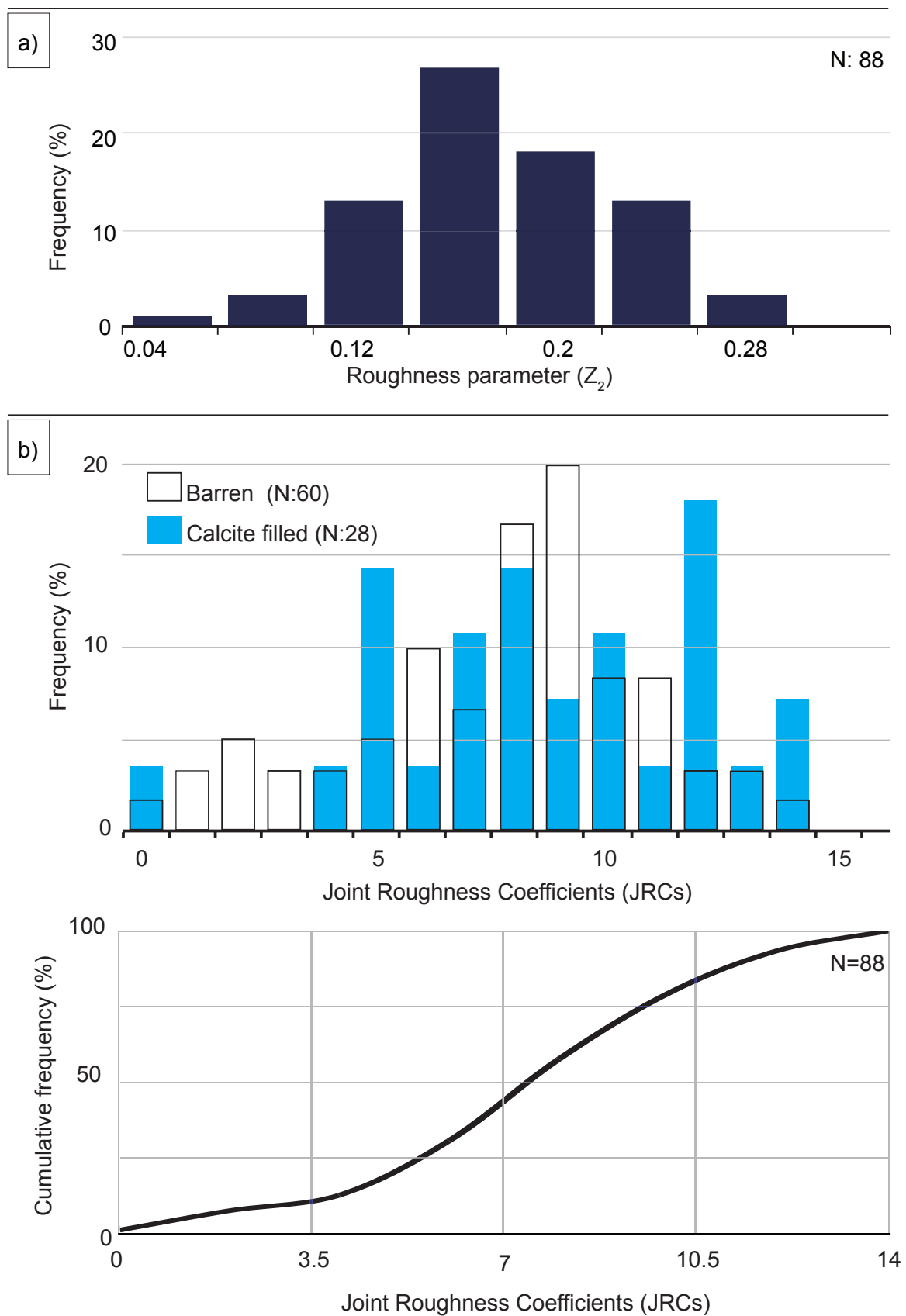


Fig. 6.3: Statistical distributions of the Z_2 roughness parameter values; c) the equivalent of the Z_2 values after conversion to the joint roughness coefficients (JRCs) scale; and d) cumulative distributions of the JRC values in (c).

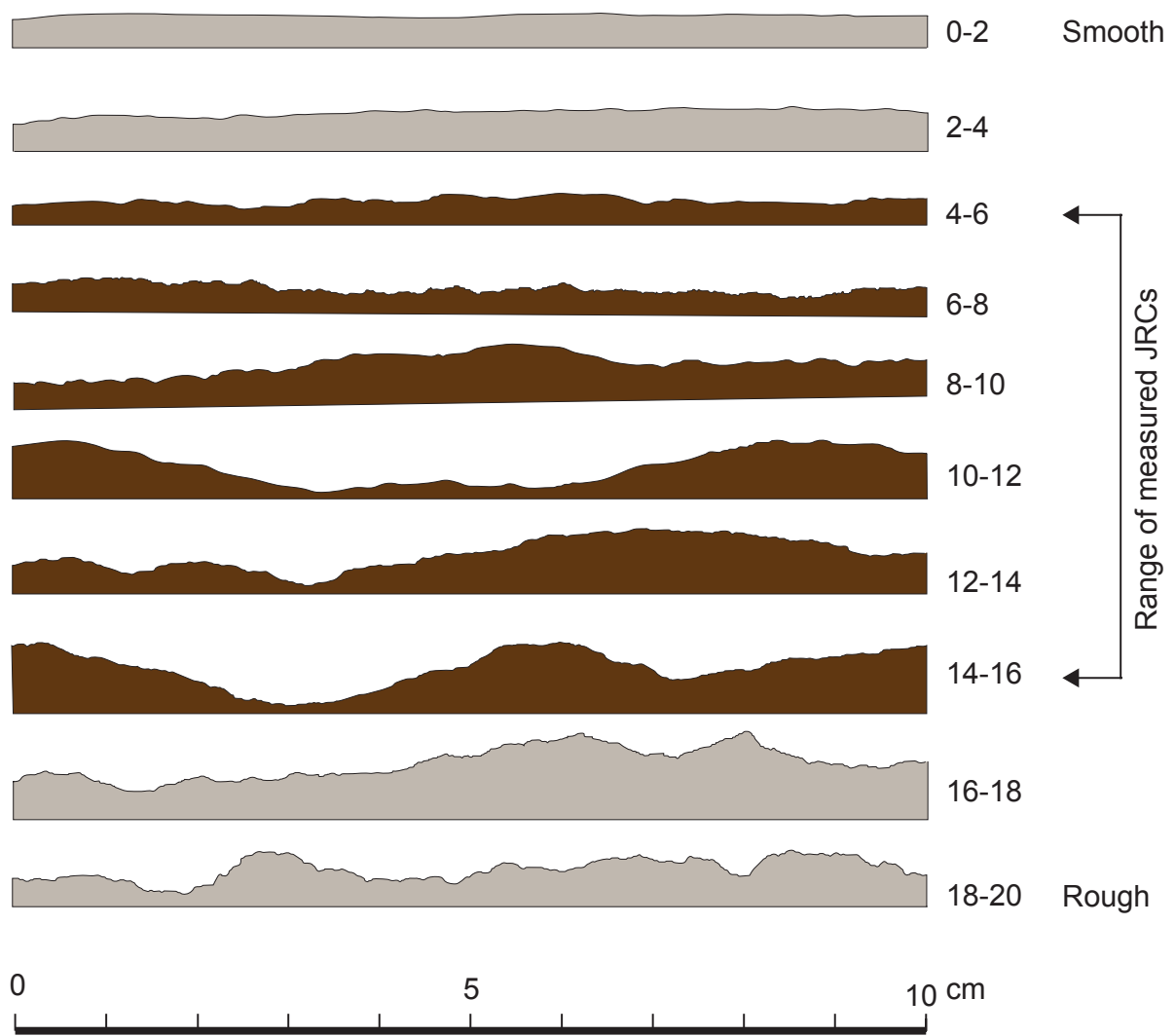


Fig. 6.4: The graphical representations of the measured roughness using the JRC scale.

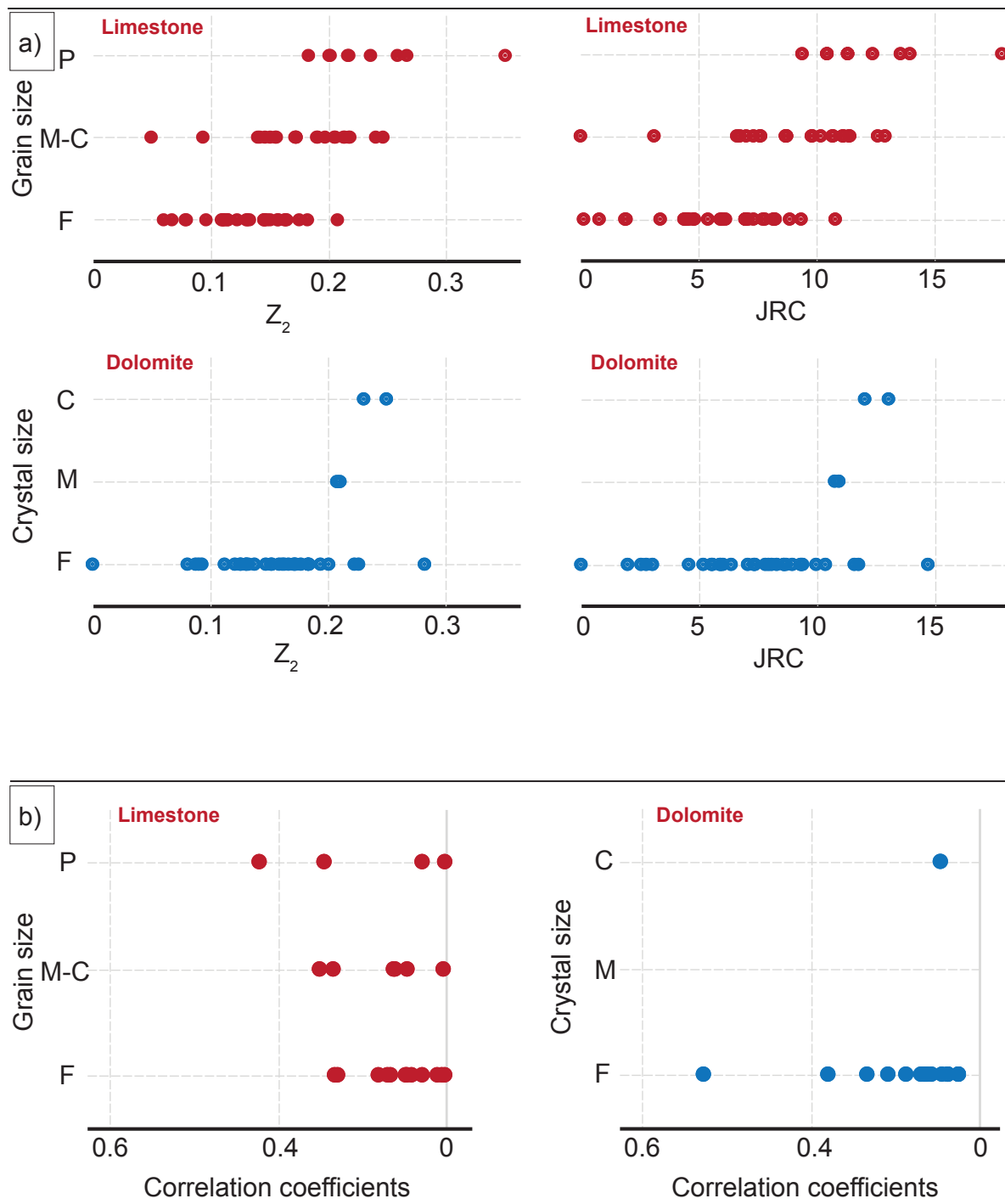


Fig. 6.5: The measurements on fracture roughness and wall mismatch are correlated to the lithology of host carbonate rocks, displaying a) increasing roughness of limestone fractures with increasing grain size, but this correlation is weak in dolomite, and b) increasing probability of wall mismatch, despite being limited, with increasing grain size of limestones and no correlation established from dolomite fractures. F: fine; M-C: medium to coarse; P: pebble.

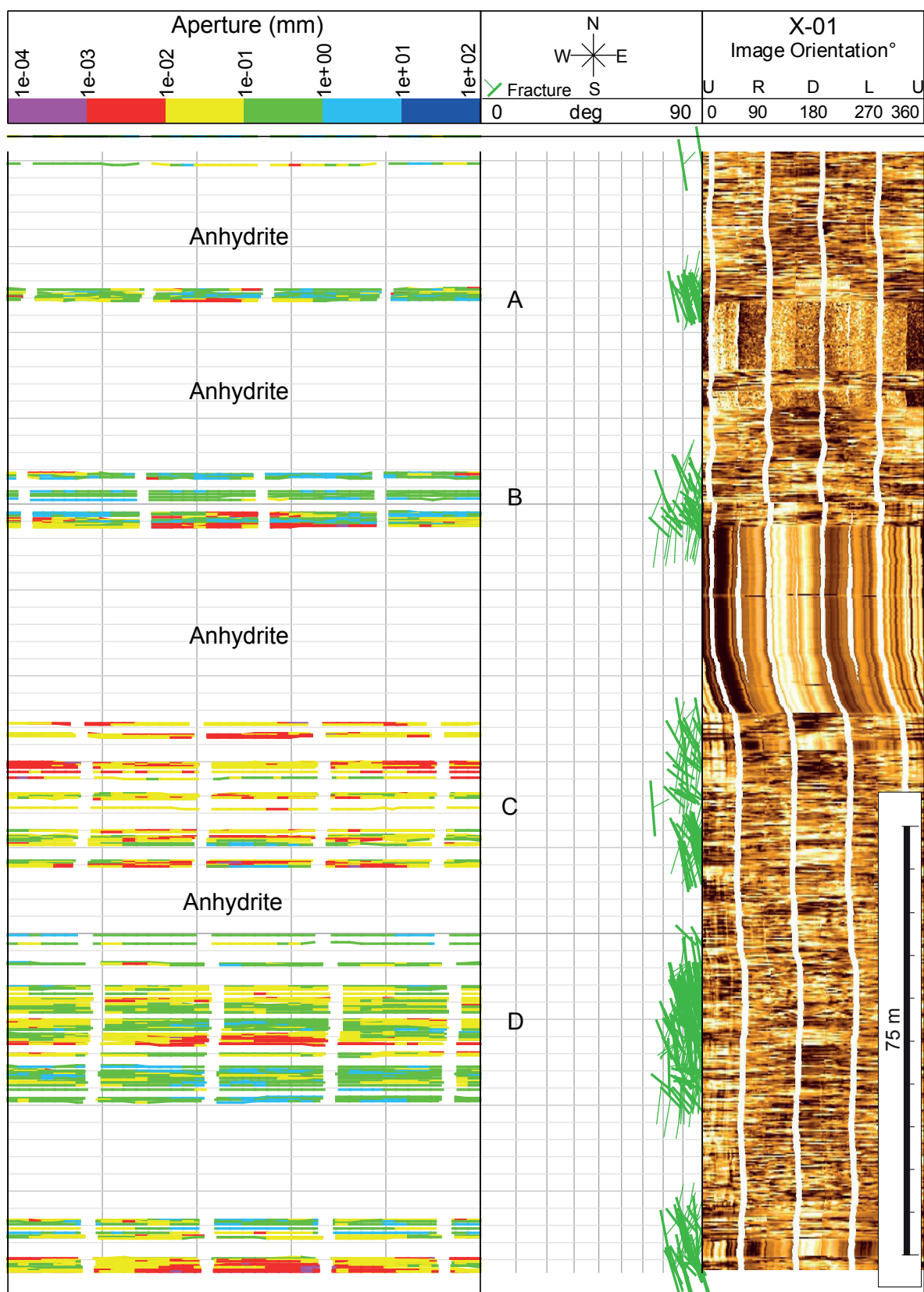


Fig. 6.6: The barren fractures detected and interpreted from the borehole images of X-01 display variations of aperture sizes (see color codes), indicating mismatch of fracture walls.

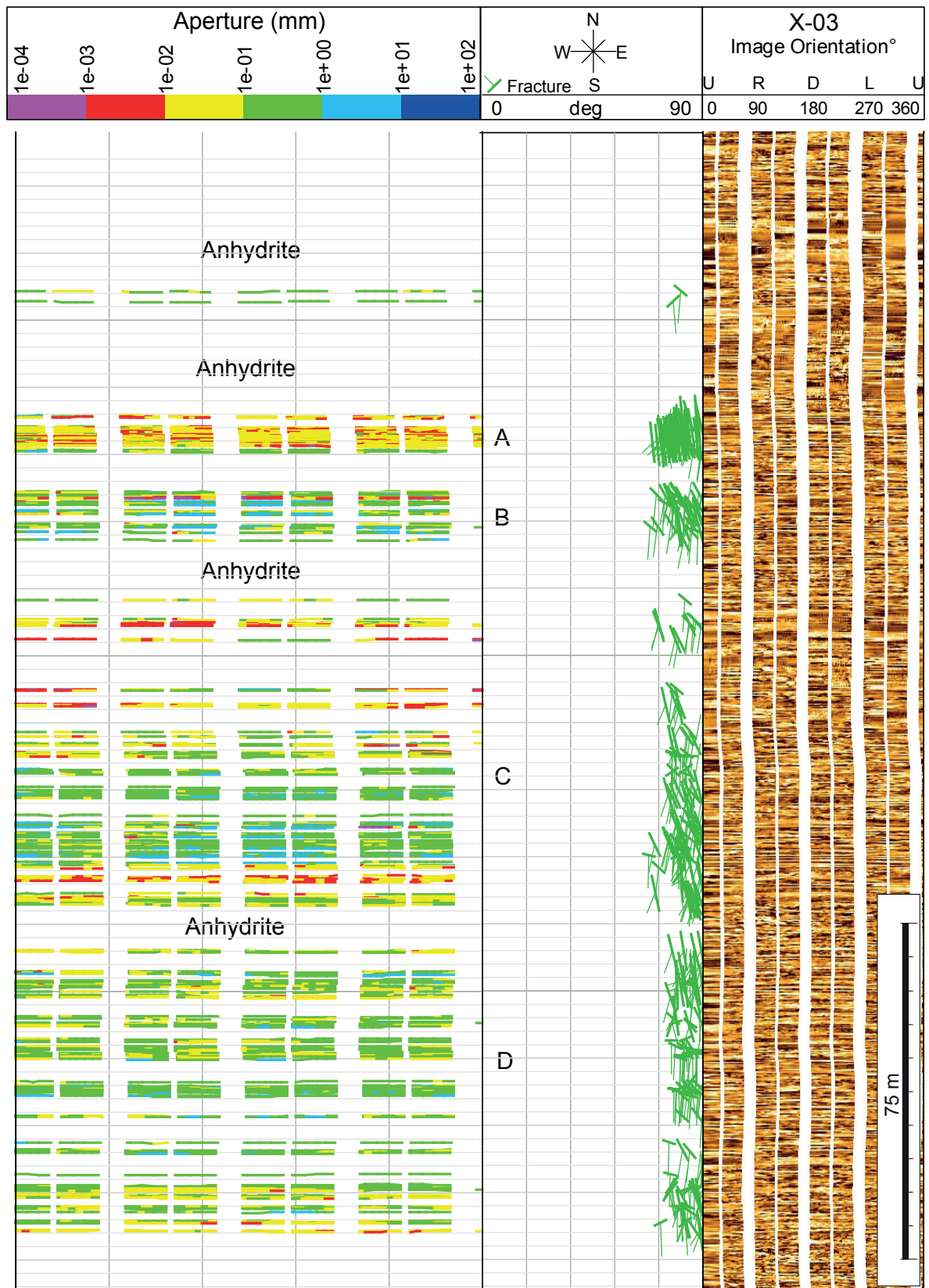


Fig. 6.7: The barren fractures detected and interpreted from the borehole images of X-03 display variations of aperture sizes (see color codes), indicating mismatch of fracture walls.

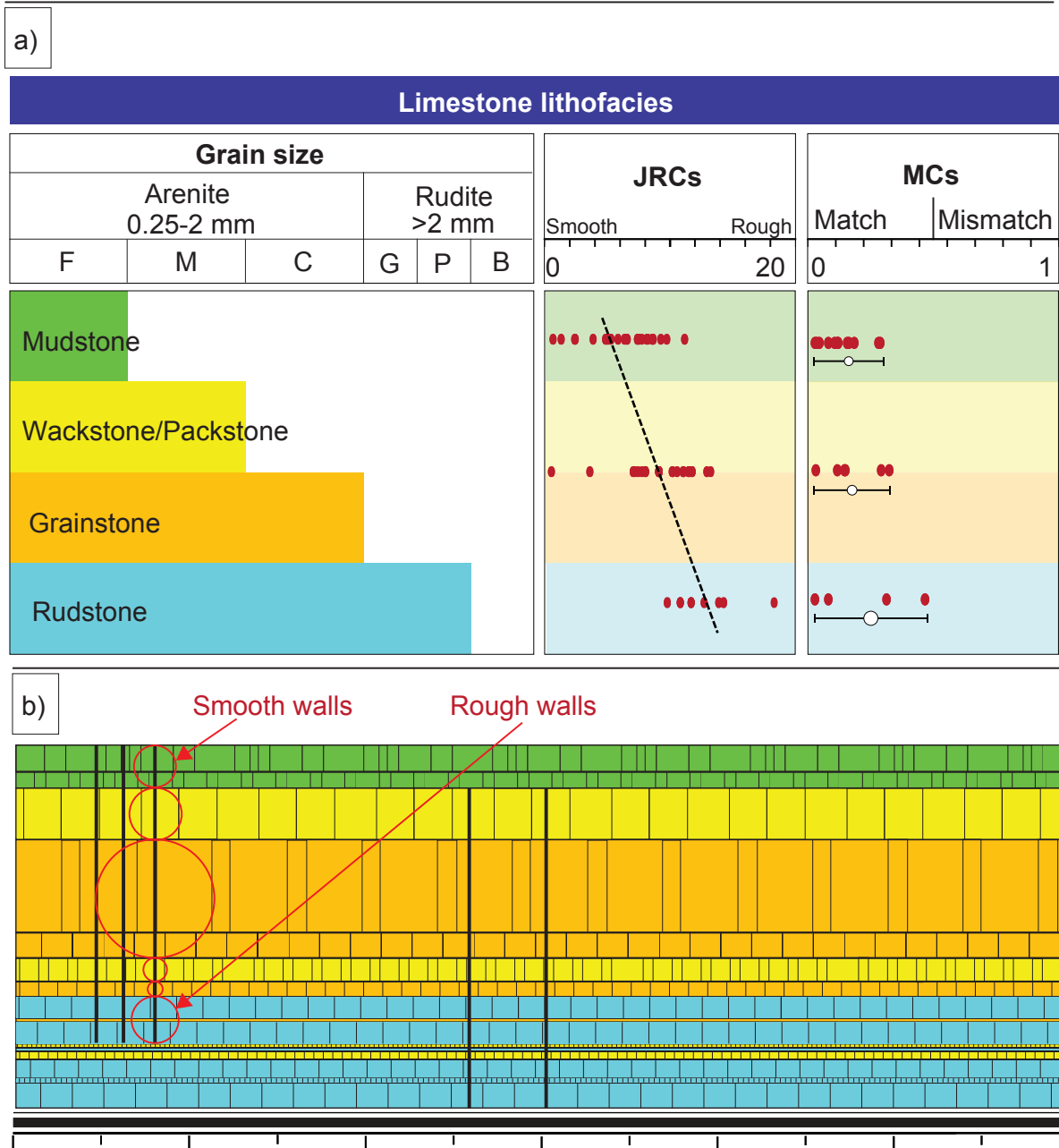


Fig. 6.8: a) Plots comparing the JRCs and MCs (red circles) of fracture roughness and wall mismatch with the limestone lithofacies. b) Sketch demonstrates roughness is dependent on lithology; the throughgoing fractures are expected to exhibit vertical anisotropy in roughness magnitudes that reflect the host lithology.

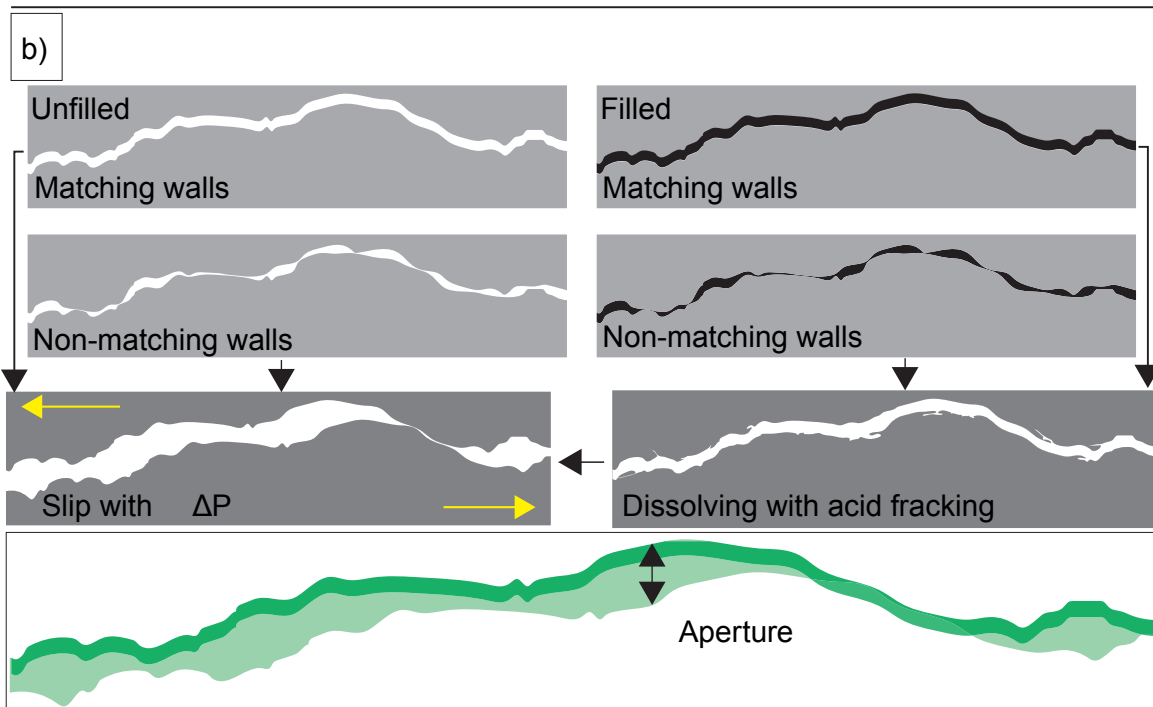
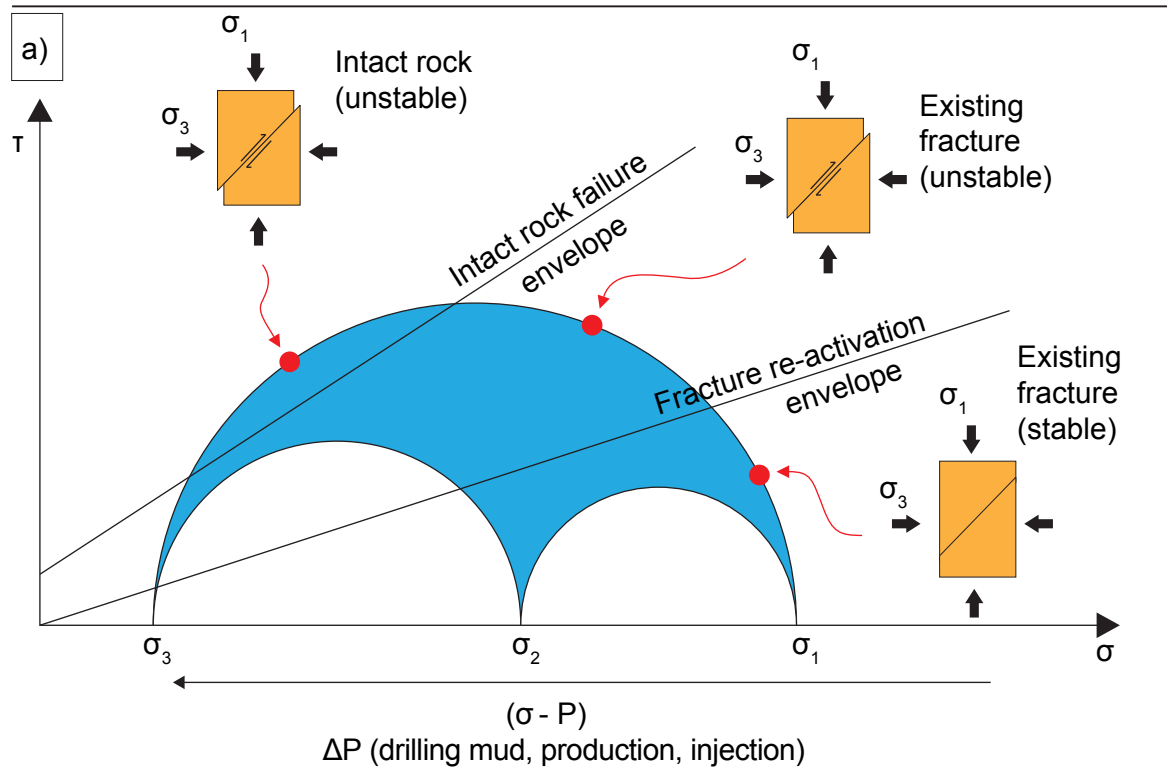


Fig. 6.9: a) Mohr–Coulomb diagram for fracture failure potential, with the role of fluid pressure reducing the principal stresses in reservoir rocks. b) Different possible paths of rough apertures that may evolve from mineralized and barren fractures under the geological conditions and reservoir production dynamics.

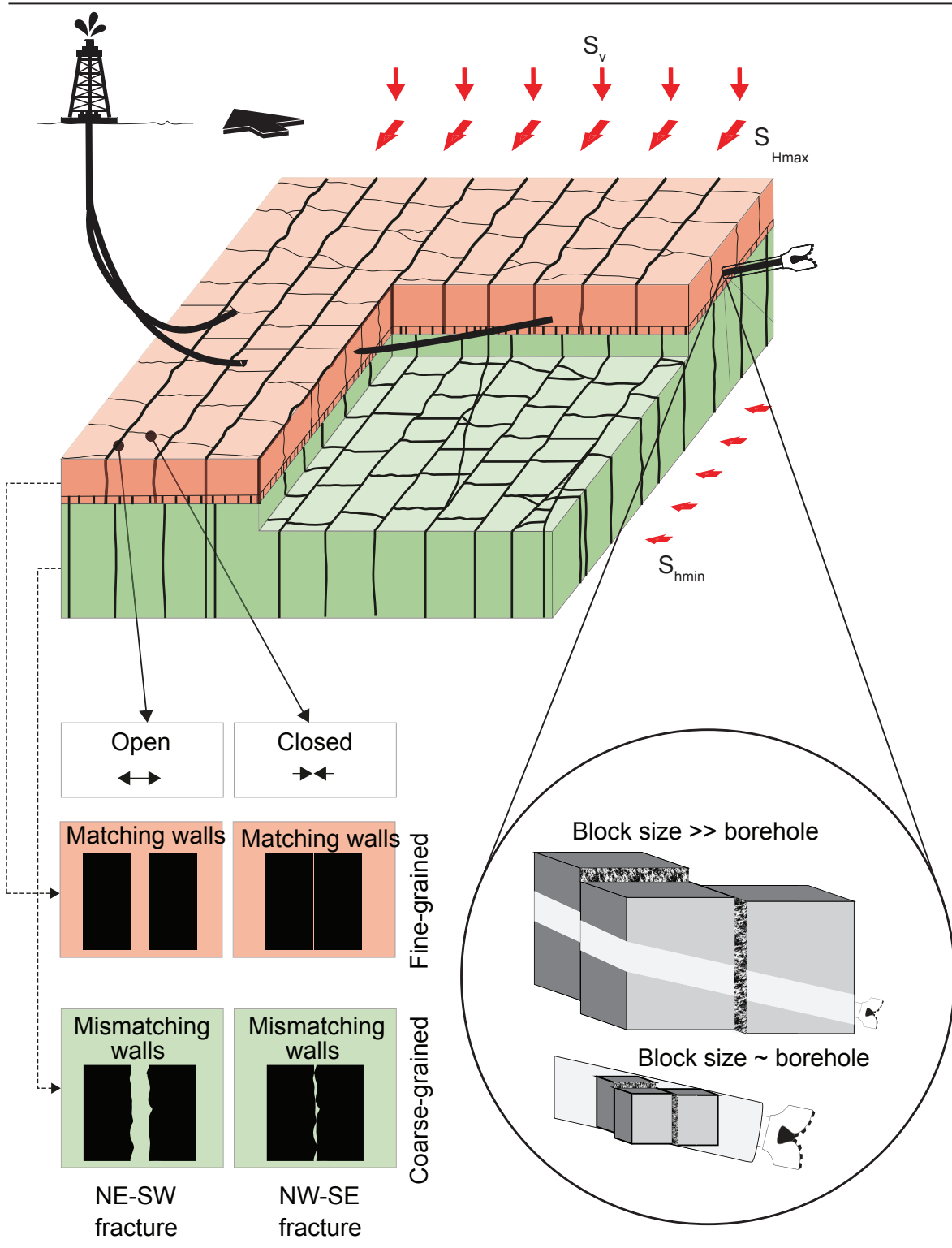


Fig. 6.10: A framework model for two carbonate layers of muddy and grainy lithofacies that are cut by the NE–SW and NW–SE regional systems of barren fractures in the Arab carbonate reservoirs in Eastern Arabia. The model demonstrates that the NW–SE fractures in coarse-grained layers have apertures despite their walls being closed under the present-day S_{Hmax} resulting from tectonic compression. Other related subsurface parameters that bear implications to the directional borehole stability are considered in the framework, such as the size of fractured blocks. Small blocks can be displaced to fall in the borehole according to the equilibrium between load of gravity (S_v) or tectonics (S_{Hmax}), roughness, and friction.

7 CONTROLS ON THE ABUNDANCE OF FRACTURE SYSTEMS IN GENTLY DEFORMED CARBONATES: OBSERVATIONS AND DISCUSSION

ABSTRACT

This chapter addresses the major controls on the abundance of fracture systems in the carbonates of the Arab and Rus Formations in the study areas, of the dome and homocline, described in Ch. 2. The fractures in these carbonates show similar and different properties. The most notable similar properties are the dominance of barren fractures that are confined to layers, display subvertical dips, and form sets of NE–SW and NW–SE orientations. The fractures display significantly differing ranges of abundance. On averages, fractures are less abundant in the Rus carbonates in the dome outcrops than in the Arab reservoirs in the dome subsurface. Fractures in the Arab carbonate outcrops in the homocline are notably less abundant than in the Arab reservoirs in the dome. Besides, fractures in the homocline outcrops are less abundant than expected from the FSLT model. Lithology and thickness of carbonate layers control fracture spacing in the Rus carbonates, whose thickness is mostly between 1 m and 5 m, and fracture spacing mostly between 2 m and 5 m. The controls of lithology on fracture abundance in the Arab carbonates are more recognizable in the reservoirs in the dome than in the outcrops in the homocline, possibly because of the low fracture abundance in the homocline outcrops. Nevertheless,

the major mechanisms that resulted in different abundance of barren fracture systems in these gently deformed carbonates are the fold bending of the dome and homocline and paucity of fracture mineralization. The Arab reservoirs in the dome subsurface experienced small but more tectonic extension associated with the cyclic uplifts and layer bending than the subtle and nearly flat outcrops in the homocline and the dome. The paucity of processes that mineralize fractures is indicated by the prevalence of barren fractures; the calcite and gypsum veins make up small percentages ranging from 0% to 10% in these carbonates. Other fracturing and controlling mechanisms (i.e., exhumation and hydraulic fracturing) are either absent or indiscernible from the nature of the described fracture systems, level of sediment burial, and tectonic setting.

7.1 INTRODUCTION

This chapter presents and discusses the frameworks of the mechanisms that controlled the abundance of fracture systems in the gently deformed interior of the Arabian Platform (see Ch. 2). Fracture systems were studied from the Late Jurassic Arab carbonate reservoirs in a low-relief dome in Eastern Arabia and the Arab carbonate outcrops in the homocline in Central Arabia (see Ch. 2 and Ch. 3). Furthermore, fractures were studied from the Cenozoic Rus carbonates in the outcrops of the dome; the results are presented in this chapter.

The study areas share many stratigraphic and structural analogies. The Arab carbonates in the outcrops and reservoirs in the study areas display the same lithofacies and the alternations of mud-supported and grain-supported carbonate layers (see Ch. 4). Also, comparing fracture abundance in the Rus carbonates with those in the Arab carbonates in the dome is considered here as a case study on fractures developed in one dome structure (i.e., structural analogy) but in rocks of different stratigraphy, burial history, and lithological properties.

The dome and homocline were formed by tectonic processes that produced folds of very gentle structural dips in the Mesozoic and Cenozoic strata. The dome was formed by the slow rise of a salt pillow, and the homocline may be related to the reactivation of basement faults (see Ch. 2). The Rus carbonates make up most of the dome outcrops and show structural dips ranging between $1^{\circ}.1'$ and $1^{\circ}.3'$ (Teel, 1973). The outcrops of the Arab carbonates are conformable with the Mesozoic outcrops in Central Arabia and show about $0^{\circ}.3'$ structural dips in the homocline. The Arab carbonate reservoirs are located in the dome, at about 1.4 km below the Rus outcrops, and show structural dips of about 5° (see Ch. 2 and Ch. 4).

The chapter is structured in sections as follows.

- 1) The first section includes measurements of fracture abundance in the Rus carbonates.
- 2) The second section includes a summary of the key observations on properties of fracture systems in the Arab reservoirs and outcrops. The section is based on the results obtained and discussed in Ch. 4, Ch. 5, and Ch. 6.
- 3) The third section includes comparisons of fracture abundance in the Rus and Arab carbonates.

Furthermore, fracture abundance from these carbonates is compared with the measurements of

fracture abundance reported in the literature.

- 4) The fourth section discusses the mechanisms that played major roles in the development of fracture systems in the Arab and Rus carbonates, as typical cases for gently deformed carbonates.

7.2 FRACTURES IN THE RUS CARBONATES IN THE DOME: RESULTS AND ANALYSES

Fracture spacing and layer thickness were measured from 11 sites of the Lower, Middle, and Upper Rus carbonates in the central and northwestern flanks of the dome (see Ch. 2.6.2). Most of the measurements were collected from the Middle Rus, which is a massive layer of limestone sandwiched between the shale-rich Upper Rus and marl-rich, cavernous Lower Rus carbonates (Tab. 10-8). The top and base boundaries of the Middle Rus layers are well defined for measurements of fractures and layer thickness (Fig. 7.1). The top boundaries of the Lower Rus layers are well defined, but the base boundaries are not apparent at most sites (Fig. 7.1 and Fig. 7.2).

Barren fractures are the most common features of the Middle Rus, which has been called “the jointed limestone” (e.g., Weijermars, 1999). The observed fractures are of vertical dips (mostly around 90°), and display normal dips to the nearly flat strata in the outcrops. Mineralized fractures were found in a few areas as gypsum veins (Fig. 7.2). The occurrence of veins is insignificant in the outcrops and can be estimated to be less than 2% of the outcrop fractures (Tab. A-7). Stylolites were neither observed along the scanlines nor encountered in any area of the outcrops.

The spacing between the measured fractures is irregular. The spacing measurements are presented in statistical distributions in Fig. 7.3. The fractures demonstrate a wide range of spacing, from about 1 m to 10 m. The fracture spacing is mostly between 2 m and 5 m (Fig. 7.1). The large spacing of fractures was commonly observed in the thick carbonate layers of the Middle and Lower Rus.

The thickness of the layers in the Rus carbonates ranges from 1 m to 5 m. Furthermore, the thickness of the Middle Rus varies from one location to another (Fig. 7.2). The layers less than 1 m thick are seemingly absent in the dome outcrops, making the layer of Rus carbonates thicker than those of the Arab carbonates, which were observed in the outcrops as interbedded layers of thickness mostly less than 1.1 m (Fig. 7.3). The range of fracture spacing in the Rus carbonates consistently changes with the thickness of host layers, showing more fractures in thinner layers than in thicker layers (Fig. 7.3).

7.3 FRACTURES IN THE ARAB CARBONATES

7.3.1 Barren Fractures

In the Arab-D outcrops in the homocline, the barren fractures are mostly layer-normal and layer-bounded (see Ch. 4). The strikes of these fractures in the outcrops have mostly NW–SE, E–W, and NW–SE orientations. In the Arab reservoirs (A, B, C, and D) in the dome, barren fractures are layer-normal of mostly NW–SE, E–W, and NW–SE orientations. The heights of fractures were not obvious from the borehole datasets, but variations in fracture abundance along boreholes indicate that the heights of fractures are confined to certain lithological units.

The common properties of the barren fracture system in the Arab carbonates is that it is barren, normal to bedding, confined to lithology, and exhibits regional trends that were previously recognized in the platform interior (Hancock et al., 1984; Ameen et al., 2010; Al-Fahmi et al., 2014; Ameen, 2014; MacPherson and Ameen, 2014; Thagafy et al., 2017). Despite that this system displays the common features of certain orientations and lack of mineralization, the abundance of this system considerably varies between study areas.

The abundance of barren fractures can be described using statistical models, because of their ubiquity and varying spacing. The results in Ch. 5 indicate that the spacing of fractures in the core is more reliable for modeling fracture abundance than is the fracture spacing in the borehole images. The spacing values of barren fractures have an arithmetic means of about 31 cm and standard deviations of 24 cm (see Ch. 1.3.5.3). The differences in fracture abundance between boreholes are negligible and reflect shortages of the borehole datasets to adequately sample fractures. Nevertheless, the results from describing the core and borehole images indicate that fractures in the reservoirs are oversaturated (Fig. 7.4). Mean fracture spacing is mostly smaller than the thickness of the lithological units.

Fracture abundance in the Arab-D outcrops in the homocline is undersaturated (Fig. 7.4). Field measurements show that fracture spacing is larger than the thickness of host layers. Previous studies demonstrated similar low fracture abundance in the CAG, which is the region of maximum curvature in the homocline (Abdlmutalib and Abdullatif, 2017). Fracture abundance in the Arab-D carbonates in the homocline is not only lower than in equivalent reservoirs, but it also seems to be much lower than expected from the typical FSLT model of fracture abundance in layered rocks.

7.3.2 Mineralized Fractures

The mineralized fractures in the Arab reservoirs are predominantly calcite veins. Some key observations can be mentioned here on calcite veins, despite their small occurrence in the Arab reservoirs.

- 1) The calcite veins were found to be strongly associated with the rock stylolitization, and often observed to be linked and mixed with the stylolite organic materials (see Ch. 4.5.3.1).
- 2) The veins have a tendency to increase in abundance in the lower sections of the Arab reservoirs, in X-03 and X-04 boreholes in the dome flank. These observations must be accompanied with the fact that the datasets from the boreholes were obtained from different depths and locations that differ in their structural position in the dome and its present-day fluid contents (oil–water contact).
- 3) The calcite veins exhibit varieties of calcite crystal sizes and shapes, which make it difficult to relate their mineralization to a single mechanism. The petrographic analyses indicate calcite cementation is not limited to the vein bodies, but rather exists in surrounding rock pores. The veins are composed of aggregates of calcite crystals that were possibly precipitated from fluid dissolution in dilational (open fracture) sites (Bons et al., 2012).
- 4) The calcite veins have the same chemical signatures of the host reservoir rocks. The $\delta^{13}\text{C}$ values of the calcite veins are similar to those of the dolomites in the Arab reservoirs, and typical of those in modern marine sediments (e.g., Azer and Peebles, 1998). These $\delta^{13}\text{C}$ values clearly differ from those of the Arab-D outcrops, which were altered in open systems of meteoric water circulation (Eltom et al., 2014). In addition, the calcite veins exhibit a signature of strontium isotopes that is similar to that of the host rock and stylolites, indicating a common strontium reservoir. The $^{87}\text{Sr}/^{86}\text{Sr}$ values of the calcite veins, as well as of their host rock and stylolite material, demonstrate a close range of values that are similar to the $^{87}\text{Sr}/^{86}\text{Sr}$ curves of the Late Kimmeridgian seawater (McArthur et al., 2012; Wierzbowski et al., 2017).

Calcite veins are difficult to model; their small number and clustering challenge any attempt to fit their spacing to statistical distributions. Their modeling seems only possible as a small percentage in these carbonates that may reach 10% in the dome flanks, below the present-day oil–water contact.

7.4 ABUNDANCE OF FRACTURES IN THE RUS AND ARAB CARBONATES: COMPARISONS

The fractures in the Rus carbonates in the dome show both similar and different properties with respect to those of the Arab carbonate fractures in the dome and homocline. The most notable similar properties are the dominance of barren fractures that are subvertical and confined to layers. In addition, the barren fractures in the Rus carbonates are of dominant NE–SW and NW–SE orientations (see Ch. 2.6.2). The abundance of veins in these carbonates is very low, ranging from 0% to a maximum of 10% in the flanks of the dome and below the oil–water contact in the Arab carbonates.

Barren fractures display significantly differing ranges of abundance in these carbonates (Fig. 7.4). Fracture spacing in the Rus carbonates displays a linear relationship to the thickness of the host layers. This linear relationship is useful for comparing fracture spacing in the Rus carbonates with that in the Arab carbonates, despite the two rock formations differ in lithofacies, range of thicknesses, and geologic history. The linear relationship indicates that fractures in the Rus carbonates in the dome are balanced saturated; they are more abundant than the fractures in the Arab carbonate outcrops in the homocline and less abundant than the fractures in the Arab reservoirs below (Fig. 7.4a). The linear relationship between fracture spacing and layer thickness does not seem to be present in the Arab carbonate outcrops and is difficult to be obtained from the core and borehole imaging datasets for the Arab reservoirs.

It is possible to assume that the thick reservoir units may include unrecognized thinner mechanical units of narrow fracture spacing (Fig. 7.4b). If so, the reservoir fracture plots in Fig. 7.4a would be shifted toward a lower fracture abundance. This assumption can narrow the range of the corrected fracture spacing but does not make fractures in the reservoirs equate to the low abundance of the outcrop fractures. Assuming that the reservoirs have layer thicknesses similar to those in the outcrops, i.e., with a range from 0.1 m to 1.2 m, the spacing of reservoir fractures remains smaller than the thickness of layers, unless all reservoir layers are less than 0.3 m thick. This is considered unlikely possible, for two reasons. Firstly, modeling of the reservoirs displays varying layers whose thicknesses range between 0.1 m and 3.4 m, and whose majority are thicker than 0.5 m (Fig. 7.4b), see (Al-Awwad and Collins, 2013). Secondly, fractures in layers of 0.3 m could have been partially observed terminating in the domain of boreholes (in core and borehole images), because of their short height (Ch. 4.3).

Another factor that potentially reduces the spacing of the reservoir fractures in Fig. 7.4a is the inclusion of more than one set, because the FSLT model is typically constructed from a single fracture set (Ch. 1.5.1). The X-01 and X-03 boreholes display different spreads of fracture azimuths (Ch. 4.3.2; Fig. 4.13). It is estimated that about 70% of the spacing measurements in Fig. 7.4a belong to the NW-SE fractures. The remaining 30% of the measurements are for E-W and NE-SW fractures. The core from X-01 is more ideal to measure the spacing of the NW-SE fracture set than the core from X-03. X-01 is subnormal to the NW-SE fracture set; therefore, about 85% of the intersected fractures are from the NW-SE set. The core from X-01 displays an average value of 29 cm, with 22 cm standard deviation, for the spacing of all intersected fractures (Ch. 4.3.5; Fig. 4.34). The averaged spacing from X-01 can be increased by as much as 4 cm, if we exclude the 15% of fractures that do not belong to the NW-SE set. The NE-SW and E-W fractures are scattered along the core; they are not specific to a layer in the Arab reservoirs.

Furthermore, the averaged spacing from X-01 is very close to the 33-cm spacing from X-03, which intersected about 48%, 32%, and 18% of NW-SE, E-W, and NE-SW fractures, respectively (Ch. 4.3.5). The similarity of fracture spacing from the two boreholes reflects two factors, (i) the spacing is not regular so it is presented as averages from traversed layers of different thicknesses, and (ii) the fractures are mostly from sets of small spacing. These factors can further be explained by a hypothetical case of a layer in which fractures make two systematic orthogonal sets, with 31-cm spacing for each set, see (Fig. 7.5). Traversing boreholes would display 31-cm spacing for normal boreholes and 44 cm for oblique (i.e., 45-degree) boreholes (Fig. 7.5). The maximum difference in spacing from the normal borehole and oblique borehole is only 13 cm. This is a rather small value to significantly shift measurements of narrow spacing, like those in Fig. 7.4a, from oversaturation to undersaturation. The observations in Fig. 7.4a may have been different if the reservoir fractures were arbitrary (non-systematic), and with large and different spacing (i.e., larger than 1 m) (Fig. 7.5).

Still, the ranges of corrected fracture spacing in the Arab reservoirs indicate that the fractures are oversaturated (Fig. 7.6). Accordingly, fracture spacing is very low in the Arab outcrops in the homocline, moderate in the Rus carbonates in the dome outcrops, and high in the Arab reservoirs in the dome subsurface (Fig. 7.6). Fracture spacing values in the Arab and Rus carbonates are compared in Fig. 7.7

with the measurements of fracture spacing versus layer thickness of many carbonate formations published in the literature. This comparison yields some interesting information that can be summarized in the following points:

- 1) The ranges of fracture spacing were mostly reported from thin carbonate layers, whose fractures tend to be more abundant than fractures in thicker layers (see citations in Fig. 7.7).
- 2) The linear relationships were reported from carbonate layers of contrasting mechanical properties, such as a competent thin layer of limestone sandwiched between marl or shale layers (e.g., Huang and Angelier, 1989; Wennberg et al., 2006).
- 3) The studies that proposed linear relationships (e.g., Huang and Angelier, 1989) were biased toward sampling particular sets of joints, and did not take all fractures into account, as Priest and Hudson (1976) have done. This issue can, however, be resolved by presenting fracture spacing as statistical distributions like those in Fig. 7.6a.

In this research, the linear relationship is only apparent from the measurements obtained from the Rus carbonates in the dome. The Rus carbonates are an ideal case of a brittle limestone sandwiched between non-competent carbonates of marl-rich and shale lithofacies (Abdullatif, 2010; Al-Fahmi, 2012). The case study of the Rus carbonates, however, significantly differs from previous cases in that the measured layer thicknesses are greater than 1 m. Nevertheless, it seems that the contrast in mechanical properties of carbonates and the low degree of tectonic extension (i.e., gentle doming) can lead to such a linear relationship between fracture spacing and layer thickness (e.g., Hobbs, 1967; Wennberg et al., 2006).

The results on fracture abundance are apparently against the use of fractured outcrops as analogy to fractured reservoirs, despite the study areas in the Arab carbonate platform sharing the analogy of lithology, layer-cake stratigraphy, and gentle deformation in a tectonically stable region. The results are also against the theory that fractures of exhumed rocks must be more abundant than those of buried reservoirs. These observations provide a basis for discussing the possible major controls on fracture abundance in gently deformed carbonates.

7.5 CONTROLS ON FRACTURE SYSTEMS IN GENTLY DEFORMED CARBONATES

Although deciphering the causes and controlling mechanisms of rock fractures is typically a

difficult task for many possible load paths (e.g., Engelder, 1985), some key observations from this research can help identify the most likely scenarios for major controls on the abundance of fracture systems in gently deformed carbonates. Fracturing of layered sedimentary rocks can be acknowledged to be an “irreversible” and “cumulative” process. Irreversible means that fractures cannot be erased unless lost as structural features due to rock dissolution, metamorphism, or melting. Cumulative means that new cycles of loads can further cause fractures in already fractured rock blocks, reducing block sizes of layered rocks when meeting the criteria of fractures.

Some key observations are required from the study areas to answer some enquiries on fracture systems, such as the following:

- 1) How were the fracture systems in buried reservoirs and exhumed outcrops developed?
- 2) Were the fracture systems produced by a single event, or rather multiple events and different mechanisms that were operative over different domains of time and areas?
- 3) Can fractures be reliably predicted using stratigraphic and structural analogs in an entire carbonate platform such as the Arab carbonates?

Several load paths can cause, or aid, carbonate fracturing under various types of tectonic processes that may include burial, exhumation, erosion, compression, and extension. Furthermore, rock properties can influence the behavior of layered rocks to fracture, including rock tensile and shear strengths, bed-parallel slips, flow of ductile units, fluid pressure, and diagenesis. These factors will be considered in analyzing the key observations on properties of fracture systems in the study areas.

7.5.1 Development of Calcite Veins and Stylolites

The development of calcite veins can be explained from their (i) small occurrences in the Arab reservoirs, (ii) association to stylolites, and (iii) chemical and petrographic properties.

The stylolite planes are consistently parallel, and their teeth normal, to the reservoir bedding planes. Their chemical signatures match those of the calcite veins and host rocks. It is suggested here that they are among the earliest deformation (compaction) events in the Arab reservoir rocks that were formed under the overburden pressure. The stylolites in the Arab reservoirs in the dome are not different from those frequently reported in the Arab and other carbonate reservoirs in Eastern Arabia (e.g., Alsharhan and Sadd, 2000). The burial depth where stylolitization begins is not well constrained in

the Arabian Platform, because stylolitization is typically subject to the factors of water chemistry, clay contents, and organic material (Alsharhan and Sadd, 2000).

The pressure solutions can begin between 300 and 600 m of burial depth (Alsharhan and Sadd, 2000), and as the sediments continue to accumulate, the pressure dissolution increases with increasing overburden pressure (e.g., Dunnington, 1967). Nevertheless, the migration of oil into carbonate reservoirs has been considered to halt diagenetic processes (e.g., Oswald et al., 1995; Cox et al., 2010). Evidence for such possibility is the relative increase in the number of stylolites and calcite veins in the lower water-filled section of the Arab-D, below the oil section (see Ch. 4). The stylolitization and fracture mineralization may have stopped in the Arab reservoirs after the oil migrated into the reservoir pores and fractures.

Stylolites were not observed in the Arab-D outcrops, but it remains uncertain to suggest that they do not exist and that the sediment burial was too shallow for stylolitization. The absence of stylolites in the Rus carbonate outcrops can be explained by the very shallow burial of sediments, which did not exceed 75 m depth (Al-Fahmi, 2012).

The calcite veins are extensional fractures according to their orientations and mode of displacement (Ch. 4). It does not seem from petrographic analyses that the veins were developed due to a single event, although the chemical analyses indicate that the calcite veins developed in the early stages of rock burial that cause rock stylolitization (Ch. 4). Some of the veins were possibly formed as barren fractures, and then later filled by calcite cements transported under gravity by calcite-rich solutions. Other veins were possibly formed as tension gashes under the pressure dissolution that formed the stylolites, (Nelson, 1981), and during the shallow burial (>300 m) of the Arab rocks.

The development of stylolites provides important insights on the development of calcite veins, but does not explain what controlled their occurrences. The calcite veins in the Arab reservoirs and outcrops must have had spatiotemporal controls that limited their occurrences. The possible major mechanisms are listed as follows.

- 1) Deposition of the sealing Hith anhydrite that prevented penetration of meteoric water from the above formations into the Arab carbonates, and hence prevented further diagenesis, from Early Cretaceous to the present-day. The Hith anhydrite has been an effective sealing rock

that contained the vast oil resources in the Arab reservoirs in Eastern Arabia.

- 2) Prevalence of pore systems in the Arab carbonates that may have acted as channels and depositional sites of calcite-rich solutions more than existing fractures during early burial and diagenetic processes.
- 3) Oil emplacement, after growth of anticlinal and domal structures, in the Cretaceous may have halted fracture mineralization in the oil-filled sections of the Arab reservoirs. The oil emplacement and structural growth in the platform interior have been considered a controlling factor of the diagenetic processes of the carbonate cementation and stylolitization (e.g., Cox et al., 2010; Paganoni et al., 2016).
- 4) Lack of the tectonic deformations that can change the setting of nearly flat and layer-cake stratigraphy of the Arabian Platform interior. Calcite-rich solutions of connate water are expected to move downward under gravity. The oil and water were segregated in the reservoirs of the region because of their different density, by which light oil tops heavy water.

7.5.2 Development of Barren Fractures

Like the calcite veins, the barren fractures in the study areas of the Arab and Rus carbonates are extensional fractures according to their orientations and modes of displacement. Furthermore, the fractures are mostly formed in sets of NE–SW, SW–SE and E–W orientations. The major difference between barren fractures is their varying abundance in the study areas. The barren fractures in the Arab reservoirs in the dome are more abundant than the fractures in the homocline and dome outcrops (Fig. 7.6).

Controls of rock lithofacies on fracture abundance are present in the Arab carbonate outcrops in the homocline, but they are indistinct from statistical distributions because of the low fracture abundance and the ranges of layer thicknesses, typically less than 1.2 m. The fracture abundance could have been different if all layers in the Arab carbonates were greater than 1 m. The lithological controls cannot be proposed here to explain the difference between fracture abundance in the Arab outcrops and reservoirs, because they have similar lithofacies. The major controls on the abundance of barren fractures are the difference in magnitudes of loads on rocks and lack of mineralization processes in these carbonates.

As one part of the Arab carbonate platform is currently buried and the other part is exhumed, it is

fundamental to consider if their fractures were controlled by the processes of burial, exhumation, and elevated fluid pressure (overpressure). These processes are in competition with the tectonic processes of extension and compression. The differential stresses in rocks are expected to result in recoverable and non-recoverable deformations (i.e., fractures) in rocks under these processes. The focus is, therefore, on the possible major loads that led to fractures and controlled the properties of fracture systems.

7.5.2.1 Possible Controls of Sediment Burial and Overpressure

If barren fractures were formed under loads of burial, earliest fracturing of the Arab carbonates may have started after the rock was formed as solid material from unconsolidated sediments. If burial-driven fractures developed, they remain in the rocks if the rocks were brought to surface by exhumation processes. The uplift process is not a reversal of the burial process, because it does not remove the rock compaction, cementation, and permanent deformation (i.e., fractures).

Sediment burial is indisputably associated with increasing overburden and hydrostatic loads (Fig. 7.8). These processes can be associated with both compressive and tensile stresses that may result in rock fracturing. The bed-parallel stylolites formed with orientations normal to the vertical overburden stress. Hence, the stylolites are interpreted as products of the compressive stresses that compacted the sediments and forced out their connate fluids at shallow depths of burial between 300 and 900 m. The systems of barren fractures and veins are different in orientation and mode of displacement; they formed by tensile stresses parallel to the bed planes.

The presence of calcite veins as possible tension gushes brings up the question on the role of fluid overpressure, especially in the subsurface where all stresses are typically considered compressive (e.g., Cosgrove, 2001). But regions of fluid overpressure were not encountered in the drilling of the Arab reservoirs in the Arabian Platform. Furthermore, the migrated oil did not seem to produce fractures, because of the high rock porosity that accommodated oil and displaced in situ water. Clues for paleo-hydrofracturing are not present in the Arab carbonates. Other studies did not seem to consider hydrofracturing as a possible mechanism, except in areas of rapid fluid expulsion or where fluid flow is hindered by low-permeability sediments (Narr and Burruss, 1984; Cosgrove, 2001; Sibson, 2003; Tan et al., 2014). Furthermore, the burial depths of the Arab and Rus carbonates are relatively shallow to account for hydrofracturing, even from a theoretical basis (Fig. 7.8). The Mission Canyon Formation in

the Little Knife field were buried to at least its present depth of 3 km, but fluid inclusion evidence indicates the fluid pressure gradient was normal hydrostatic when the fractures formed; hence, the overpressure was not considered a contributing factor to fracture development (Narr and Burruss, 1984). It is yet uncertain to define a depth datum at which burial-related and overpressure fractures can dominate in carbonates in sedimentary basins.

The system of calcite veins in the Arab reservoirs can still be debated, whether it was controlled under the force of fluid expulsion in restricted domains or rather cementation of calcite in preexisting barren fractures. The view in this research is that development of the calcite vein system was controlled by diagenetic processes rather than hydraulic processes, and that the diagenesis in fractures was limited in space and time domains.

7.5.2.2 Possible Controls of Sediment Uplift

Later exhumation for part of the Arab carbonate platform had likely unloaded the overlying burdens in Central Arabia. But as the burial of the Arab carbonates is shallow (i.e., less than 1.6 km), the geothermal and mechanical effects that are associated with the burial and exhumation are expected to be negligible. The thermal control on fracture development cannot be considered, in absence of the conditions that may drive fracturing under thermal contraction caused by cooling during exhumation (e.g., English, 2012). Also, the rocks lack the initial overpressured stage, in which the initial compressive stresses are low before uplift and cooling events (English, 2012).

The described barren fractures in the reservoirs and outcrops are inherently opening-mode fractures of systematic orientations. They can be interpreted as products of tensile stresses that were operative across the platform, but of different magnitudes. It is unlikely to propose that the burial and uplift processes had controlled the barren fracture systems, because neither the properties of fractures nor those of the geologic setting of the reservoirs and outcrops show clues for such mechanisms.

7.5.2.3 Possible Controls of Tectonic Extension (Folding)

Rock extension by folding seems the major mechanism that was operative in the study areas and across the Arabian Platform. In general, tectonic processes are unlikely to result in exhumation and uplift of sedimentary layered rocks without bending them. This mechanism is not unusual for fracture development, as it has been extensively studied in folded regions. The unusual case of this research is

that these regions are nearly flat, in the spectrum of the folds that were mostly studied from Variscan, Alpine, Alleghanian, and Laramidian orogenic belts.

The study areas of the Arab carbonates slightly vary in degree of bending; the outcrops in the homocline represent the flattest parts of the platform interior, and the dome represents the mostly elevated and bent part. The cross-sections of these regions typically require tens of vertical-scale exaggerations to allow the observation of folds (Ch. 2). These small differences in fold curvature degrees seem to account for the notable difference in fracture abundance across the Arab carbonate platform between regions of gentle folds (Fig. 7.6).

The platform interior was tectonically stable, except for subtle extension associated with the development of the anticlines, domes, and the sprawling homocline (see Ch. 2.5). It is suggested here that the general bending of the homocline resulted in regional NE–SW, SW–SE, and E–W systems in Eastern and Central Arabia (Fig. 7.9). These trends are predicted from the fold-fracture model described in Ch. 1.5.2. Fig. 7.8 includes several probabilities for patterns of the major fracture systems, but P4 represents a scenario in which widely spaced regional fractures dictated the orientation of subsequent fractures that developed due to growth of local structures (i.e., the dome). The Arab reservoirs in the dome experienced multiple episodes of growth and a higher degree of curvature than the outcrops in the homocline (see Ch. 2.5). The growth of the dome seemingly infilled fractures in the Arab reservoirs between regional fractures. In general, regional fractures, and structural discontinuities, can control the orientation of subsequent fractures (e.g., Bergbauer and Pollard, 2004).

The continuous growth of the dome resulted in fracturing of the Cenozoic Rus carbonates in the NE–SW and NW–SE fracture systems (Al-Fahmi et al., 2014). Although the dome has a low relief structure in outcrops and very gentle dips, it is known as a high structural relief in the otherwise flat region of the platform interior (Tleel, 1973). Infilling fractures between regional fractures may have also happened in the Cenozoic Rus outcrops. If so, such process is expected to have happened in other anticlines and domes in the Arabian Platform interior. The development of barren fractures was apparently progressive, with episodes of extension that bent and fractured the flat rock strata of the Arabian Platform. Accordingly, fracture abundance in the platform of the Arab carbonates ranges between the abundance of fractures in the Arab reservoirs in the dome and that in the Arab outcrops in

the homocline.

Finding that fracture abundance varies drastically in such regions can fundamentally be used to argue that layered carbonates are very sensitive to fracturing under layer extension. The carbonates of the Arab reservoirs reached the level of oversaturation in fracture spacing at low degrees of strain below 2% of layer extension (see Ch. 2.5). Producing further fractures gets harder when layered rocks are broken into smaller blocks. Instead, the fractures in layers ultimately coalesce, leading to strain localization and macro-scale shear failure, in a manner that has been proposed from testing samples in the laboratory (e.g., Hoek and Martin, 2014). Accordingly, the response of layered carbonates to ongoing stress is seemingly directed towards faulting. This seems to be the case of the Mesozoic and Cenozoic strata in Central Arabia, in which the strata bending produced fractures before the region evolved into a graben system. Bed-parallel slips are another process that can take place (Cooke and Underwood, 2001) when layers are uplifted or overturned by sharp-curvature folding.



Fig. 7.1: Photographs of the outcrops of the Middle Rus carbonates in the dome. The wood rule placed on the rock is 2 m.

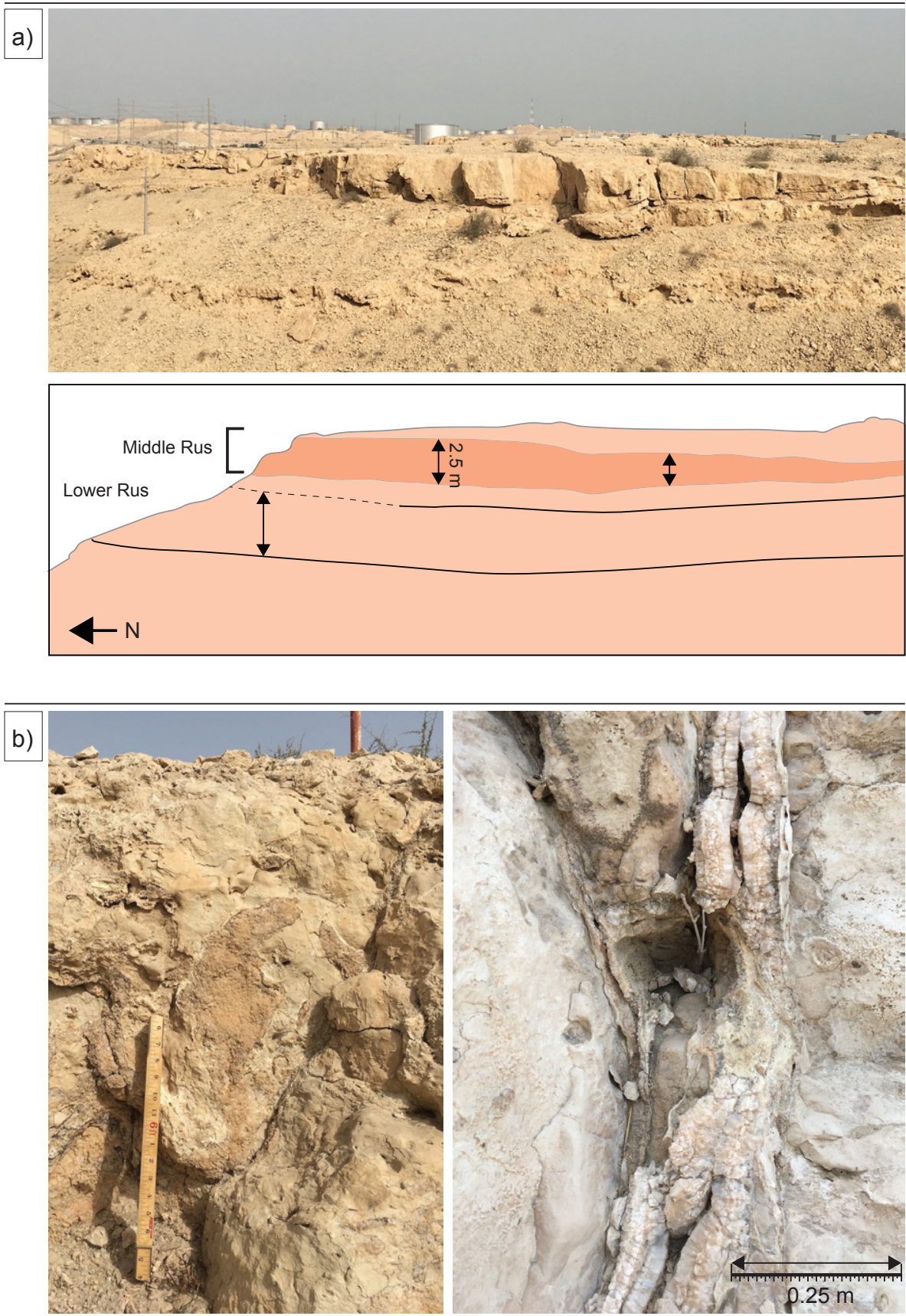


Fig. 7.2: a) A typical hill in the dome outcrops that shows variations in the thickness of the Middle Rus carbonates. b) Examples of fractures filled by gypsum crystals (gypsum veins in the Middle Rus).

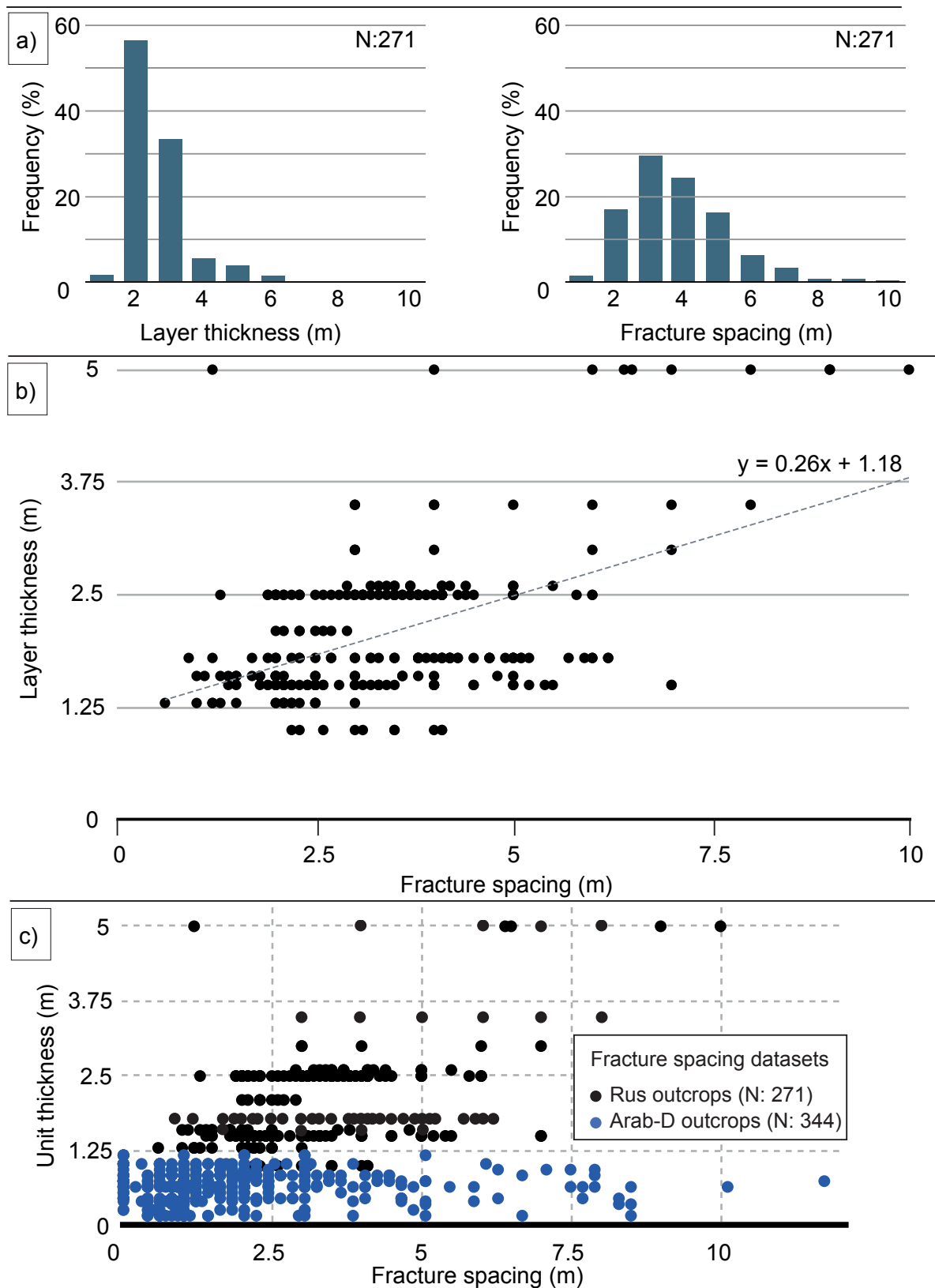


Fig. 7.3: a) Frequency distribution of fracture spacing in the Cenozoic Rus carbonates and the thicknesses of measured layers. b) Plots of fracture spacing measurements, without averaging, show a relationship between fracture spacing and layer thickness of the Rus carbonates. c) Measurements of fracture spacing in the Rus carbonates and the Arab-D outcrops,

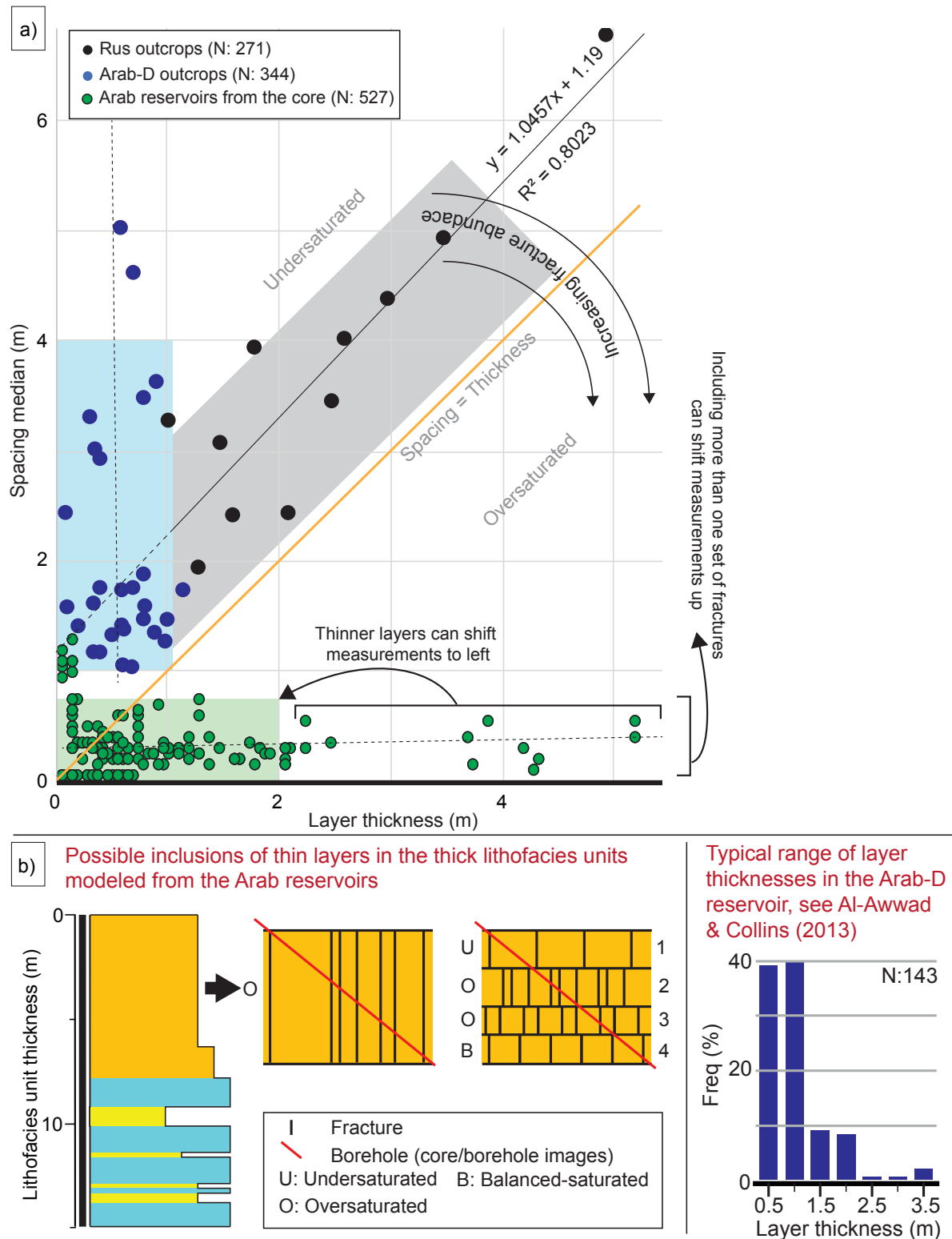
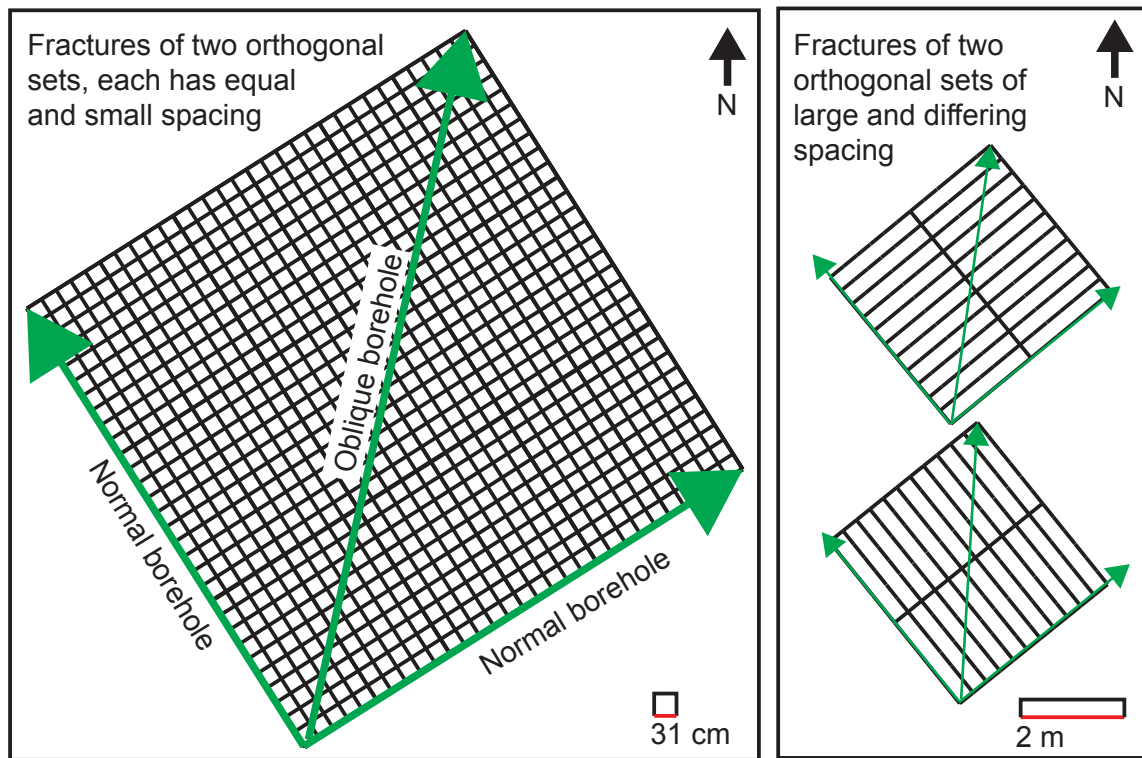


Fig. 7.4: a) Plots of fracture spacing against layer thicknesses of the Rus and Arab carbonates. b) sketches show the possible division of a thick lithological unit into smaller layers, and a frequency distribution for typical thicknesses of the Arab reservoir layers, obtained from Al-Awwad and Collins (2013).

Map view



Cross section

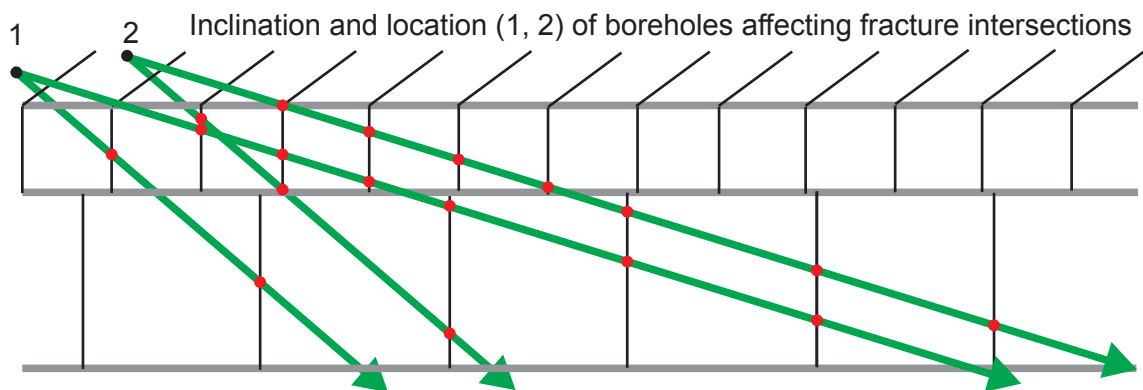


Fig. 7.5: a) Diagrams showing two orthogonal sets of fractures intersected by boreholes of different orientations and locations to demonstrate possible effects on measurements of fracture spacing.

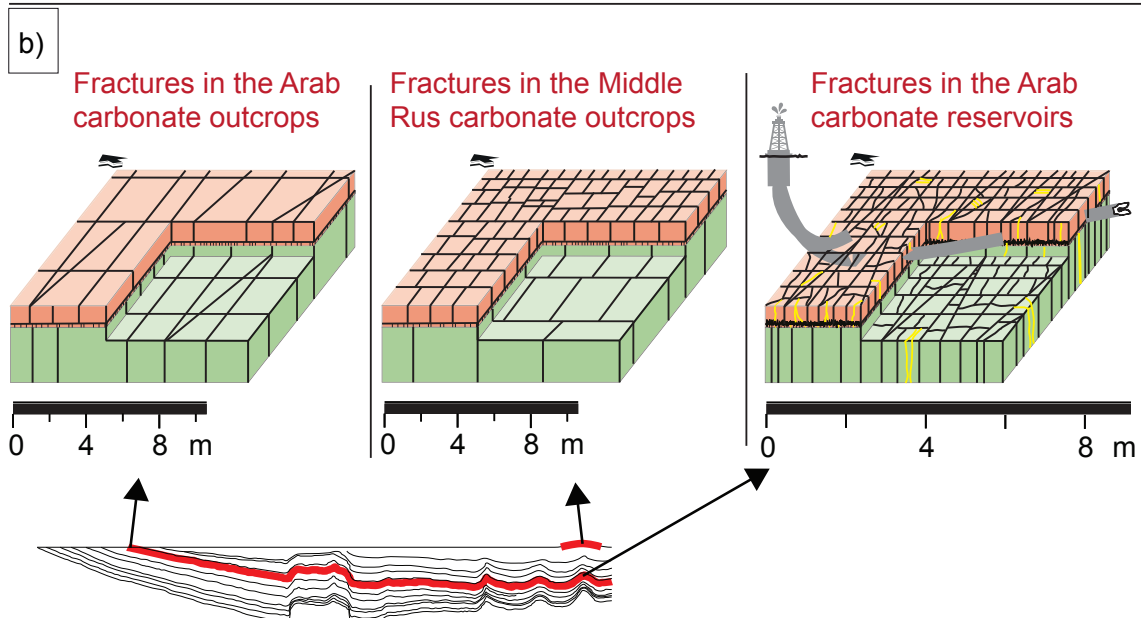
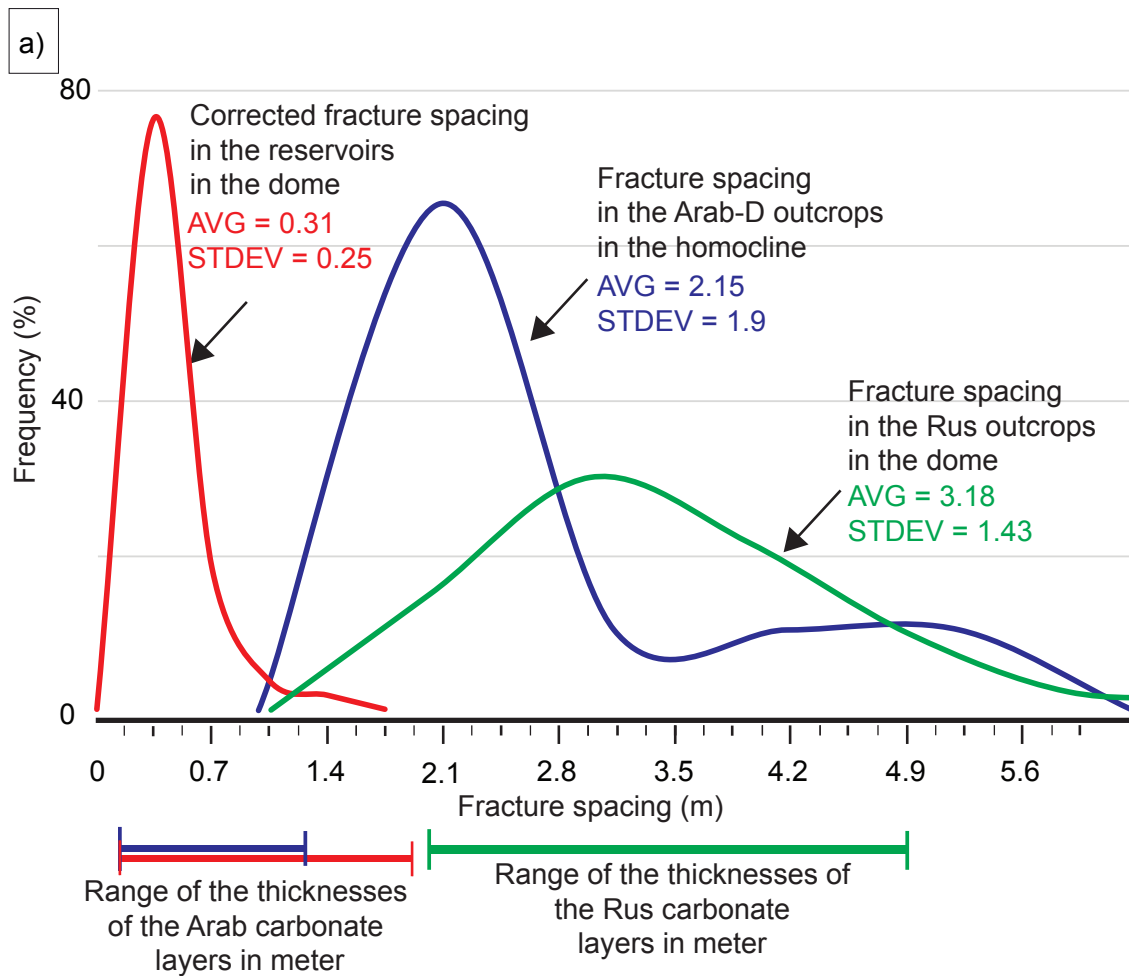


Fig. 7.6: a) Frequency distributions of fracture abundance in the study areas in the gently deformed interior of the Arabian Platform. b) Generalized models for prevailing fracture properties of abundance, orientation, and relations to lithology of host carbonates.

Note: The range of layer thicknesses for the Arab reservoirs in the dome are assumed to be equivalent to those in the Arab outcrops, between 0.1 and 1.2m.

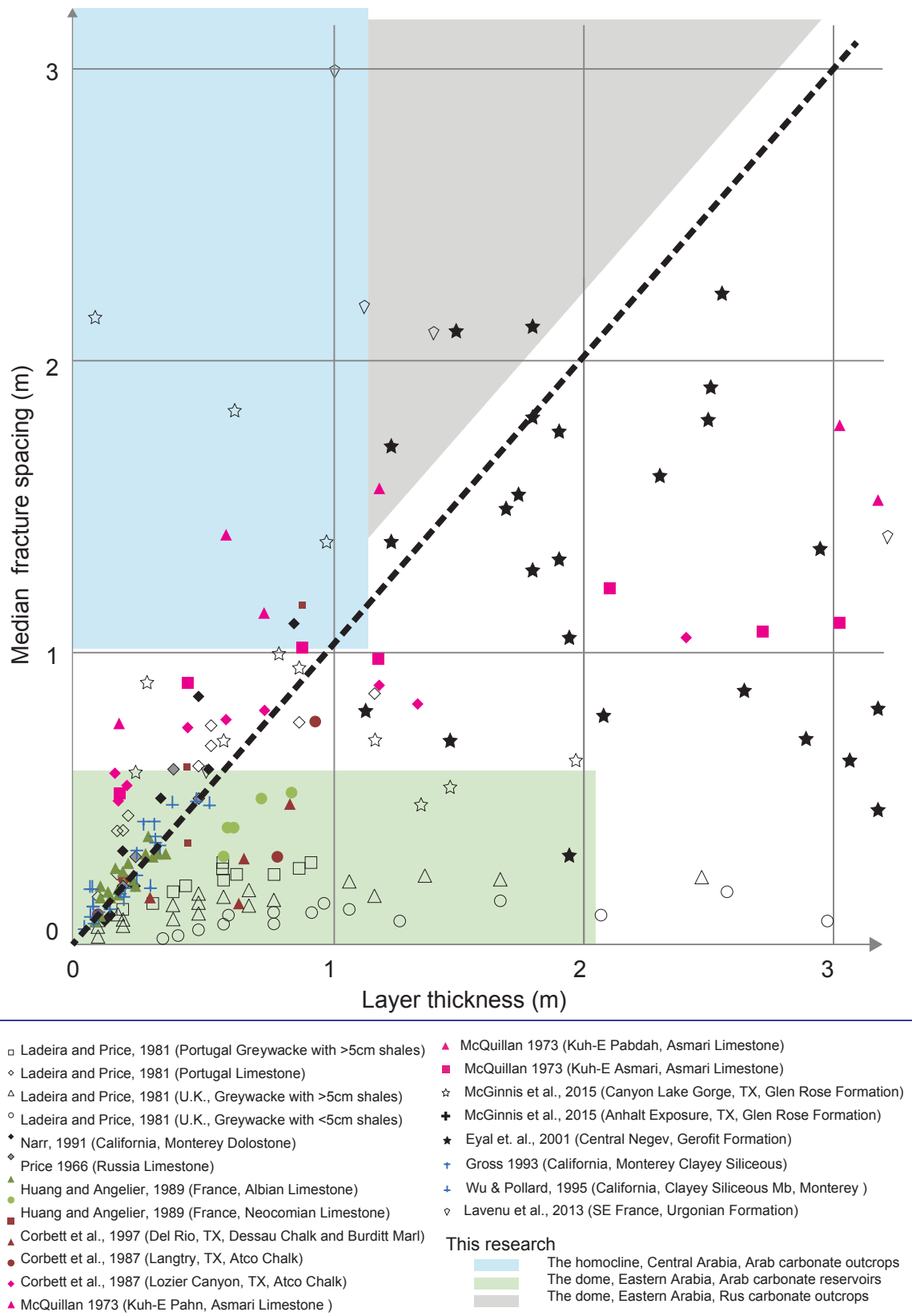


Fig. 7.7: Comparisons of measurements on fracture spacing versus thicknesses of carbonate layers from the literature and this research. Fracture spacing of this research is generalized in color-coded domains for each study area (see also Fig. 7. 4).

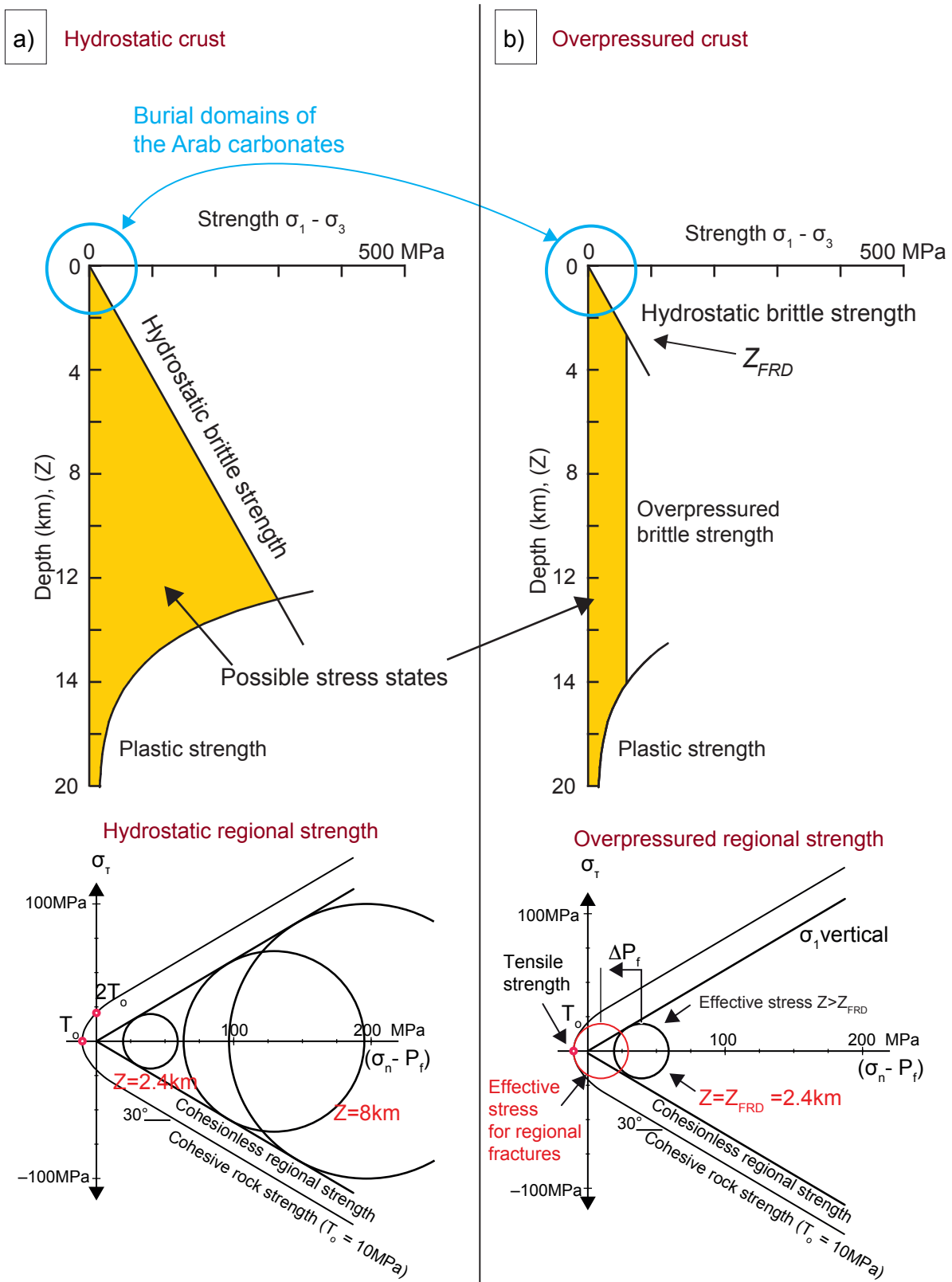


Fig. 7.8: a) The classic and typical strength-depth graph of the linear increase of brittle strength and hydrostatic pore-fluid pressure. b) The constant-strength model for overpressured crust for disequilibrium-compaction mechanism, in which fluid pressures are hydrostatic above the fluid-retention depth (Z_{FRD}) and overpressured below, increasing parallel to the lithostatic gradient. The Arab carbonates are a shallow environment with low hydrostatic pressure. Modified from Suppe (2014).

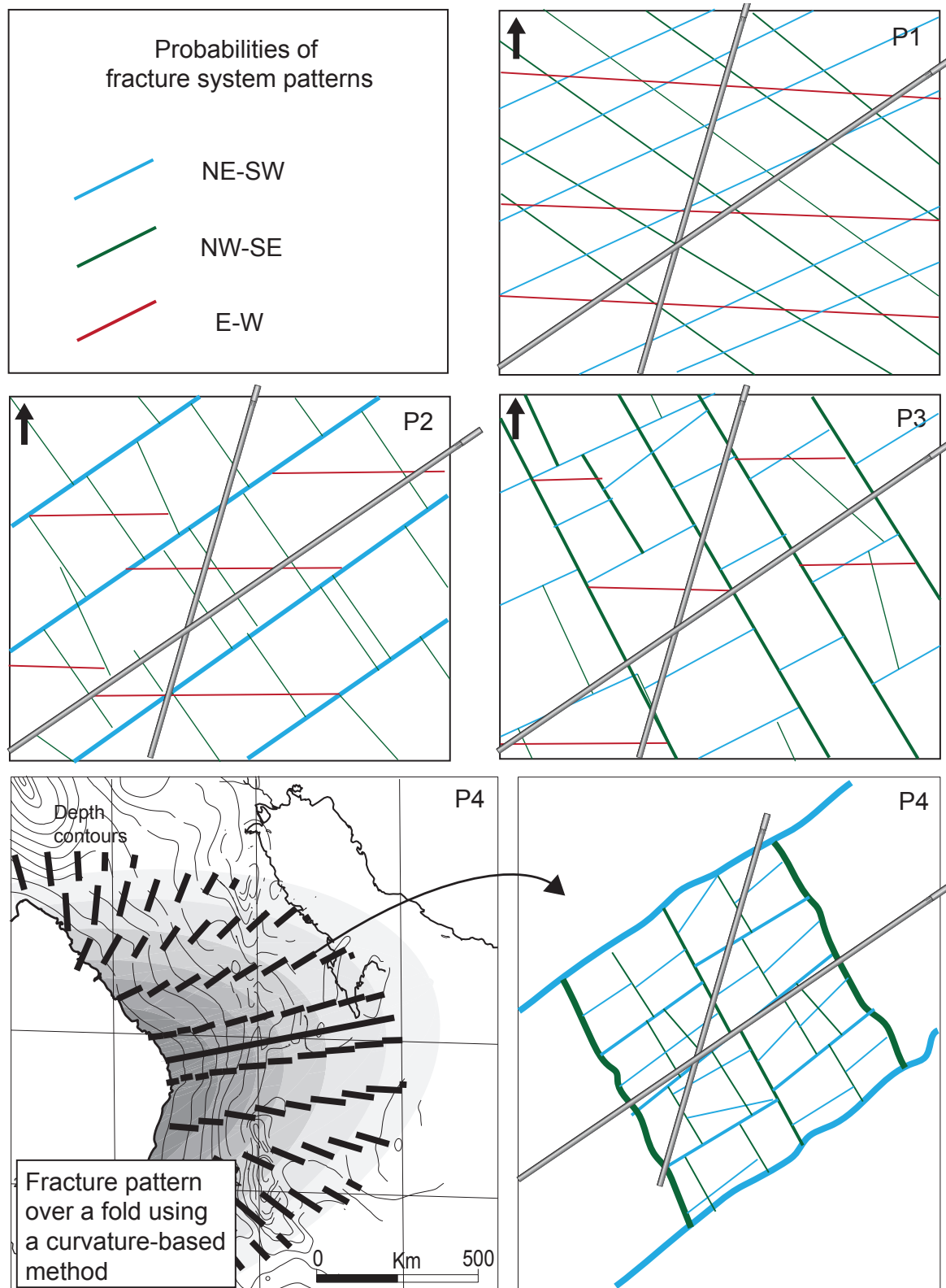


Fig. 7.9: Probabilities for the spatial distributions of the major fracture systems in the Arabian Platform interior, based on fracture strikes. In P4, right, fractures of consistent regional trends (thick blue lines) are assumed to have formed first in the layers of the platform, then the regions of the layers between regional fractures were saturated by fractures of similar strikes that were driven by the folding mechanism (i.e., salt-related doming) in the platform.

8 SUMMARY AND FUTURE WORK

The findings of this research are structured into two sections. The first section outlines the conclusions of the results presented in Ch. 4 and Ch. 7 regarding the major factors that govern or influence the abundance of fracture systems in the Arab and Rus carbonates as study cases for gently deformed carbonates. The second section outlines the results presented in Ch. 5 and Ch. 6 regarding the factors that affect borehole imaging of fractures and the significance of describing fracture properties of orientation, aperture, and roughness for modeling fracture abundance in carbonate reservoir rocks. These sections are followed by a third section that includes some suggestions for further research, hoping that the results in this research open the door for further studies on measurements and modeling of fractures and their properties in buried carbonates.

The new aspects of the research methods and results are highlighted in the following points.

- 1) This research is providing the first attempt to describe, categorize, and compare systems of barren fractures and calcite veins in a carbonate platform that extends from outcrops to subsurface in a region of relatively passive tectonics and shallow burial depth (less than 2 km).
- 2) The research adopts unorthodox methods of comparing statistical ranges of fracture abundance in layers of different lithofacies and thicknesses from outcrop and subsurface

reservoirs. The statistical modeling approach served the need to consider all fractures intersected by scanlines in outcrops and boreholes in subsurface reservoirs.

- 3) The measurements of fracture abundance in reservoirs were based on excellent quality datasets of core and borehole images from geometrical boreholes, which were neither normal nor parallel to the reservoir fractures or host rock layers.
- 4) The research includes new observations from comparing fractures in core with corresponding sections of borehole images that were acquired using a modern electrical tool, FMI HD.
- 5) The research includes the first roughness measurements of barren fractures and calcite veins in a viable carbonate reservoir. The measurements were obtained after developing a new combination of non-destructive numerical methods to describe roughness and wall mismatches of core barren fractures and calcite veins.
- 6) The research includes the first evidence presented from two boreholes of different orientations showing that that fracture apertures, and hence permeability, in subsurface reservoirs are dependent on the present-day stress field and mismatch of fracture roughness walls.

8.1 CONTROLS ON FRACTURE ABUNDANCE IN GENTLY DEFORMED CARBONATES

In this research, systems of carbonate fractures and their abundance were studied from areas in the subsurface reservoirs and outcrops in the Arabian Platform interior. The platform interior is of gentle deformation, in contrast with the regions of intense deformation, including the platform margins in the Taurus, Zagros, and Oman Mountains. The Arab carbonates are exposed in Central Arabia in a nearly flat homocline, of about $0^{\circ}.3'$ structural dip. The Arab reservoirs are located in Eastern Arabia at 1.4 km below surface in a low-relief dome of about 5° structural dip. The Rus carbonates make up most of the dome outcrops and show structural dips ranging between $1^{\circ}.1'$ and $1^{\circ}.3'$. The maximum shortening in the platform interior is in the subsurface of the studied dome, which is sharper in curvature and higher in structural dips than the homocline, anticlines, and other domes. The shortening of the Arab reservoirs in the dome is in the range of 2%, which is very low when compared with the 20–30% shortening that happened in the platform margins in

the Zagros Mountains.

The primary observations and results from this research are as follows.

- 1) The fractures in the Late Jurassic Arab and Cenozoic Rus Formations in the Arabian Platform interior are mostly barren, confined to layers, and show subvertical dips to nearly flat strata.
- 2) The occurrence of mineralized fractures (veins) in these carbonates is of very low abundance ranging from 0% to 10% of the rock total fractures. The paucity of fracture mineralization reflects inhibiting factors; in the Arab reservoirs these include (i) the deposition of the Hith anhydrite, which prevented the circulation of meteoric water through overlain rock formations, (ii) the oil emplacement, which halted diagenesis in the oil-bearing rocks; and (iii) the tectonic setting, which did not disturb the nearly flat setting of such porous carbonates in which fluids are driven downward by gravity and segregated by fluid density.
- 3) The abundance of barren fractures varies significantly; these gently deformed carbonates show the three possible scenarios for fracture abundance: undersaturated, balanced saturated, and oversaturated. Fractures are undersaturated in the Arab carbonate outcrops in the homocline, balanced to undersaturated in the Rus carbonates in the dome outcrops, and oversaturated in the Arab reservoirs in the dome.
- 4) Most of the barren fractures exist in sets of NE–SW, NW–SE, and E–W orientations, which were considered as evidence of initially regional systems that controlled the orientation of subsequent fractures in the platform interior.
- 5) The major mechanisms that resulted in such difference in fracture abundance are the folding; fracture abundance reflects the magnitudes and shapes of the folds between the study areas, although the difference in structural dips and general curvatures is very small.
- 6) Mechanisms of exhumation, overpressure, and uplift are indiscernible from the properties of the fracture systems, the level of sediment burial, and tectonic setting.
- 7) The observations of fracture abundance indicate that multilayered carbonates are very

sensitive to fracturing under tectonic extension, which in the Arab reservoirs in the dome reached low degrees of about 2% dilation strain. The results indicate that fractures can vary drastically and reach an oversaturation level in such gently flexed carbonates.

- 8) The lithology and thickness of carbonate layers show some controls on fracture spacing. This is more distinct in the Rus carbonates than in the Arab carbonates. Fracture spacing in the Rus carbonates displays the classical linear relationship to the thickness of host layers. The linear relationship seems to reflect a strong mechanical contrast between the layers of the Rus carbonates and a simple tectonic extension in a very shallow depth of rock burial (less than 75 m). The controls of lithology on fracture abundance in the Arab carbonates are present, especially in the reservoirs where mud-supported lithofacies show more fractures than the grain-supported lithofacies. But the linear relationship is indistinct in the Arab carbonates, because fractures are undersaturated in the outcrops and fracture heights and mechanical stratigraphy are not well defined in the reservoirs.

The results from the study areas reveal insights on the factors controlling fracture abundance in gently deformed carbonates. The research results are not limited to applications in the Arabian Platform. The results on fracture abundance discourage the use of fractured outcrops as analogy to fractured reservoirs, despite the study areas in the Arab carbonate platform sharing the reservoirs' lithology, layer-cake stratigraphy, and gentle deformation. In addition, fracture abundance in the homocline outcrops is not only lower than in the equivalent reservoirs, but it also seems to be much lower than expected from generic models and many well-studied outcrops around the world. The homocline outcrops display a possible baseline for the lowest levels of fracture abundance in such gently deformed carbonates.

8.2 FACTORS INFLUENCING FRACTURE DETECTION USING GEOPHYSICAL METHODS

This research also provides important results and insights on the electrical borehole imaging of fractures in carbonate reservoir rocks. The bias of borehole orientation to sample fractures is well known, and so the attention is given to the sampling bias of modern tools of electrical borehole

imaging. Electrical borehole imaging is treated in the petroleum industry as an economical replacement of core sampling and a reliable source of information on reservoir fractures and other rock features. But the analysis of borehole images of excellent quality indicates that they provide low and inconsistent measurements of fracture abundance, based on what was observed from intervals of corresponding core. This led to the identification of some major factors that influence borehole imaging of fractures that include size of fracture widths, roughness, and present-day stress field. The observations of these factors are summarized as follows.

- 1) Fractures were detected in borehole images because they exhibit sizes greater than about 2 mm. But this size is not a clear cutoff for imaging resolution, because some 0.5-mm wide calcite veins were also detected in the borehole images. These calcite veins were detected because they are highly resistive in a highly conductive interval of the host rock.
- 2) The electrical borehole images reveal that the magnitude of the fracture aperture depends on the present-day stress field. The barren fractures that are aligned with the S_{Hmax} in Eastern Arabia were found to be completely or partially open, with apertures that are large enough to be easily detected by the borehole imaging. The non-aligned barren fractures were mechanically closed; the drilling fluids did not permeate into fractures.
- 3) Some of the non-aligned barren fractures were detected in the borehole images, but they were found to display partial opening preserved between the mismatches of their rough walls. The fractures of the Arab carbonate reservoirs exhibit moderate to high roughness between 5 and 15 on the JRC scale. Most of the smooth and rough fractures have matching walls, and only a minority of rough fractures exhibit an obvious wall mismatch. The roughness and mismatch of the fracture walls were found to reflect the lithology of the host carbonates, and therefore are called “fabric-dependent” in this research to be distinguished from the roughness produced by rock sliding and friction. The values of roughness are higher in coarse-grained rock and lower in fine-grained rock and can accordingly be predicted from describing the carbonate lithofacies such as

mudstones, packstones, grainstones, and rudstones.

Borehole imaging is essential for measurements of fracture properties including mineralization, orientation, and aperture size. But relying on borehole images to measure fracture abundance can lead to erroneous estimations, especially for estimating the abundance of certain fracture systems based on their detectable apertures and orientations. For example, the dominant trends obtained using plots of rose diagrams can reflect the tendency of borehole images to sample the fractures with relatively large and open apertures. Such dominant trends are misleading to be used as paleostress trajectories in the tectonic analyses of sedimentary basins. Nevertheless, the bias of borehole imaging toward detecting large and open fractures is very useful for modeling the preferred fluid flow directions in subsurface reservoir rocks. From this perspective, borehole imaging seems to act as a machine that filters information on reservoir fractures.

8.3 FUTURE WORK

The ideas listed here for future research emerged while solving some related problems in this research, or they were explored, but the results obtained were not significant to be included in the preceding chapters.

8.3.1 Refining the Ranges of Abundance of Fracture Systems

This research includes ranges of fracture abundance in gently deformed carbonates using first-order categories based on the properties of mineralization, height, dip, width, strike, and roughness. Among emerging topics for future work are studying and refining the ranges for the abundance of these fracture categories and for higher-order categories of fracture systems in carbonates in different tectonic settings. One example is included here, although there are seemingly several examples for future work. It seems realistic to follow this research by studying the abundance of the NE–SW barren fracture systems and other systems in the Arab reservoirs across the Arabian Platform. However, doing this would require acquiring a number of costly directional cores via boreholes of different orientation and location in the crests and flanks of some anticlines and domes in which the Arab carbonates are producing reservoirs.

8.3.2 Fracture Patterns

Although fracture orientations are described in this research, it is still uncertain to conclude

the most likely scenarios for fracture patterns in the Arab and other carbonate reservoirs. Studying fracture patterns is only possible from top surfaces of carbonate layers in outcrops. One possible way to look at the fracture pattern is to shift the methods of measuring and averaging orientations of fractures toward measuring the exact shapes and sizes of areas left unfractured in layered rocks. This way, we would treat the problem of modeling fracture patterns as a geometrical and mechanical problem that can be solved using probabilistic models.

8.3.3 Fracture Apertures

Estimating fracture aperture remains among the biggest challenges in the modeling of subsurface reservoir rocks, although fracture aperture in buried rocks is typically expected to be small, less than 1 mm. Nevertheless, the small variation of aperture size, between 0.1 mm and 1.1 mm, is significant in the practice of fluid flow modeling of reservoir rocks. This research provides ranges for fracture apertures in the Arab carbonate reservoirs and insights on the factors that make the apertures dynamic. But the methods used to estimate aperture size are borehole imaging and core samples. It is worthy to consider other independent techniques that can provide more direct measurements for fracture apertures under reservoir conditions.

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10 APPENDIX

Procedures of Strontium Isotope Analyses

This is a summary of the steps needed to get $^{87}/^{86}\text{Sr}$ data.

The column racks are such that 12 samples (11 natural samples plus a blank) can be run at once. Resin washing is done in a batch with a dedicated teflon vial set, so that can be done at any time, including before teflon cleaning. But leaching samples and the column method require clean teflon in advance.

Teflon and resin cleaning take multiple days but do not require continuous attention; rather, 2-3 trips into the lab each day, for only several minutes at a time.

Teflon cleaning (~3 days):

- *First step, on newly-ordered teflon only:* Wyatt lab: wash in acetone. Slosh in beaker for one minute. Leave acetone to evaporate. Rinse teflon in DI water twice.
- Reflux in 1ML in each vial concentrated HNO_3 and put on hotplate overnight.
- Drain HNO_3 into waste container the next day and put Teflon into a quartz beaker.
- Rinse Teflon with MQ water and drain.
- Fill up beaker with enough 40% HCl to submerge Teflon then put on hotplate overnight.
- Pour away acid to container the next day (save the cleaning acid!) and rinse with MQ once.
- Add 30% HNO_3 to submerge the Teflon and put on hotplate overnight.
- Next day drain the acid to a container, and rinse twice in cold MQ.
- Submerge Teflon in MQ and put on hotplate for 3 hours. Repeat 2-3 more times.
- Leave to dry on the bench covered in a kimwipe OR in a fume hood.

Requires (2L) jugs of cleaning acid (HNO_3 and HCl) and ~50 mL conc HNO_3

Weighing samples (~ 0.5 day)

Leaching samples, to analyze phases separately (~1 day for each leach):

Exchangeable fraction: MQ (pH ~3)

Carbonates: dilute ascorbic (avoid organic)

Oxides: citric acid plus hydrous hydrazine—probably don't need

Organics: HNO_3 + H_2O_2 , heat to 85°C for 2 hours

Residual: HF

Requires clean acids as noted, ~100 mL each

Resin cleaning (~2 days):

MQ x 5, then HNO₃-MQ-**HNO₃**-MQ-HNO₃-MQ-**HNO₃**-MQ-MQ
 bold HNO₃s are 3M, non-bold are 0.1 M. Keep 3M HNO₃s to < 3 hours
 Store in “weak” HNO₃: 0.1 M

Requires ~ 100 mL clean conc. HNO₃

Chemical separation (column method) (~7 hours, more or less continuous):

- 150 µL resin slurry
- Wash with 200 µL MQ
- 2 mL 6M HCl
- 2X 2 mL MQ
- 1 mL 7M HNO₃
- Resin condition: 1 mL 2M HNO₃
- Sample load into two sets of 250 µL 2M HNO₃
- Wash sample out with 250 µL and 150 µL 2M HNO₃
- Elute matrix with 1 mL 7M HNO₃
- Collect Sr in 1.5 mL 0.05M HNO₃
- Dry Sr fraction overnight at 90C

Requires ~200 mL clean conc. HNO₃, HCl

Sample	Offset correction 87/86Sr	2s
ECRM7521	0.707827	0.000062
H1	0.707045	0.000062
H2	0.706956	0.000062
H3	0.706944	0.000062
H4	0.706931	0.000062
H5	0.706947	0.000062
H6	0.706960	0.000062
H9	0.706955	0.000062
H10	0.707006	0.000031
H11	0.706933	0.000062
H12	0.706954	0.000062
H13	0.706936	0.000062
H14	0.706928	0.000062
S1	0.706971	0.000062
S2	0.707019	0.000062
S3	0.707030	0.000031
C1	0.706978	0.000031
C2	0.706927	0.000031
C3	0.706946	0.000031
C4	0.707041	0.000031
C5	0.707018	0.000031
C8	0.707061	0.000031
Procedural blank		
Blank, before run, 2nd batch	0.709093	0.000031
Blank, mid run, 2nd batch	0.709618	0.000031

Tab. 10-1: Measurements of strontium isotopes.

Lab	Sample	Raw	Raw	Raw	Raw	finger	Beam	corrected	corrected	point
number		d ¹³ C	d ¹⁸ O	<i>d¹³C</i>	<i>d¹⁸O</i>	used	pressure	d ¹³ C	d ¹⁸ O	
A16/0201	Calcite vein C1	13.452	20.117	<i>2.148</i>	<i>-4.906</i>	no	6.70E-09	2.43	-4.96	32
A16/0202	Calcite vein C2	13.164	19.548	<i>1.852</i>	<i>-5.490</i>	no	6.70E-09	2.15	-5.53	33
A16/0203	Calcite vein C3	13.842	20.555	<i>2.584</i>	<i>-4.386</i>	no	6.70E-09	2.84	-4.52	34
A16/0204	Calcite vein C4	13.232	19.658	<i>1.973</i>	<i>-5.286</i>	no	6.71E-09	2.22	-5.42	35
A16/0205	Calcite vein C5	14.075	21.535	<i>2.657</i>	<i>-3.690</i>	yes	1.18E-08	3.05	-3.54	36
A16/0206	Calcite vein C6	13.555	17.858	<i>2.273</i>	<i>-7.126</i>	no	6.68E-09	2.62	-7.22	37
A16/0207	Calcite vein C7	13.412	16.754	<i>2.142</i>	<i>-8.209</i>	no	6.69E-09	2.51	-8.33	38
A16/0208	Calcite vein C8	13.363	17.248	<i>2.043</i>	<i>-7.804</i>	no	6.68E-09	2.44	-7.83	39
A16/0209	Calcite vein C9	13.612	18.245	<i>2.310</i>	<i>-6.774</i>	no	6.69E-09	2.67	-6.83	40
	Standards									
	x mean	13.42	23.21					2.35	-1.77	
	sigma							0.08	0.14	
	diff	-11.33	-25.07							

Tab. 10-2: Measurements of stable isotopes.

Sample ID	Sample Type	ID	Well #	87/86Sr	d ¹³ C	d ¹⁸ O
S1	Stylolite	XX795.6	X-01	0.706971		
H1	host rock of S1	XX796	X-01	0.707045		
C1	calcite vein	XX 798	X-01	0.706978	2.434926142	-4.959307406
H2	host rock of C1	XX 798	X-01	0.706956		
O1	Open fracture	XX 990	X-01			
H3	host rock of O1	XX 990	X-01	0.706944		
C2	calcite vein of H1	XX 796	X-01	0.706927	2.146687252	-5.528270592
C3	calcite vein	XX 747.6	X-01	0.706946	2.836500083	-4.52171308
H4	host rock of C3	XX 747.6	X-01	0.706931		
C4	calcite vein	XX50	X-03	0.707041	2.215567416	-5.418305337
H5	host rock of C4	XX50	X-03	0.706947		
C5	calcite vein	XX 61.2	X-03	0.707018	3.052111171	-3.541186788
H6	calcite vein	XX 61.2	X-03	0.706960		
S2	Stylolite	XX 90.5	X-03	0.707019		
H7	host rock of S2	XX 90.5	X-03			
H8	host rock of C6	XX 20	X-03			
H9	host rock of C7	XX 003.2	X-03	0.706955		
C8	calcite vein	XX 104.5	X-03	0.707061	2.436972264	-7.831177903
H10	host rock of C8	XX 104.5	X-03	0.707006		
S3	Stylolite	XX 129.5	X-03	0.707030		
H11	host rock of S3	XX 129.5	X-03	0.706933		
C9	calcite vein	XX 134	X-03		2.669090973	-6.833669291
H12	host rock of C9	XX 134	X-03	0.706954		
H13	host rock	XX 971.6	X-01	0.706936		
H14	host rock	XX 989	X-01	0.706928		

Tab. 10-3: Measurements of strontium and stable isotopes for the same samples.

Borehole	Reservoir	FMI length	Core	Core length
		m		m
X-01	All	196.6		90.2
	A	39.0	C1	14.3
	B	23.8	C2	8.8
	C	93.3	C3	27.4
	D	40.5	C4	39.6
X-02	All	514.8		
	A	59.4		
	B	25.6		
	C	108.5		
	D	321.3		
X-03	All	205.1		169.2
	A	18.3	C5	22.9
	B	13.4	C6	10.1
	C	45.4	C7	41.8
	D	128.0	C8	94.5
X-04	All	344.7		
	A			
	B	16.8		
	C	92.4		
	D	235.6		

Borehole	Reservoir	Barren fractures	Barren fractures	Mineralized fractures	Mineralized fractures	Barren fra / length	Barren fractures / length	Mineralized fractures / length	Mineralized fractures / length
		In core	In BHI	In core	In BHI	In core	In BHI	In core	In BHI
X-01	All	308	222	34	7	3.4	1.1	0.4	0.0
	A	43	24	10	0	3.0	0.6	0.7	0.0
	B	26	30	2	6	2.9	1.3	0.2	0.3
	C	118	168	10	1	4.3	1.8	0.4	0.0
	D	121		12		3.1	0.0	0.3	0.0
X-02	All		462		1		0.9		0.0
	A		85		0		1.4		0.0
	B		16		0		0.6		0.0
	C		185		0		1.7		0.0
	D		176		1		0.5		0.0
X-03	All	357	294	120	24	2.1	1.4	0.7	0.1
	A	47		3		2.1	0.0	0.1	0.0
	B	11	2	1	0	1.1	0.1	0.1	0.0
	C	73	91	11	6	1.7	2.0	0.3	0.1
	D	226	201	105	18	2.4	1.6	1.1	0.1
X-04	All		1497		20		4.3		0.1
	A								
	B		16		1		1.0		0.1
	C		387		4		4.2		0.0
	D		1094		15		4.6		0.1

Tab. 10-4: Number of the fractures interpreted from the core and borehole images (BHI) of X-01, X-02, X-03 and X-04.

Property	From the core	From the borehole images (FMI-HD and FMI-LWD MicroScope HD)
Mineralization	Barren fractures: Fractures part the core and exhibit no filling minerals or traces of cement. The walls of barren fractures display the same fabrics of the host rocks and oil stains. Mineralized fractures: Fractures filled with mineral crystals are distinguishable from those of their host rock. Mineralized fractures can be traced around the core circumference except the ones terminating at bedding and stylolite planes. Filling minerals are identified using stain techniques as well as thin section petrography. The filling mineral of fractures is calcite, except for a large fracture filled by anhydrite. The filling degree of calcite cement was complete, and calcite cement was often observed filling rock pores adjacent to filled fractures.	Barren fractures: They appear as conductive (dark) planar features (due to penetration of conductive mud). They cut bedding planes of the host rock and exhibit no trace of (resistive) minerals, such as calcite, along their apertures. Mineralized fractures: They appear as resistive planar features cutting bedding planes. Filled fractures exhibit no pores (i.e., no dark conductive features) within their mineral filling zones, as the filling minerals are impermeable to conductive drilling mud infiltrates. Filling mineral is determined to be calcite from the corresponding core.
Dip	Barren fractures: They dominantly and consistently exhibit high dip angles that are obvious from fracture intersections with the nearly flat bedding and stylolite planes. The dip angles are roughly 90° to bedding planes, and their structural dips are mostly less than 5°. Note: Dips of fractures indicate that there is no sampling bias of boreholes. Borehole deviations were optimal to intersect subvertical fractures. Mineralized fractures: Most mineralized fractures exhibit high dip angles (~90°) that are obvious from their intersections with bedding and stylolite planes. There were many examples of fractures with high dip angles to the bed-parallel stylolite planes. Some calcite-filled fractures have branches whose dips deviate from the vertical. Filling calcite is often observed to be mixing with the stylolite organic materials.	Barren fractures: They dominantly dip with angles greater than 80°. Mineralized fractures: They mostly exhibit high angles (>70°). Lower angles, between 70° and 60°, are also measured, although with much lower abundance.
Strike	Barren fractures: Measuring fracture strike was not possible, because the core is not oriented (i.e., without a reference line for the core in-situ azimuth). Orienting the core using the borehole images was also not possible. From visual descriptions, most fractures	Barren fractures: Note: For convenience, fracture strikes are reported to one side of the azimuthal projection (from 0 to 180° azimuth). Accordingly, a 20° striking fracture would be naturally striking 200° as well, and can also be defined as a NE–SW striking fracture.

	are cutting the core in a parallel set, and mostly matching the NW–SE striking set measured from the corresponding borehole images. Mineralized fractures: No measurements on fracture strikes were possible. But most fractures are observed in a parallel set from the core, and the few detected from borehole images are mostly matching a NW–SE striking set.	From boreholes X-01 and X-02, fractures exhibit a range of strikes between 90° and 180°, but most of the fractures strike around 130°. From X-03, fractures range from 40° to 180°, and most of the fractures strike NW–SE between 110° and 150°. From X-04, strikes of fractures range from 30° to 180°, and with two dominant strikes between 70°–90° and 140°–160°, respectively. From borehole comparison, fractures exhibit a wider range of strikes from X-03 and X-04 than from X-01 and X-02. Note: Combined probabilistic plotting for the 2124 fractures from all borehole images shows that most fractures have a NW–SE strike at a range between 120° and 150°. Strike distributions show that boreholes minimized or missed the parallel and nearly parallel fractures. The fracture distributions are corrected for borehole intersection biases using a density weighting method presented and described in Palmström (1996). Mineralized fractures: From borehole X-01, 7 mineralized fractures are interpreted, 2 of which strike nearly north–south, and other 5 strike northwest–southeast between 100° and 140°. From LWD images of well X-02, only a single filled fracture with large width is interpreted. It strikes 140°. From X-03, 24 filled fractures are interpreted. Their strikes range between 60° and 170°, with distribution peaks at 90° and 110° but no clear dominant strikes. From X-04, 20 mineralized fractures ranging in strikes between 30° and 150° are interpreted. They have no clear dominant strikes. Detected mineralized fractures are generally limited from borehole images—only 52 filled fractures. Their combined probabilistic plotting from all boreholes shows most of these fractures range in strikes between 80° and 130°.
Size	Barren fractures: Measurements on aperture sizes (mechanical gabs) from fitted core are provided. The rough fractures have large apertures exceeding roughly 2 mm, and smooth fractures have closely matching walls with apertures of less than 2 mm. Note: Aperture measurements seem valid for a relative range of size distributions, but absolute values are not expected to be accurate for subsurface reservoirs, as they may require assumptions and corrections to account for possible aperture reduction due to core packing into the coring barrel, or aperture enlargement due to rock extension at surface conditions.	Barren fractures: Measurements on aperture sizes (mechanical and hydraulic) from X-1 and X-03 are provided. Aperture sizes range from 1.1 mm to 0.1 m. The mean apertures are correlated from both boreholes (X-01 and X-03), with mean apertures increasing toward the fractures striking E–W and NE–SW (~60–100°), and decreasing toward the fractures striking NW–SE (~120–180°). Apertures are mostly smaller in X-01 than in X-03. Visually, apertures vary considerably from those with relatively narrow apertures and partial traces to those few with strong conductive (dark) and relatively large apertures.

	Mineralized fractures: Measurements on width sizes are provided. Measurements include the largest and smallest sections as well as the typical sizes estimated from using a digital comparator. Mineralized fractures are dominantly thin and less than 2 mm. There are two filled fractures with exceptionally large widths at one location in well X-03 within the Arab-D reservoir. One is a 7.5-cm-wide anhydrite vein, and the other is a 4-cm-wide calcite vein.	These with large apertures are far more obvious from the LWD images of X-02 as compared with the wireline images. These large fractures are not related to image pixelation, because the LWD images display other open fractures with narrow apertures similar to the aperture of fractures on wireline images of X-1 and X-03. Mineralized fractures: Measurements on width are determined from the core and compared with observations of fracture traces from borehole images. Analyses show limited observations for calcite-filled fractures. But some of the detected filled fractures from borehole images of X-01 and X-03 are as thin as 0.5 mm. Detected thin filled (resistive) fractures are within a conductive rock section of high porosity. The LWD images provided very limited observations; only one single filled fracture of large width was observed in X-02.
Roughness and wall mismatch	Barren fractures: Roughness measurements are presented in Ch. 6. Correlations between core and borehole images indicate that barren fractures with rough apertures are more frequently observed from corresponding images than are fractures with narrow and matching walls. Comparing roughness parameters (Z_2) indicates that the fractures detected in borehole images have mismatched walls, while missing fractures have matching walls. Statistically, most fractures have matching walls, and only a minority display wall mismatch due to their host rock fabrics. Mineralized fractures: Roughness measurements are presented in Ch. 6 and (Al-Fahmi et al., 2018). Calcite-filled fractures display roughness, wall match, and wall mismatch that are similar to the same properties of barren fractures. Larger fractures exhibit rougher walls, and small fractures exhibit smoother walls. Wall mismatch is noted in some fractures.	Barren fractures: Apertures vary along individual fracture profiles, indicating roughness and wall mismatch. In addition, the mean apertures of the fractures display a difference between mechanical apertures and hydraulic apertures (indicating wall mismatch). Apertures are more varying in sizes along fractures profiles in X-01 than they are in X-03. This indicates wall mismatch. Mineralized fractures: Measurements on roughness are not possible due to the limited resolution of fracture traces and limited observations of fractures.
Displacement	Barren fractures: They cut bedding, lamina, and stylolite markers without any displacement other than their original opening-mode displacement. Mineralized fractures: They cut bedding and stylolite markers without shear displacement.	Barren fractures: They cut bedding, lamina, and stylolite markers without shear displacement. Mineralized fractures: They cut bedding and stylolite markers without shear displacement.

Tab. 10-5: Summary of fracture descriptions from core and corresponding borehole images.

Seq. No.	Amplitude	Circumference	radian	Z_2	JCR_ Z_2	Real dip	Phase	Correlation
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1	3.7561225	36.83	5.8616814 6	0.2136926 3	11.104924 3	32.651478 5	- 31.28000 1	0.9954386 9
2	3.7495949	36.83	5.8616814 6	0.1906392 6	9.7789205 1	32.606224 1	-31.27	0.9955118 3
3	2.4507791 4	36.83	5.8616814 6	0.0500756 9	0	22.689908 2	-31.268	0.9973949 8
4	2.4997299 3	36.83	5.8616814 6	0.0938121 2	3.1212966 6	23.095974	- 31.25799 9	0.9943018 6
5	9.3266684	49.53	7.8829507 8	0.1736106 3	8.7504297 8	49.795366 2	-44.319	0.9934864
6	9.2940350 4	49.53	7.8829507 8	0.2066603 6	10.707876 7	49.696327 1	-44.32	0.9990443
7	4.0563502 7	49.53	7.8829507 8	0.2407431 3	12.577934 5	27.229130 5	-47.5	0.9840516 4
8	4.0171896 9	49.53	7.8829507 8	0.1729222 7	8.7078810 8	27.003632 6	- 47.56700 1	0.9923391 3
9	5.9654129 4	49.53	7.8829507 8	0.1654805 5	8.2427225	37.116597 6	- 45.94200 1	0.9940937 8
10	5.9915197 8	49.53	7.8829507 8	0.1647719 5	8.1979234	37.237062 2	-45.937	0.9940948 5
11	4.5523802 3	49.53	7.8829507 8	0.6805315 2	30.263543 1	30.006327 9	- 45.49000 2	0.9919735 2
12	4.4838497 7	49.53	7.8829507 8	0.2258091 3	11.774924 1	29.631392 5	- 45.49100 1	0.9903621 1
13	4.8069219 2	49.53	7.8829507 8	0.4996905 7	23.954913 1	31.374326 8	- 44.67499 9	0.9885178 2
14	4.638697	49.53	7.8829507 8	0.2824069	14.702392 1	30.474570 2	-44.59	0.9796858 4
15	9.9102448 1	49.53	7.8829507 8	0.2106495 7	10.933874 9	51.500092 2	-44.597	0.9939522 7
16	9.8307242 9	49.53	7.8829507 8	0.2078274 8	10.774206 8	51.275004 4	-44.632	0.9941172
17	2.6274905 2	36.83	5.8616814 6	0.2469957 4	12.907178 7	24.144261 5	- 31.41200 1	0.9768495
18	2.6539973 6	36.83	5.8616814 6	0.3505022 7	17.879824 5	24.359642 7	-31.357	0.9720311 8
19	1.8488520 9	36.83	5.8616814 6	0.1976385 6	10.189097 7	17.505980 6	-31.385	0.9958270 2
20	1.8242154 5	36.83	5.8616814 6	0.1407277 8	6.6201033 6	17.286693 1	-31.403	0.9959261 4
11	5.9612909 8	36.83	5.8616814 6	0.1469235 7	7.0380486 1	45.482747 2	-32.521	0.9978483 9
10	6.263733	36.83	5.8616814 6	0.1511195 8	7.3164153 2	46.899143 6	- 32.48400 1	0.9959461 7
1	2.6344292 4	36.83	5.8616814 6	0.2175974 7	11.32275	24.200712 7	- 35.66899 9	0.8959865 6
12	2.6344287 6	36.83	5.8616814 6	0.2170836 8	11.294194 4	24.200708 5	- 35.67900 1	0.8593193 3
14	2.2046439	36.83	5.8616814 6	0.1724087 4	8.6760872 4	20.611858 9	- 34.83499 9	0.9823209
13	2.140971	36.83	5.8616814 6	0.1561316 3	7.6442107 8	20.064668 3	-34.798	0.9857842 3

16	2.0932162 9	36.83	5.8616814 6	0.2301850 9	12.012736 6	19.651748 2	-31.216	0.9848064 2
15	2.0932163 2	36.83	5.8616814 6	0.2496715 8	13.046884 6	19.651748 2	-31.159	0.9830803 9
17	1.9260779 5	36.83	5.8616814 6	0.1468111 3	7.0305386 5	18.189915 4	- 35.58700 2	0.9961401 2
18	1.949955	36.83	5.8616814 6	0.1512998 6	7.3282937 8	18.400306 3	- 35.37599 9	0.9944624 3
20	2.6742238 8	36.83	5.8616814 6	0.2189551 1	11.398053 3	24.523501 7	- 33.49499 9	0.9936786 9
19	2.523003	36.83	5.8616814 6	0.1424912 4	6.7399236 4	23.288179 4	-33.562	0.9935180 5
2	2.920953	36.83	5.8616814 6	0.2674241 1	13.956509 5	26.487702 3	-30.812	0.9947708 2
3	3.2154341 5	36.83	5.8616814 6	0.1837901 9	9.3706521 3	28.747060 9	-30.785	0.9919330 5
5	4.584384	36.83	5.8616814 6	0.1732828 2	8.7301769 2	38.028768 9	- 35.76699 8	0.9947061 5
4	4.807236	36.83	5.8616814 6	0.1552892 1	7.5894642 7	39.355626 5	- 35.77899 9	0.9909149 4
7	2.618511	36.83	5.8616814 6	0.0610797	0.1542270 1	24.071133 3	-30.993	0.9966598 7
6	2.7219769 1	36.83	5.8616814 6	0.0676648 7	0.8020296 9	24.908664 8	-30.966	0.9983374 5
9	5.7782343 3	36.83	5.8616814 6	0.1829910 4	9.3225541 2	44.589288 6	-34.181	0.9974448 1
8	5.825988	36.83	5.8616814 6	0.1096510 2	4.3789359 8	44.825060 9	- 34.17200 1	0.9965544 9
9	2.7936072 7	49.53	7.8829507 8	0.1460319 2	6.9784175 3	19.513629	- 47.07899 9	0.9810053 7
10	2.745855	49.53	7.8829507 8	0.1585520 5	7.8007409 8	19.204690 5	- 47.06800 1	0.9674161 7
56	7.067592	49.53	7.8829507 8	0.1106006 9	4.4515384 5	46.969824 1	-48.646	0.9986141 3
55	7.0675922 4	49.53	7.8829507 8	0.1125056 1	4.5962945 2	46.969830 5	-48.646	0.9986510 3
58	4.671933	49.53	7.8829507 8	0.1321797	6.0290390 8	28.955213 5	- 47.53900 1	0.9896411 3
57	4.488876	49.53	7.8829507 8	0.2082430 1	10.797780 6	27.836117 6	- 47.47600 2	0.9782615 3
20	3.135846	49.53	7.8829507 8	0.1483301 2	7.1317710 1	47.634852 4	- 48.79600 1	0.9969785 8
19	3.215436	49.53	7.8829507 8	0.1458104	6.9635767 6	47.687347 4	- 48.79999 9	0.9973111 7
22	5.380284	49.53	7.8829507 8	0.1912088 4	9.8125605 5	16.159950 4	- 44.62599 9	0.9011935
21	5.324571	49.53	7.8829507 8	0.2146108 1	11.156310 2	16.053163	- 44.62300 1	0.9536078 6
28	3.756648	49.53	7.8829507 8	0.1308046 6	5.9323055 1	37.207778 8	- 44.16500 1	0.9939251 5

27	3.7646038 4	49.53	7.8829507 8	0.0793888 8	1.8860954 4	36.839050 4	- 44.16999 8	0.9957734 3
23	5.069883	49.53	7.8829507 8	0.0802410 7	1.9618636	44.105768 7	-44.534	0.9978522 7
24	5.0778407 9	49.53	7.8829507 8	0.1117513 9	4.5391192 3	44.313819 6	-44.52	0.9962818 6
26	5.722521	49.53	7.8829507 8	0.1149190 3	4.7780508 5	39.033320 2	- 47.21300 1	0.9950844
25	5.6110945 1	49.53	7.8829507 8	0.0968729 8	3.3716743 9	39.449716 8	-47.209	0.9980381 7
29	3.637263	49.53	7.8829507 8	0.1574191 2	7.7276138 4	49.2385	-44.402	0.9965018 6
30	3.6054308 9	49.53	7.8829507 8	0.1757152 8	8.8800324	49.287777 5	-44.43	0.9961175 9
31	8.1738964	49.53	7.8829507 8	0.1831331 2	9.3311124 9	41.878384	- 46.03599 9	0.9968437
32	8.11818	49.53	7.8829507 8	0.1767293 6	8.9422184 7	41.878384	- 45.98199 8	0.9939118 6
34	4.663974	49.53	7.8829507 8	0.1337626 9	6.1398200 4	30.653676 4	- 48.67800 1	0.9891568 4
33	4.6958080 6	49.53	7.8829507 8	0.1230832 2	5.3800053 8	29.658988 7	-48.652	0.9815735 8
5	8.4444974 8	49.53	7.8829507 8	0.2002808 9	10.342168 4	21.692732 6	- 45.26599 9	0.9934958 2
6	8.444499	49.53	7.8829507 8	0.1938918 9	9.9703964 7	22.190443 5	- 45.21799 9	0.9916555 9
36	2.4036107 1	49.53	7.8829507 8	0.1838515 1	9.3743389 8	34.314409 1	-45.812	0.9959933 8
35	2.395659	49.53	7.8829507 8	0.2220539 2	11.569117 8	34.037246	-45.812	0.9956889 2
38	4.8788689 4	49.53	7.8829507 8	0.1632562 8	8.1017948 3	25.480320 6	- 45.51800 2	0.9821102
37	4.886826	49.53	7.8829507 8	0.1726438 9	8.6906514 6	25.527424 9	-45.527	0.9856631 2
40	8.731023	49.53	7.8829507 8	0.1321593 1	6.0276086 7	32.746935 6	-49.118	0.9932190 8
39	8.7389838 2	49.53	7.8829507 8	0.1308472	5.9353055 1	32.787831 3	- 49.11299 9	0.9935618
42	2.8095311 3	49.53	7.8829507 8	0.1709723 1	8.5869179 7	35.977294 2	- 49.48899 8	0.9926514
41	2.841363	49.53	7.8829507 8	0.1373348 5	6.3875686 2	35.443340 1	- 49.45999 9	0.9936972 3
44	3.780525	49.53	7.8829507 8	0.1253137	5.5411759 9	24.769036 5	- 44.24499 9	0.9947726 1
43	3.5576800 4	49.53	7.8829507 8	0.1257027 4	5.5691496 3	24.577989	-44.237	0.9946892 3
46	5.833947	49.53	7.8829507 8	0	0	0	0	0
45	6.0170100 7	49.53	7.8829507 8	0.1120226 7	4.5597054	45.842270 6	- 44.56499 9	0.9311757 1
48	4.234188	49.53	7.8829507 8	0.1609285	7.9533410 8	30.610846 5	- 44.37699	0.9886500 2

							9	
47	4.0590918 2	49.53	7.8829507 8	0.1828204 4	9.3122732 2	30.781928 7	-44.319	0.9888058 9
50	3.8044064 9	49.53	7.8829507 8	0.1206895 1	5.2055076 8	16.957136 9	-45.098	0.9951844 8
49	3.876033	49.53	7.8829507 8	0.0805066 6	1.9853994 6	16.904241 3	- 45.05899 8	0.9983894 2
52	2.3081040 5	49.53	7.8829507 8	0.1520214 4	7.3757703 8	31.753972 1	-45.035	0.9966512 9
51	2.324028	49.53	7.8829507 8	0.1516650 4	7.3523343 3	31.795769 9	-45.034	0.9966590 4
54	3.637263	49.53	7.8829507 8	0.0897300 6	2.7813424 6	47.922207 2	- 45.38299 9	0.9980553 4
53	3.6770571 5	49.53	7.8829507 8	0.0870869 1	2.5573402 5	47.948180 7	- 45.38299 9	0.9980140 3
7	4.3615351	49.53	7.8829507 8	0.1661851 9	8.2871819 9	19.616389 1	- 44.17200 1	0.9979183 7
8	4.162557	49.53	7.8829507 8	0.1587981 2	7.8165914 3	19.821414 1	- 44.21799 9	0.9977383
3	8.643474	49.53	7.8829507 8	0.1301053 4	5.8829256	25.621580 7	- 44.38000 1	0.9961022 7
4	8.6593956 4	49.53	7.8829507 8	0.0929520 5	3.0502555 1	24.290306 7	- 44.39099 9	0.9983394 7
11	2.284233	49.53	7.8829507 8	0.2180562 5	11.348221 4	36.504118 1	-44.903	0.9934072 5
12	2.2683157 3	49.53	7.8829507 8	0.2059297 4	10.666264 4	37.354312	- 44.92200 1	0.9923279 9
14	5.9851656 9	49.53	7.8829507 8	0.2016265 9	10.419761 5	28.241706 6	- 45.72599 8	0.9699661 7
13	5.905578	49.53	7.8829507 8	0.2017418 9	10.426398 2	27.244883 5	-45.737	0.9661307 9
1	7.64064	49.53	7.8829507 8	0.2368060 5	12.368559	25.762533 9	- 47.42100 1	0.9889937 6
2	7.6963522 7	49.53	7.8829507 8	0.2596186 9	13.560167 8	26.183286 3	-47.388	0.9913908 2
16	6.3910742 1	49.53	7.8829507 8	0.1474614	7.0739349 9	16.319884 6	- 46.76499 9	0.9866497 5
15	6.486585	49.53	7.8829507 8	0.1714325 5	8.6155264 6	16.426426 9	- 46.79299 9	0.9851324
17	9.1448893	49.53	7.8829507 8	0.1153670 9	4.8115967 5	24.769036 5	- 45.65499 9	0.9980369 2
18	9.160809	49.53	7.8829507 8	0.1638846 3	8.1416971 4	25.007045 3	-45.652	0.9959014 1

Tab. 10-6: Measurements of fracture roughness.

Seq. No.	MCs	STDEV-A	Avg. JRC	JRC top	JRC base	delta JRC	MCs
11	0.268118324	0.2614666 6	7.1772320 3	7.3164153 2	7.0380487 4	0.2783665 7	0.268118324
1	0.001066098	0.0285781 7	11.308472 1	11.32275	11.294194 2	0.0285558	0.001066098
14	0.092757234	0.1216046 6	8.1601490 3	8.6760872 4	7.6442108 2	1.0318764 3	0.092757234
16	0.042428027	0.0465748 7	12.529810 6	12.012736 6	13.046884 5	1.0341479	0.042428027
17	0.256431624	0.0954898 1	7.1794162 3	7.0305386 5	7.3282938	0.2977551 5	0.256431624
20	0.121573044	0.1497953 6	9.0689883 8	11.398053 3	6.7399234 8	4.6581298 1	0.121573044
2	0.288881147	0.2376416 5	11.663580 9	13.956509 5	9.3706522	4.5858573 3	0.288881147
5	0.118502284	0.3006071 8	8.1598205 6	8.7301769 2	7.5894641 9	1.1407127 4	0.118502284
7	0.136648695	0.1388686 6	0.4781283 4	0.1542270 1	0.8020296 7	0.6478026 5	0.136648695
9	0.131985097	0.2778849 9	6.8507449 7	9.3225541 2	4.3789358 1	4.9436183 1	0.131985097
9	0.09118155	0.2094214 9	7.3895791 9	7.8007409 8	6.9784174	0.8223235 8	0.09118155
56	0.001114493	0.0119763 1	4.5239165 4	4.5962945 2	4.4515385 6	0.1447559 5	0.001114493
58	0.263811502	0.3942376 8	8.4134097 3	10.797780 6	6.0290389 1	4.7687416 5	0.263811502
20	0.009912593	0.0633067 7	7.0476739 2	6.9635767 6	7.1317710 9	0.1681943 3	0.009912593
22	0.006632812	0.0655545 3	10.484435 1	11.156310 2	9.8125600 8	1.3437500 8	0.006632812
28	0.095326511	0.1767997	3.9092003 9	1.8860954 4	5.9323053 4	4.0462099	0.095326511
23	0.056477528	0.1343241 5	3.2504914 3	4.5391192 3	1.9618636 4	2.5772555 9	0.056477528
26	0.020686846	0.0690410 4	4.0748626 5	3.3716743 9	4.7780509	1.4063765 1	0.020686846
29	0.124242971	0.2230354 4	8.3038231 6	8.8800324	7.7276139 3	1.1524184 7	0.124242971
31	0.15983982	0.1189215 6	9.1366656 6	8.9422184 7	9.3311128 6	0.3888944	0.15983982
34	0.084102116	0.2434082 8	5.7599127 4	5.3800053	6.1398201	0.7598147 2	0.084102116
5	0.088933148	0.0713191 4	10.156282 6	9.9703964 7	10.342168 8	0.3717723 4	0.088933148
36	0.309192138	0.1298633	10.471728 5	11.569117 8	9.3743391	2.1947787 1	0.309192138
38	0.078106779	0.1369109 7	8.3962233 3	8.6906514 6	8.1017952	0.5888562 7	0.078106779
40	0.001405013	0.0162645 3	5.9814571 9	5.9353055 1	6.0276088 7	0.0923033 6	0.001405013
42	0.06643174	0.1622731 4	7.4872432 5	6.3875686 2	8.5869178 8	2.1993492 6	0.06643174
44	0.039793445	0.1106003 5	5.5551627 4	5.5411759 9	5.5691494 9	0.0279735 1	0.039793445
48	0.07659547	0.1557823 8	8.6328071 1	9.3122732 2	7.9533410 1	1.3589322 1	0.07659547
50	0.218950787	0.0575423 6	3.5954536 1	1.9853994 6	5.2055077 6	3.2201082 9	0.218950787
52	0.000712738	0.0089263 6	7.3640524 5	7.3523343 3	7.3757705 7	0.0234362 4	0.000712738
54	0.027300914	0.0559764 9	2.6693413 8	2.5573402 5	2.7813425 1	0.2240022 5	0.027300914

7	0.167143229	0.0359606	8.0518866 4	7.8165914 3	8.2871818 5	0.4705904 2	0.167143229
3	0.605765571	0.1846217 9	4.4665905 1	3.0502555 1	5.8829255 1	2.83267	0.605765571
11	0.300330452	0.1095630 8	11.007243 1	10.666264 4	11.348221 8	0.6819573 6	0.300330452
14	0.055114507	0.1522570 6	10.423079 9	10.426398 2	10.419761 7	0.0066365	0.055114507
1	0.442859829	0.1703084	12.964363 4	13.560167 8	12.368558 9	1.1916089 4	0.442859829
16	0.025837727	0.0617819 1	7.8447307 4	8.6155264 6	7.0739350 3	1.5415914 2	0.025837727
17	0.080564156	0.1460621 4	6.4766470 1	8.1416971 4	4.8115968 7	3.3301002 7	0.080564156

Tab. 10-7: Measurements of fracture wall mismatch.

Spacing	Thickness		Site	Fracture type	Spacing	Thickness		Site	Fracture type
2.3	1.8	Middle Rus	1	Barren	3.5	1	Middle Rus	6	Barren
5.1	1.8	Middle Rus	1	Barren	2.6	1	Middle Rus	6	Barren
6.2	1.8	Middle Rus	1	Barren	3.5	1	Middle Rus	6	Barren
4.3	1.8	Middle Rus	1	Barren	4.1	1	Middle Rus	6	Barren
3.2	1.8	Middle Rus	1	Barren	4	1	Middle Rus	6	Barren
4.2	1.8	Middle Rus	1	Barren	4.1	1	Middle Rus	6	Barren
5.1	1.8	Middle Rus	1	Barren	2.2	1	Middle Rus	6	Barren
4.3	1.8	Middle Rus	1	Barren	3	1	Middle Rus	6	Barren
4.2	1.8	Middle Rus	1	Barren	3.1	1	Middle Rus	6	Barren
5	1.8	Middle Rus	1	Barren	2.9	2.1	Middle Rus	7	Barren
4	1.8	Middle Rus	1	Barren	2.3	2.1	Middle Rus	7	Barren
2.2	1.8	Middle Rus	1	Barren	2.7	2.1	Middle Rus	7	Barren
4.2	1.8	Middle Rus	1	Barren	2.1	2.1	Middle Rus	7	Barren
5	1.8	Middle Rus	1	Barren	2	2.1	Middle Rus	7	Barren
5.2	1.8	Middle Rus	1	Barren	2.5	2.1	Middle Rus	7	Barren
2	1.8	Middle Rus	1	Barren	2.6	2.1	Middle Rus	7	Barren
2.5	1.8	Middle Rus	1	Barren	2.3	2.1	Middle Rus	7	Barren
4.1	1.8	Middle Rus	1	Barren	2.3	2.1	Middle Rus	7	Barren
3.3	1.8	Middle Rus	1	Barren	2.5	1.5	Middle Rus	8	Barren
1.9	1.8	Middle Rus	1	Barren	1.5	1.5	Middle Rus	8	Barren
3.9	1.8	Middle Rus	1	Barren	4	1.5	Middle Rus	8	Barren
4.7	1.8	Middle Rus	1	Barren	3.3	1.5	Middle Rus	8	Barren
4.9	1.8	Middle Rus	1	Barren	7	1.5	Middle Rus	8	Barren
1.7	1.8	Middle Rus	1	Barren	1.9	1.5	Middle Rus	8	Barren
3.8	1.8	Middle Rus	1	Barren	2.1	1.5	Middle Rus	8	Barren
6	1.8	Middle Rus	1	Barren	2.6	1.5	Middle Rus	8	Barren
4.1	1.8	Middle Rus	1	Barren	2	1.5	Middle Rus	8	Barren
4.5	1.8	Middle Rus	1	Barren	2	1.5	Middle Rus	8	Barren
6.2	1.8	Middle	1	Barren	1.4	1.5	Middle	8	Barren

		Rus					Rus		
3	1.8	Middle Rus	1	Barren	4.5	1.5	Middle Rus	8	Barren
3.8	1.8	Middle Rus	1	Barren	2	1.5	Middle Rus	8	Barren
4.1	1.8	Middle Rus	1	Barren	2.4	1.5	Middle Rus	8	Barren
5	1.8	Middle Rus	1	Barren	2.5	1.5	Middle Rus	8	Barren
2.3	1.8	Middle Rus	1	Barren	3.5	1.5	Middle Rus	8	Barren
3	1.8	Middle Rus	1	Barren	3.3	1.5	Middle Rus	8	Barren
3.5	1.8	Middle Rus	1	Barren	4	1.5	Middle Rus	8	Barren
1.2	1.8	Middle Rus	1	Barren	3.3	1.5	Middle Rus	8	Barren
6	1.8	Middle Rus	1	Barren	2	1.5	Middle Rus	8	Barren
5	1.8	Middle Rus	1	Barren	1.9	1.5	Middle Rus	8	Barren
3.8	1.8	Middle Rus	1	Barren	4.5	1.5	Middle Rus	8	Barren
4.2	1.8	Middle Rus	1	Barren	5.5	1.5	Middle Rus	8	Barren
5.9	1.8	Middle Rus	1	Barren	5	1.5	Middle Rus	8	Barren
2.7	1.8	Middle Rus	1	Barren	7	1.5	Middle Rus	8	Barren
3.5	1.8	Middle Rus	1	Barren	5.2	1.5	Middle Rus	9	Barren
3.8	1.8	Middle Rus	1	Barren	3	1.5	Middle Rus	9	Barren
4.7	1.8	Middle Rus	1	Barren	2.2	1.5	Middle Rus	9	Barren
2	1.8	Middle Rus	1	Barren	2.5	1.5	Middle Rus	9	Barren
2.7	1.8	Middle Rus	1	Barren	3.1	1.5	Middle Rus	9	Barren
3.2	1.8	Middle Rus	1	Barren	2.2	1.5	Middle Rus	9	Barren
0.9	1.8	Middle Rus	1	Barren	2	1.5	Middle Rus	9	Barren
5.7	1.8	Middle Rus	1	Barren	2.1	1.5	Middle Rus	9	Barren
4.7	1.8	Middle Rus	1	Barren	2.2	1.5	Middle Rus	9	Barren
2	1.6	Upper Rus	3	Barren	2.5	1.5	Middle Rus	9	Barren
4	1.6	Upper Rus	3	Barren	2.5	1.5	Middle Rus	9	Barren
2.5	1.6	Upper Rus	3	Barren	2.4	1.5	Middle Rus	9	Barren
3.6	1.6	Upper Rus	3	Barren	2.1	1.5	Middle Rus	9	Barren
2	1.6	Upper Rus	3	Barren	2.6	1.5	Middle Rus	9	Barren
3	1.6	Upper Rus	3	Barren	2.5	1.5	Middle Rus	9	Barren

5	1.6	Upper Rus	3	Barren	4	1.5	Middle Rus	9	Barren
1.7	1.6	Upper Rus	3	Barren	3.4	2.6	Middle Rus	10	Barren
2	1.6	Upper Rus	3	Barren	3.5	2.6	Middle Rus	10	Barren
2	1.6	Upper Rus	3	Barren	3.7	2.6	Middle Rus	10	Barren
2	1.6	Upper Rus	3	Barren	3.3	2.6	Middle Rus	10	Barren
3	1.6	Upper Rus	3	Barren	3.2	2.6	Middle Rus	10	Barren
2	1.3	Middle Rus	3	Barren	4.1	2.6	Middle Rus	10	Barren
3	1.3	Middle Rus	3	Barren	4.4	2.6	Middle Rus	10	Barren
2.5	1.3	Middle Rus	3	Barren	5	2.6	Middle Rus	10	Barren
2.2	1.3	Middle Rus	3	Barren	4.1	2.6	Middle Rus	10	Barren
2.1	1.3	Middle Rus	3	Barren	3.5	2.6	Middle Rus	10	Barren
2.5	1.3	Middle Rus	3	Barren	5	2.6	Middle Rus	10	Barren
2.1	1.3	Middle Rus	3	Barren	4.2	2.6	Middle Rus	10	Barren
1.5	1.3	Middle Rus	3	Barren	3.7	2.6	Middle Rus	10	Barren
2.3	1.3	Middle Rus	3	Barren	5.5	2.6	Middle Rus	10	Barren
2.5	1.3	Middle Rus	3	Barren	2.9	2.6	Middle Rus	10	Barren
1.2	1.3	Middle Rus	3	Barren	2.2	2.5	Lower Rus	11	Barren
2	1.3	Middle Rus	3	Barren	2.8	2.5	Lower Rus	11	Barren
1.3	1.3	Middle Rus	3	Barren	4.1	2.5	Lower Rus	11	Barren
0.6	1.3	Middle Rus	3	Barren	3.1	2.5	Lower Rus	11	Barren
1	1.3	Middle Rus	3	Barren	3.8	2.5	Lower Rus	11	Barren
1.2	1.3	Middle Rus	3	Barren	2.5	2.5	Lower Rus	11	Barren
2.1	1.3	Middle Rus	3	Barren	3.1	2.5	Lower Rus	11	Barren
2.2	1.3	Middle Rus	3	Barren	3	2.5	Lower Rus	11	Barren
4	3	Middle Rus	3	Barren	2	2.5	Lower Rus	11	Barren
3	3	Middle Rus	3	Barren	2.3	2.5	Lower Rus	11	Barren
6	3	Middle Rus	3	Barren	2.6	2.5	Lower Rus	11	Barren
7	3	Middle Rus	3	Barren	2.7	2.5	Lower Rus	11	Barren
3	3	Middle Rus	3	Barren	3.8	2.5	Lower Rus	11	Barren
3	3	Middle Rus	3	Barren	3.5	2.5	Lower Rus	11	Barren

8	3.5	Middle Rus	3	Barren	2	2.5	Lower Rus	11	Barren
4	3.5	Middle Rus	3	Barren	1.9	2.5	Lower Rus	11	Barren
4	3.5	Middle Rus	3	Barren	2	2.5	Lower Rus	11	Barren
5	3.5	Middle Rus	3	Barren	2.1	2.5	Lower Rus	11	Barren
3	3.5	Middle Rus	3	Barren	3.2	2.5	Lower Rus	11	Barren
7	3.5	Middle Rus	3	Barren	2.3	2.5	Lower Rus	11	Barren
6	3.5	Middle Rus	3	Barren	3.7	2.5	Lower Rus	11	Barren
4	3.5	Middle Rus	3	Barren	4	2.5	Lower Rus	11	Barren
3	3.5	Middle Rus	3	Barren	3.1	2.5	Lower Rus	11	Barren
6.4	5	Lower Rus	3	Gypsy filled	2	2.5	Lower Rus	11	Barren
10	5	Lower Rus	3	Barren	1.3	2.5	Lower Rus	11	Barren
9	5	Lower Rus	4	gypsy filled	1.9	2.5	Lower Rus	11	Barren
1.2	5	Lower Rus	4	gypsy filled	3.5	2.5	Lower Rus	11	Barren
6.5	5	Lower Rus	4	Barren	5	2.5	Lower Rus	11	Barren
7	5	Lower Rus	4	Barren	4.1	2.5	Middle Rus	11	Barren
9	5	Lower Rus	4	Barren	3.3	2.5	Middle Rus	11	Barren
8	5	Lower Rus	4	Barren	4.1	2.5	Middle Rus	11	Barren
4	5	Lower Rus	4	Barren	3.5	2.5	Middle Rus	11	Barren
6	5	Lower Rus	4	Barren	3	2.5	Middle Rus	11	Barren
1.8	1.6	Middle Rus	4	Gypsy filled	4.5	2.5	Middle Rus	11	Barren
1.5	1.6	Middle Rus	4	Barren	3.6	2.5	Middle Rus	11	Barren
1.4	1.6	Middle Rus	4	gypsy filled	3.5	2.5	Middle Rus	11	Barren
1.8	1.6	Middle Rus	4	gypsy filled	4.1	2.5	Middle Rus	11	Barren
2.1	1.6	Middle Rus	4	Barren	5	2.5	Middle Rus	11	Barren
1.8	1.6	Middle Rus	4	Barren	3.5	2.5	Middle Rus	11	Barren
2.5	1.6	Middle Rus	4	Barren	5.8	2.5	Middle Rus	11	Barren
1.3	1.6	Middle Rus	4	Barren	2.1	2.5	Middle Rus	11	Barren
3.6	1.6	Middle Rus	4	Barren	4	2.5	Middle Rus	11	Barren
4.8	1.6	Middle Rus	4	Barren	3.9	2.5	Middle Rus	11	Barren
1	1.6	Middle Rus	4	Barren	3.8	2.5	Middle Rus	11	Barren

3.8	1.6	Middle Rus	4	Barren	3.5	2.5	Middle Rus	11	Barren
2	1.6	Middle Rus	4	Barren	3.7	2.5	Middle Rus	11	Barren
2	1.6	Middle Rus	4	Barren	3.1	2.5	Middle Rus	11	Barren
1.1	1.6	Middle Rus	4	Barren	5	2.5	Middle Rus	11	Barren
1.5	1.6	Middle Rus	4	Barren	6	2.5	Middle Rus	11	Barren
5.4	1.5	Middle Rus	5	Barren	2.9	2.5	Middle Rus	11	Barren
2.4	1.5	Middle Rus	5	Barren	3.9	2.5	Middle Rus	11	Barren
3.4	1.5	Middle Rus	5	Barren	3.8	2.5	Middle Rus	11	Barren
5	1.5	Middle Rus	5	Barren	4.3	2.5	Middle Rus	11	Barren
2.8	1.5	Middle Rus	5	Barren	3.4	2.5	Middle Rus	11	Barren
2.3	1.5	Middle Rus	5	Barren	4.1	2.5	Middle Rus	11	Barren
3	1.5	Middle Rus	5	Barren	6	2.5	Middle Rus	11	Barren
3.2	1.5	Middle Rus	5	Barren	2.3	2.5	Middle Rus	11	Barren
2.5	1.5	Middle Rus	5	Barren	3	2.5	Middle Rus	11	Barren
2.5	1.5	Middle Rus	5	Barren	4.4	2.5	Middle Rus	11	Barren
1.8	1.5	Middle Rus	5	Barren	3	2.5	Middle Rus	11	Barren
2.1	1.5	Middle Rus	5	Barren	3.6	2.5	Middle Rus	11	Barren
2.3	1	Middle Rus	6	Barren					

Tab. 10-8: Measurements of fracture spacing in the Rus carbonates in the dome.