Fractures of the Dammam Dome Carbonate Outcrops: Their Characterization, Development, and Implications for Subsurface Reservoirs

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FRACTURES OF THE DAMMAM DOME CARBONATE OUTCROPS: THEIR CHARACTERIZATION, DEVELOPMENT, AND IMPLICATIONS FOR SUBSURFACE RESERVOIRS

A Thesis Presented

by

MOHAMMED IBN MAGBOOL ALFAHMI

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

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September 2012

Geosciences
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ABSTRACT

Fractures of the Dammam Dome Carbonate Outcrops: Their Characterization, Development, and Implications for Subsurface Reservoirs

SEPTEMBER 2012

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The exposed Tertiary carbonates of the Dammam Dome present an opportunity to study fractures in outcrops within the oil-producing region of Eastern Saudi Arabia. The study focuses on: 1) the characterization of fractures, 2) interpretation of their fracturing mechanism, and 3) the implications for the deep carbonate reservoirs of the Dammam Dome. The characterization of the outcrop fractures is integrated with structural analysis of the near-surface horizons mapped from reflection seismic and well data. Fractures are observed within all exposed carbonate units, but predominantly within the widely exposed Middle Rus unit. The fractures are opening-mode, bed-bound joints that form orthogonal sets (NW-SE and NE-SW trending joints). The trends of through-going, primary NW-SE trending joints do not correlate with the trends of remote regional stress associated with compression of Zagros uplift, suggesting they did not develop due to that orogenic event. The primary joints also seem to have developed independently of the observed karst features and interpreted near-surface faults. The analysis of joint pattern and their spacings generally seem to reflect the fold growth of the strata, position on fold and mechanical stratigraphy. The study results provide a first-order conceptual fracture model for the subsurface reservoirs to guide future development.
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INTRODUCTION

Fractures are the most ubiquitous structure in the Earth’s crust, occurring in a wide variety of rock types and tectonics environments (e.g. Pollard and Aydin, 1988). Their role as fluid conduits within hydrocarbon reservoirs propelled research since the 1960s (e.g. Stearns & Friedman, 1971, Nelson, 1985), to characterize their distributions and analyze their impact on reservoir production. Fractures in hydrocarbon reservoirs can be sometimes induced by drilling and production practices, but this study only considers outcrop analogues to reservoir fractures developed due to naturally driven stresses.

Characterization of naturally-occurring fractures in reservoirs relies on a multidisciplinary approach to interpret different subsurface data sets from borehole images, core samples, wireline logs, and several other detection methods drawing on reservoir dynamics (e.g. Ozkaya at el, 2007). However, this suite of data sets is not always available, and if available, data coverage and quality are frequently insufficient to adequately constrain 3D models of reservoir fractures. Some fracture parameters cannot be observed in core samples or image logs (e.g. fracture length, cross-cutting relationships) and observations from wells are also influenced by directional sampling bias (e.g. Wennberg at el, 2006). In addition, fractures are mostly sub-seismic geologic features in reservoirs. Despite observations that some reflection seismic attributes may add values for fracture detection (e.g. Al-Dossary & Marfurt 2006; Chopra & Marfurt 2007), rock joints and the faults with offset less than 10m are not resolved even from the images of high-quality seismic methods (e.g. Jolley et al, 2007). The modeling of reservoir fractures also requires evaluation of other reservoir rock properties (e.g. distribution of matrix porosity and permeability) (e.g. Nelson, 2001), so the impact of fractures on reservoir behavior can be evaluated separately from the role of original rock matrix and digenesis. The data
shortages encountered by workers investigating subsurface fractures stimulate studying fractures in outcrops that can be used as subsurface reservoir analogues.

The study of outcrops should improve our understanding of the different geologic settings that cause fractures and the factors that influence their patterns. Consequently, implications from outcrop studies can be integrated in the characterization and modeling of subsurface reservoir fractures (e.g. Casini et al, 2011). This should be practical if outcrops share some elements of the geologic settings (e.g. structural history) imprinted in their deeper reservoirs such as the case of the Dammam Dome.

The Dammam Dome is a notable geologic feature as its carbonate outcrops form a relatively high topography in the otherwise flat extent of the eastern Arabian Peninsula (e.g. Tleel 1973). Several studies have established the stratigraphy of the Dome’s outcrops together with surrounding areas within the Arabian sedimentary basin (Steineke et al. 1958, Powers, 1966, Tleel 1973, Jado et al 1983, Irtem, O. 1986, Weijermars, R. 1998). However, less is known about the structures developed within the Dome’s outcrops; notably the large fractures, and lineaments that can be discerned from satellite imagery.

This study focuses on the characterization of the outcrop fractures, interprets the fracturing mechanisms that produced them and identifies the factors that may have influenced their distributions and patterns. The methodology integrates field data from fracture characterization within outcrops with structural analysis of the near-surface horizons.

Possible causes for the development of these fractures include: 1) the tangential stress associated with folding growth of strata in response to active deep seated salt diapirism, 2) remote compressional stress associated with Zagros uplift, 3) stress induced by development or
reactivation of local structures, and 4) a combination of these previous mechanisms. The study also discusses potential implications of the study results on development of the deep hydrocarbon reservoirs of the Dammam Dome.
1. GEOLOGIC BACKGROUND

1.1. Introduction

The Dammam Dome is located in the Eastern Province of Saudi Arabia (Fig.1, a). The cities of Dammam and Khobar are located on the Dome’s gentle sloped flanks toward the western shoreline of the Arabian Gulf. The Dhahran area is located on the Dome’s central region, which includes Saudi Aramco headquarters and King Fahd University of Petroleum and Minerals (KFUPM). At the Earth’s surface, the Dammam Dome is expressed as oval-shaped, relatively high topography extending about 9 miles along its major northwest-southeast axis, which trends N30-40°W, and covering an area of approximately 60 square miles (Tleel, 1973). From the subsurface, the geometry of horizons appears to be less elliptical (more circular) with a relative north-south trending elongation. The field study area includes well-exposed outcrops within the limits of the rimrock formed by the Eocene beds mapped by Tleel (1973) (Fig.1, b).

The discovery of the Dammam Dome was a historical event as the first hydrocarbon field discovered within the Arabian mainland. In this dome, on March 1938, Standard Oil of California (SOCAL, later was joined by other companies and named Aramco) found economic oil from drilling the Dammam 7 Well. Details on the discovery of the Dammam Dome can be found in several resources, such as Wallace Stegner’s book “Discovery! The Search for Arabian Oil)” and many Aramco reports. The credit for the discovery of the Dome goes to the SOCAL geologists who were, then, motivated by the discovery of oil in the Bahraini Awali dome. SOCAL secured a concession with the Saudi government in early 1930s, and geologists began to explore the hills along the western shoreline of the Arabian Gulf. By 1934, the field mapping of S. B.
Henry and J. W. Hoover and their team on a geological structure that they had named the Dammam Dome was completed, and drilling exploratory wells followed their recommendations. The failure of finding economic oil within the Cretaceous stratigraphical traps, that were found to be oil-bearing rocks in Bahrain, Iraq and Iran, had almost doomed the continuity of the exploration program. But the company made a critical shift in the drilling program in response to geologists’ insistence to drill wells into deeper horizons. The deep drilling that penetrated the Jurassic strata established the roots of SCOCAL in the Arabian Desert. We currently realize that the Paleozoic and Jurassic petroleum systems of the Arabian Peninsula form two of the most prolific petroleum-producing systems in the world (Pollastro, 2000).
Figure 1: (a) Map of Arabian Peninsula with location of the Dammam Dome (red square), and (b) the geological map of the Dammam Dome outcrops, from Weijermars (1998) and after Tleel (1973).
1.2. Regional Geology

In Charles Doughty’s words: “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” (Travels in Arabia Deserta, 1880). Despite the conspicuous simplicity of this historical statement compared to today’s unraveled complex tectonostratigraphy, it still encapsulates the two main geological provinces of the Arabian Peninsula: the Arabian Shield and the Arabian Shelf (Fig. 1, a). Both provinces are tectonically part of the Arabian plate, one of the youngest Earth’s lithospheric plates, which began to separate from Africa by the Red Sea rifting 25-30 million years ago (e.g. Johnson, 1998). The Arabian shield was together accreted with the Nubian Shield in northeastern Africa and consists of crystalline Precambrian basement that rocks range in age from about 950 to 550 million years (e.g. Vail, 1985). These basement rocks are exposed in the western third of the Arabian Peninsula and locally in Oman, and are overlain by the Phanerozoic sedimentary rocks of the Arabian Shelf in central and eastern Arabia (e.g. Johnson, 1998).

The Arabian Shelf includes a sequence of continental and marine sedimentary rocks that range in age from Cambrian to Pliocene and cover about two-third of Arabian Peninsula (e.g. Powers et al., 1966, Sharland et al, 2004). The long evolution history of the Phanerozoic successions in central and eastern Arabia was mainly controlled by the Precambrian basement architecture, salt diaprisms, plate movement, collision with the Eurasia, and rise and fall of sea level of the Tythes Ocean (e.g. Ziegler, 2001, Beydoun 1988, Alsharhan, 1997, 1986, Christian 1997, Kent, 1985, Ayres, 1982, Husseini, 1988, 1991).
The recent regional studies (e.g. Husseini, 2000, Ziegler, 2001) (Fig.2) have attributed the structures within the sedimentary section from Upper Permian to Holocene to the northerly, northwesterly and northeasterly trending fault systems emanating from the deep-seated Precambrian basement. The northerly trending structures were linked to the Amar Collision (640–620 Ma) of the Rayn Plate with the Arabian-Nubian shield, and the ensuing Najd Rift (570–530 Ma) (Husseini, 2000). Examples of the well-known northerly structural trends are the Summan Platform and En-Nala Anticline of Ghawar and Safaniya; the world largest on-shore and off-shore hydrocarbon fields, respectively. The northwesterly set of structures is represented by the Najd Faults in the Arabian Shield. The northeasterly trending set includes the Dibba Fault and the Wadi al Batin lineament, and appears to control the distribution of Infra-Cambrian salt basins of the Arabian Gulf and Oman (e.g. Husseini & Husseini, 1990; Loosveld et al., 1996, Husseini, 2000). Large hydrocarbon fields in Saudi Arabia are low-relief compressional basement-cored uplifts, typically bounded by a steep frontal fault and in some cases a backthrust (e.g. Xiao et al. 2002 from Johnson 2008). Johnson (2008) reported that interpreted seismic images for the deep pre-Khuff formation geometries indicate that the origin of some structures involves multiple shortening episodes. The shortening occurred during several Phanerozoic compressional or transpressional events, including the structural uplifts coinciding in time with the Hercynian orogeny. The observation of contractional structural relief (due to reverse faults) within seismic images on the margins of the structures is the strongest evidence for regional contraction. In general, anticlinal structures of the major Saudi Arabian oil fields seem to follow the northerly and northeasterly trends. The structural styles of these fields are believed to be developed as drape folds over rejuvenated basement uplifts, with important exceptions to this generalization including the Dammam Dome (e.g. Ayers, 1982, Edgell, 1991) (Fig. 3).
Figure 2: Structural interpretation of the Arabian Plate as it relates to the distribution of the Late Permian to Holocene paleofacies (modified after Zeigler, 2001)
1.3. Origin of the Dammam Dome

The structural domes of Dammam in Saudi Arabia and Awali in Bahrain are attributed to salt diapirism in the subsurface (Edgell, 1991). The deep-seated salt intrusion below the Dammam Dome was first interpreted on the basis of the structure geometry and the strong negative gravity anomaly coinciding with the outlines of the Dome (Powers et al., 1966). Furthermore, a great part of the eastern part of the Phanerozoic sequence of the Arabian Plate is underlain by the Eocambrian Hormuz Salt (Beydoun, 1991), Fig. 3. The Hormuz salt series and their equivalents deposited in a broad network of subsiding basins stretching from the Arabian peninsula, through Iran, Afghanistan, Pakistan and India (Player 1969; Falcon, 1967; Stocklin, 1968; Gorin et al., 1982, Talbot and Alavi, 1996; Edgell, 1996; Husseini, 2000; Konert et al., 2001; Jeroen et al., 2003).

Approximately 160 Hormuz salt diapirs have extruded in the Zagros Mountains and their foreland, and about 20 of the islands in the Southern Gulf owe their existence to the Hormuz salt (Player, 1969; Kent, 1958, 1979, 1987; Edgell, 1996; Talbot 1998; Bahroud 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). The Hormuz salt is believed to be absent along north-south-trending Arabian arches, inherited from Panafriacan structures such as the Qatar Arch which extend to the North up to the Fars domain in the Zagros and Deyzful embayment region (Barhoudi and Koyi, 2003; Letouzey and Sherkati, 2004).

The timing of salt emplacement and structural growth of the Dammam Dome is beyond the scope of this study. However, the dome uplift during Tertiary is relevant to the investigation
of the folding-associated tangential stress in fracturing the exposed carbonate layers. Weijermars (1998) interpreted that the tectonic style of the Dammam and Bahrain areas is dominated by vertical rather than lateral displacement (Weijermars, 1998). The episodic growth of the Dammam Dome during most of the Cenozoic was estimated at rates of 7 to 7.5 m/My from the unit thickness and unconformity time gap at the apex of the dome at Jebel Umm-ar-Rus (Weijermars, 1998).

Figure 3: Geologic traverse (A-B) shows the sedimentary successions of the Arabian Shelf through Saudi Arabia to Qatar (modified after Konert, 2001). For location of section, see index map.
1.4. Stratigraphy of the Dammam Dome Outcrops

The Dammam Dome and its surrounding region near the western shoreline of the Arabian Gulf have the complete sedimentary succession of the Arabian shelf (Fig.3). The Dome was one of the first structures to be mapped in the region, following the beginning of oil exploration. Consequently, its locality name “Dammam” was given to one of the Tertiary classified carbonate formations in Saudi Arabia and was adopted for its equivalents in some other Gulf States.

The exposed units within the area of the Dammam Dome range in age from the Paleocene-early Eocene to Middle Miocene (e.g. Steineke et al., 1958, Powers et al., 1966, Tleel 1973, Roger 1985, Weijermars, R. 1998). The Paleocene to Early Eocene Umm ar-Radhumah (UER) formation is the lowermost Tertiary formation. The name of the formation was given by S. B. Henry and C. W. Brown in 1935 (unpub. Aramco report) and driven from Umm Radmah wells (lat. 28°41'N, long. 44°41'E), which produce water from the upper part of this formation (Tleel, 1973). Although the UER was not encountered during the fieldwork of this study, previous work reported two small outcrops of the formation within the central region of the Dammam Dome. In one outcrop, the UER Formation was described as a 3m thick section of vuggy dolomite located about 488m east of Jabel Umm ar-Rus in a topographically low area along the core of a small anticline (Tleel, 1973). The other outcrop is located within the KFUPM campus and was reported to be part of the upper UER from its distinctive lithology (Weijermars, 1998). The regional stratigraphical sequence above the UER formation includes the Rus, Dammam, Hadrukh, and Dam Formations (Fig. 4). All these Formations are present within the Dammam Dome region except the Neogene clastic formation of Hadrukh, which was reported to border the Dammam Dome rimrock.
This study focuses on the carbonate succession, especially Rus formation and its subdivisions, as it dominates the surface exposures of the Dammam Dome. Within the sequence of the Dammam Dome rocks, two unconformities were documented in previous works at different locations; at Jebel Umm-Er-Rus where the pre-Neogene angular unconformity underlies the Middle Miocene Dam Formation, and at Jebel Midra al-Janubi where Dam Formation is lying unconformably on top of Midra Shales of the Dammam Formation (e.g. Tleel, 1973), Fig. 5. The unconformity at Jebel Midra was documented to be poorly recognizable from the Jabel surface, but a new road cut into the base of the Jabel has facilitated recognition of the unconformity during the course of this fieldwork, Fig. 5.

The Rus Formation was dated to Eocene and named after its type section at Jabel Umm ar-Rus, meaning the mountain with peaks in Arabic, near the Dome central region. The type section was referred to as the "Chalky Zone" when was first established by S. B. Henry and J. W. Hoover in 1934. However, R. A. Bramkamp, in 1946, applied the name "Rus Formation" as a replacement for the term "Chalky Zone," which had been used to describe the interval between the underlying UER and the overlying Dammam Formation above (Tleel, 1973 from unpublished Aramco reports).

Tleel (1973) reported that Thralls and Hasson (1956) was the first to publish the term "Rus Formation" in their proposed units, but detailed information on the type sequence was published by Steineke et al (1958), and followed by additional stratigraphic and paleontologic data in Sanders' (1962) discussion.

Powers et al. (1966) divided the Rus Formation into three lithologic units and noted that diagnostic fossils have not been recognized in the Rus Formation. The Formation is underlain
and overlain by rocks of early Eocene age, therefore, it is presumed to be entirely early Eocene (Ypresian). The type section of Rus Formation was re-described by Tleel (1973) and divided into three informal zones selected strictly for mapping convenience and do not correspond to Power (1966) distinctions. Table (1) summarizes the different subdivisions of Rus Formation from various studies. In this study, the stratigraphic subdivisions of Tleel (1973) are employed, but with preference of using the terms: lower, middle and upper for the three units.

Table 1: Subdivisions of the Rus Formation from different authors (from Weijermars, 1998).
This study adopts the subdivisions of Weijermars (1998).

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<tr>
<td>Upper Rus Formation</td>
<td>Chalky Zone (25 m)</td>
<td>Chalky Zone (25 m)</td>
<td>Unit 3 Chalky Zone (3.6 m)</td>
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<tr>
<td>Middle Rus Formation</td>
<td>Jointed Limestone (10 m)</td>
<td>Zone of Calcite Geods (10 m)</td>
<td>Unit 2 (31.8 m)</td>
<td>Rus Formation</td>
<td>Chalky Zone</td>
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<tr>
<td>Lower Rus Formation</td>
<td>Marls (21 m)</td>
<td>Lower Rus Formation</td>
<td>Unit 1 (21 m)</td>
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The Dammam Formation was named by Bramkamp in reference to its type locality in the rim-rock of the Dammam Dome (unpub. Aramco reports, 1941 & 1964, Powers, 1966, Tleel, 1973). The formation is subdivided into five members; from oldest to youngest: Midra Shale,
Saila Shale, Alveolina Limestone, Khobar (dolomite and marl) and Alat (limestone and marl), see Fig. 4. The lower four members of the Formation are also exposed in the Dome core area at a small ridge near Aramco’s hospital (Weijermars, 1998). The Midra shale at the base of the Formation was deposited conformably on the Upper Rus Formation followed by the deposition of 0.6m limestone and then Saila shale. The upper three members, the Alat, Khobar, and Alveolina Limestone, are of Middle Eocene (Lutetian) age based on the fossil evidence (Powers et al. 1966). The presence of "Nummulites globulus" below the Alveolina Member indicates that the rest of the formation is early Eocene (Ypresian) (Tleel, 1973).

The Dam Formation is the uppermost formation in the carbonate succession deposited by the last marine transgression to cover the Dammam Dome area (Tleel, 1973). The type locality of the lower part of the Dam Formation is at Jebel Al-Lidam which is located at (lat. 26° 21'42"N, long. 49°27'42"E); about 50 km west of Jebel Umm ar-Rus and outside the Dome area (Tleel, 1973). The Dam unconformably overlies the Rus Formation at Jabal Umm ar-Rus, and the basal members of the Dammam Formation at both Jabal Midra al-Janubi and Jabal Midra ash-Shamali. The Formation was also found at two other localities nearby Jabal Midra ash-Shamali; see Tleel (1973). The Dam rocks probably range from Upper Burdigalian to Neogene (Kier, 1972), therefore, the unconformity between the Dam and the Dammam Formation corresponds to a time gap of some 22 Ma, extending from the end of the Ypresian (43.8 Ma) until the onset of the Burdigalian (21.8 Ma) (Weijermars, 1998). But as Weijermars (1998) noted, the hiatus should represent a slightly shorter time gap outside the Dammam Dome area, because of the presence, below Dam rocks, of the Aquitanian Hadrukh Formation for which deposition started some 23.7 Ma.
1.5. Structures within the Dome Outcrops

The local exposed geological features noted in Tleel’s paper (1973) included slumps, local steeply dipping anticlines and synclines. However, these structural features were mentioned without geological mapping nor geographic references, except for a syncline referenced at lat. 26°19’23”N, long. 50°06’37” E, and slumping at lat. 26°18’34” N, long. 50°08’16”E. No faults were noted at the surface, but Tleel (1973) did not rule out subsurface faults. In a recent technical report, Hariri (2004) brought attention to the surface fractures by delineating large fracture lineaments from satellite images and hypothesizing their development to the dome geometry. This work, however, lacks field observations from the large area of the outcrops located within the border of Saudi Aramco campus.
Figure 4: The Cenozoic stratigraphic column of eastern Arabian sedimentary basin, b) stratigraphic column of the Dammam Dome outcrops with the Middle Rus is highlighted by a red rectangular (from Weijermars, 1998, and after Powers, 1969, Tleel, 1973). Pictures are from my fieldwork.

Figure 5: Two photos of Dam Formation; at Jabel Umm ar-Rus (left) and at Jabel Midra Al-Janubi (right); arrows in both photos point to the unconformities discussed in the text.
CHAPTER

2. FRACTURE DEVELOPMENT ON FOLDS

2.1. Introduction

Fractures formed in association with folds may be the result of the regional stress field or the local stress associated with layer folding (e.g. Cosgrove & Ameen, 2000). Fractures may initiate when stress concentrates at a flaw, or near a crack tip then they systematically propagate perpendicular to the directions of local greatest tensile effective stress (e.g. Bergbauer & Pollard, 2004). If fractures result from local stresses associated with layer folding, they may be investigated from fold curvatures. The use of curvature in geological studies is inferred from the concept of bending theory; where the plate (e.g. rock layer) experiences longitudinal stretching at the outer arc and shortening at the inner arc, and a neutral unstrained surface separating the outer-extended and inner-contracted part, Fig.6. The tangential stress at the top of the rock layer causes strain, which can result in a fracture (e.g. Murray, 1968). The curvature properties can be also studied to infer fracture orientations from the shape of fold (e.g. Stearns and Friedman, 1972). The following two sections (2.2. & 2.3.) provide the concepts of the relationship between fold and fractures, as well as the geomechanical factors that may control (or influence) fracture development.

2.2. Conceptual Models

Conceptual models of fold-fracture relationships were formulated by the pioneering work of Stearns (Stearns, 1964, Stearns and Friedman, 1972) and later improved by others (e.g. Price and Cosgrove, 1990, Cooper, 2000, Mynatt et al, 2009). These models propose mechanical relationships between fractures and stress distributions associated with the folding process,
drawing on the principles of fracture mechanics (e.g. Griffith, 1924) and the results from rock tests (e.g. Griggs and Handin, 1960) that extension fractures form perpendicular to the least compressive stress ($\sigma_3$), splitting fractures form parallel to the greatest compressive stress ($\sigma_1$), and shear fractures form parallel to the intermediate principal stress ($\sigma_2$) and oblique to the greatest compressive stress (Fig. 7, a).

In Stearn’s model, five major fracture patterns are associated with folds (Stearns, 1968), but the model displays only two patterns found to be common enough to warrant consideration (Stearns and Friedman, 1972, Fig. 7, b, c). The model suggests that fracture sets result from folding because of their consistent orientation with respect to bending and anticlinal structure. The first pattern consists of two conjugate shear fractures and an extension fracture, which indicate that the intermediate principal stress axis ($\sigma_2$) is normal to bedding, the greatest principal stress and least principal stress axes ($\sigma_1$, $\sigma_3$) are in the plane of bedding, and $\sigma_1$ in the dip direction. The second pattern also consists of two conjugate fractures and an extension fracture, thus indicating that $\sigma_2$ is still normal to bedding and $\sigma_1$ and $\sigma_3$ are still in the bedding plane, but $\sigma_1$ is parallel with strike and $\sigma_3$ is the dip direction. Accordingly, the major joints usually cut the fold axis at 90 degrees and are also perpendicular to bedding, so that they are usually vertical or steeply dipping features. When the fold crest is well rounded such joints form a fan pattern (Price and Cosgrove, 1990). Stearns and Friedman (1972) noted that the shear fractures of these two patterns rarely show visible offset, but designated as a shear or an extension type solely on the basis of the geometry of assemblage.

The pattern of tensile fractures (joints) in Stearn’s model can be investigated from curvature computations on fold surface. The fold surfaces may be idealized either by continuous functions (e.g. Cooke et al, 2000), or by samples at points on irregular grids (e.g. Mynatt et al,
2006), see example in Fig.8. As tensile fractures open parallel to the direction of greatest instantaneous stretch, they may strike parallel to the direction of local minimum curvature and perpendicular to the maximum principal stress (Fischer et al, 2000). The directions of both minimum and maximum curvatures may account for the orthogonal sets of tensile fractures associated with a dome-shaped fold (Ozkaya, 2002).
Figure 6: A diagram for a single folded layer. Due to folding, the original length of the layer, left, is stretched at the top ($L_1$) and contracted and the bottom ($L_2$), right. The curvature is the inverse of the radius, $R$. (modified from Fossen, 2010, p. 31).

Figure 7: a) fracture-stress relationship based on laboratory rock testing of cylindrical samples (from Griggs and Handin (1960), b) Conceptual model of Stearns (1968), in which fracture sets are assumed to form symmetrically to fold axis (from Bergbauer & Pollard, 2004), c) Conceptual model of Stearns (1968) for spatial relationship between fractures and fold (from Price & Cosgrove, 1990).

Figure 8: The magnitudes (color) and vectors of minimum curvature, $K_{\min}$ (left), and maximum curvature, $K_{\max}$ (right) computed on a folded surface, trends of $K_{\min}$ are perpendicular to maximum stretching, hence, commonly used to predict tensile fracture trends. (Matlab code from Mynatt et al., 2007)
2.3. Shortcomings of Early Conceptual Models

The Stearn’s conceptual model (Fig. 7.c) had been widely used in the petroleum industry (Cooper et al. 2006), but several authors (e.g. Bellahsen et al. 2006, Shakleton et al. 2011) addressed major shortcomings on the validity of the direct use of these concepts to interpret the genesis of fractures within folded strata. These shortcomings can be considered major improvements in our understanding of the relationship between fold and fractures. The shortcomings are summarized as follows:

1) The fractures described in these models are correlated with the fold geometry at present and without considering the history of folding. The effects of the initial and transitional fold shapes on fracture development especially during lateral fold movement are not considered in the Stearn’s model (Fischer and Wilkerson, 2000, Savage et al, 2010).

2) The Stearn’s model also does not account for the joints produced by bedding slip (Cooke et al, 2000).

3) The conceptual models do not also consider the role of fractures that predate folding (e.g. Guiton et al., 2003a,b, Bergbauer and Pollard, 2004). It does not also account for reactivation of pre-folding fractures that could disturb stress fields and subsequent fracture formation and orientation (e.g. Sanz et al, 2008).

4) The models disregard the role of localized strain controlled by development or re-activation of faults, which are often associated with fold formation (e.g. Johnson and Johnson, 2002; Savage and Cooke, 2004). The development of
faults perturbs the surrounding stress field that can affect fracture formation within their influence zone (e.g. Hafner, 1951; Lajtai, 1969; Couples, 1977; Segall and Pollard, 1980; Pollard and Segall, 1987; Rawnsley et al., 1992, Fig. 9; Reches and Lockner, 1994; Cooke, 1997; Homberg et al., 1997; Martel and Boger, 1998; Kattenhorn et al., 2000; Bourne and Willemse, 2001; Maerten et al., 2002; Bellahsen et al 2006; Savage et al, 2010).

2.4. Role of Mechanical Stratigraphy

Several studies demonstrate relationships between fracture and mechanical stratigraphy; where bed interface properties control fracture termination and mechanical unit thickness controls fracture density (e.g. Narr and Suppe, 1991, Gross, 1993, Engelder et al., 1997, McQuillan 1973, Ladeira and Price, 1981; Cooke, 1997, Cooke & Underwood, 2001, Lorenz et al, 2002, Rijken & Cooke, 2001, Underwood et al, 2003, Cooke et al, 2006, Lezin et al, 2009, see Fig. 10). Mechanical stratigraphy subdivides stratified rock into discrete mechanical units defined by properties (e.g. tensile strength) that reflect rock composition and structure, as well as chemical and mechanical changes that the rock bed and bed interface undergone after deposition (e.g. Lauback et al, 2009).

The linear relationship between spacings of joints and layer thickness was theoretically first explained by Hobbs (1967), who introduced the shear-lag model of Cox (1952), and implied that joint spacings are influenced by the elastic properties of each bed. The 1D model of Hobbs consists of three discrete beds: two bounding beds and a middle bed. The two bounding beds are assumed to have the same elastic moduli and much greater thickness than the middle one. When the tensile stress applied to the three discrete beds, the three beds remain unjointed, but as extensional strain increases, a joint propagates within the middle bed after stress exceeds its
elastic strength. The stress, however, drops to zero at the surface of the developed joint and the joint surface forms a barrier to the transmission of tensile stress. The stress distribution ranges from zero at the joint surface to an equivalent value to the remote stress at an infinite point away from the joint. The development of a joint relieves the stress along the joint sides, but stress concentrates in the region between joints and new joints nucleate and infill where stress can overcome local tensile strength of the bed.

From the field, (Gross et al., 1995) reported that in a succession of different rock types with thin beds (e.g. beds ranging in thickness from about 1 to 100cm), the product of fracture density and bed thickness is approximately 1.0, so that, the thicker mechanical units have more widely spaced fractures (less fracture density) than do thinner units. Experimentally, Bai and Pollard (2000) used the finite element method to investigate the stress distribution between two adjacent fractures as a function of the fracture spacings to layer thickness ratio using a three-layer elastic model with a fractured central layer. The results show that when the fracture spacing to layer thickness ratio exceeds a critical value, the normal stress acting perpendicular to the fractures changes from tensile to compressive in the center between the fractures. Bai and Pollard (2000) concluded that this stress state transition precludes further infilling of new fractures unless either existing flaws are present or the fractures are driven by an internal fluid pressure.
Figure 9: Free surface model show that joint pattern can be perturbed in the fault vicinity; see (Rawnsley, 1992)

Figure 10: An illustration of joints confined to mechanical layers. Mechanical layer boundaries defined by lithologic contacts (lithology-controlled) (from Gross, 1993).
CHAPTER

3. METHODS

3.1. Geological Fieldwork

Google Maps, aerial photographs and a GIS application (ArcGIS) were used to outline well-exposed outcrops within the Dammam Dome area. The map of outcrops was then superimposed on the geological map of Tleel (1973) to display the locations of outcrops and the boundary of different stratigraphical units (Fig. 11). In the field, exposed units were recognized from rock types and stratigraphical positions reported in previous studies (e.g. Tleel, 1973), and from the presence of distinctive lithological markers and unconformity surfaces.

Data sets on fractures, other structural elements (e.g. karst) and stratigraphy were collected within the mapped outcrop areas (Fig. 11). Field data sets include fracture characterization, measurements of fracture orientations, and fracture spacings from the top surface of the Middle Rus carbonate unit. Fracture characterization included notes on fracture abutting relationships and dominant patterns. Lithology was also noted at every site and inclinations of host beds were collected for some exposed units. Field investigation also encompasses data sets on the karst features found within the outcrops. The fieldwork also included detailed mapping of fractures within small square areas, as well as rock rigidity measurements, see the following sections (3.1.1. & 3.1.2.).

Images from Google Maps are used to interpret fractures from the visible vegetation that linearly developed along their apertures. This practice is ground-truthed from field observations. The Google Maps are found to be valuable for interpreting large fractures and measuring their spacing for areas beyond the maps of small square areas.
3.1.1. Detailed Fracture Maps (10m*10m)

Some areas were selected to map fractures from the top of flat outcrops of the Middle Rus unit. The mapping method is motivated by the need to characterize fracture orientations, density and crosscutting relationships from small areas that represent the outcrop fractures. The method is different from the 1D scan-line survey, which is sometimes used on beds with various thicknesses to assess the control exerted by bedding on fracture characteristics (e.g. Ortega et al., 2006) and sometimes perpendicularly oriented to the most frequent fracture set to obtain fracture density (e.g. Agosta, F., 2010). In this study, the method is rather a detailed mapping for selected areas on the top surface of flat outcrops. The typical setup to map these areas can be outlined in the following:

- Finding localities on flat exposures and reasonably far from cliffs to exclude or limit number of slump induced fractures.
- Defining the boundary of a rectangular area on the ground (10m by 10m), oriented to the north with the help of a compass and a measurement tape.
- Ensuring that these areas capture the maximum number of the large fractures as their spacing exceeds 3m; therefore 2 to 3 fractures can be sampled within the map.
- Marking the corner of the rectangular area using outstanding small blocks, e.g. large stones or cones (Fig.12). The mapped area has typically 9 reference blocks on the ground besides the ease of use reference from large fractures.
- Using a gridded scaled paper.
- Sketching all fractures larger than 30cm and making larger fractures in bold lines.
The maps display all fractures that are not possibly interpreted from aerial photographs. Orientation and spacing are shown within these maps and incorporated with Google Maps for larger areas to provide insights into systematic variations in fracture orientations and spacing from outcrop to another within the north and northwestern parts of the Dammam Dome area.
Figure 11: Map of well-exposed rocks, see legend and the map of the Dammam Dome (at right). Numbers refer to field stations.

Figure 12: Procedures of the detailed mapping on (10*10m) areas, a) photo shows the setup of ground marks (dashed lines are drawn to show the mapped area), b) figure to show one example of maps: from left to right; figure of scaled gridded paper (10*10cm), a scanned figure of actual hand-drawn map with interpretation, edited version to display joint sets (colored) and sand cover on outcrop surface (details in the text).
3.1.1. Rock Rigidity Data

The Schmidt hammer is used to collect rigidity measurements from the exposed units to estimate the rock elastic properties (e.g. Young’s Modulus). The Schmidt hammer has been used in rock mechanics since the early 1960s, mainly for estimating the uniaxial compressive strength (UCS) and Young’s modulus (E) of rock materials (Aydin, 2008). The device consists of a spring-loaded piston, which is released when the plunger is pressed against a surface, Fig. 13. The impact of the piston onto the plunger transfers the energy to the rock. The extent to which this energy is recovered depends on the hardness (or impact penetration/damage resistance) of the rock (Aydin, 2008). The rock hardness/rigidity is expressed as a percentage of the maximum stretched length of the key spring before the release of the piston to its length after the rebound.

Several rigidity measurements are collected for the Middle Rus unit at different locations. The Young’s Modulus (E) for the rock is calculated from an average rigidity value and the following empirical formula from Katz at al (2000):

\[
E = 0.00013 R_{\text{corrected}}^{3.09074},
\]

where \( R_{\text{corrected}} \) is the corrected rigidity reading of Schmidt rebound hammer.

The rock rigidity readings are obtained using N-type Schmidt hammer following the suggested procedure of Aydin A, (2008). Every rebound hardness data is an average of 10 tests obtained from one location, at which the hammer is positioned vertically (+90) to the flat exposed rock. Rock surfaces are fractured and host some scattered vugs, but test points are collected from the solid parts of rocks and away from the boundaries to avoid abnormally low values due to strong dissipation of impact energy.
Figure 13: Working principle of a Schmidt hammer (Aydin, 2008)
3.2. Curvature-Based Methods

This study uses three methods based on the concept of flexure and its relation to fiber stresses to assess the role of folding in fracture development within the outcrops of the Dammam Dome.

3.2.1. Curvature Analysis of 1D Fold Model

The analysis of using 1D curvature of a folded rock layer is applied to evaluate if folding-associated tangential stress is potentially high (e.g. exceeds the tensile strength) to produce fracture within the layer. The calculated tangential stress can be evaluated against the tensile strength of the rock type obtained from laboratory rock mechanical tests. The stress resembles that of a bending beam, and can be calculated from the folded layer curvature, thickness and estimated elastic modulus of its rock type. The stress is obtained on the basis of the stress-strain relationship of elastic materials (e.g. rocks). As the folding process stretches the top of a rock layer to a greater length (L₁) than the original length (L₀), the folding associated longitudinal strain, e, at the top of the layer can be expressed as follows (see e.g. Price & Cosgrove 1990, p 190, Roberts, 2001, Turcotte & Schubert, 2002, Hunt et al, 2011):

\[ e = \frac{L_1 - L_0}{L_0} \quad (1) \]

\[ e = \frac{h/2}{R} = \frac{h/2}{(h/2) * K} \quad (2) \]

where (h) is the layer thickness, (R) is the local radius of curvature of the folded layer, and (K) represents the curvature. The curvature (K) is mathematically related to the radius (R) of an osculating circle as \( R = 1/K \) (e.g. Gray, 1997). The 1D strain (e) in (1) can be related to stress using Hooke’s law of elasticity:
\[ \sigma = E^* e = E \ast (h/2) \ast K \]  

(3)

where \((E)\) is Young’s modulus.

This study used the above formula (3), with the Young’s Modulus \((E)\) estimated for the Middle Rus layer, and overall curvature \((K)\) of the Dammam Dome. The Young’s Modulus is obtained from the analysis of field measurements of the Schmidt hammer. The 1D curvature is based on the current geometry of the near-surface units of the Dammam Dome. The geometry of the Dome could be inferred from the Tleel’s field-based maps and cross sections; however, better accuracy was obtained from using the top surface of PAMU, which is a near-surface strong seismic reflection horizon. The top surface of PAMU is mapped and gridded from both 3D reflection seismic and well logging data. The use of such a near-surface horizon could serve the objective of finding more accurate geometry for the overall Dome than relying on the field mapping of Tleel (1973). To get curvature of 1D fold model, one cross section that may represent the overall bending of a pericline structure is obtained from a perpendicular direction to its major axis. In this scenario, it is parallel to the general maximum shortening and show the maximum curvature of folded layers.

To account for the potential presence of fluid in rock pores, the effective stress \((\sigma_{ij}^*)\) is also considered in the analysis of stress intensity. The presence of pore fluid reduces the total stress components \((\sigma_{ij})\) by an amount equal to the pore fluid pressure \((p_p)\):

\[ \sigma_{ij}^* = \sigma_{ij} - \alpha P_p \]

where \((\alpha)\) is the Boit-Willis poroelastic term, which is defined as \((1-K/K_s)\), where \(1/K\) is the overall compressibility of the rock mass, and \(1/K_s\) is the compressibility of skeletal material. In saturated rocks, total stresses can be divided into two types: 1) the total normal and tangential
stresses generated by rock matrix (e.g. grains), and 2) the stress developed due to fluid pressure within pore spaces between the rock matrix. In general, the presence of pore fluid reduces the strength of the rock, and hence, enhances the tensile fracturing process. The shear stresses are not affected by presence of pore pressure (Mandl, 2005). Cracks (e.g. natural hydraulic fractures) may initiate and propagate due to increase in internal pore pressure that overcomes the total principal stress. Example of such case is the subvertical joints in sedimentary layers (e.g. Ithaca Shale) that developed due to high pore pressure exceeds the total least principal stress (σ3) and the elastic properties of rocks (Lacazette & Engelder, 1992). The least principal stress is horizontal (e.g. normal to joints) when joints develop vertically in sedimentary strata. However, the total horizontal stress (σh) is difficult to be determined, except from its proportional relation to the total vertical stress (σv) in relaxed tectonic regimes (e.g. regions without tectonic stress):

\[ \sigma_h = \frac{v}{1-v} \sigma_v \]

where v is Poisson’s ratio, and the total vertical stress (σv) can be determined from integrated density (d) of the overburden, and the acceleration of gravity (g) at depth of interest (z):

\[ \sigma_v = d*g*z \]

3.2.2. Fracture Trends from 3D Structural Restorations

The geological restoration process is one of the existing techniques for obtaining a consistent interpreted geological section from seismic or well data (e.g. de Sant et al, 2002). It is commonly used in oil industry to validate the interpretation of subsurface structures and quantify for deformation (extension/shortening), to reduce the risks of geological models used for reservoir exploration and development.
This study utilizes a volumetric restoration techniques performed on gOcad (e.g., Muron et al., 2005; Mueller et al., 2005), to build a tetrahedral-meshed model for the Dammam Dome based on the interpretation of subsurface data. The deformations within a formation are typically restored to an assumed datum, which accounts for original flat shape at the time of the deposition. The model is considered as an incompressible material (or formation) and each particle (or node) of this material is displaced during the restoration to the position at deposition time (e.g. Mallet, 2002). The restoration process allows computing a restoration vector at each node of the tetrahedral meshes. The amount of volume change at each node can be determined to analyze strain components.

The structural restorations are applied to a full model includes all mapped shallow and deep horizons of the Dammam Dome, Fig. 14. This study is focused on the strain inferred from the development of fold and fault structures within the shallow section, Fig. 15, 16. The shallow section is divided into two meshed units: the upper unit (ARUM) and the lower faulted unit (PAMU), following the naming conventions of Saudi Aramco. The shallow section does not include the interval between the upper unit (ARUM) and the Middle Rus for the lack of accurate structure map from the Earth’s surface. Interpretation of the 3D seismic data indicates that ARUM unit is not faulted. At central region of the Dome, the top surface of ARUM is about -170ft true vertical depth sub-sea (TVDSS). But faults are observed from reflection seismic data within the PAMU. The PAMU is the lower unit of the shallow section and its top surface is about -500ft (TVDSS) at the central region.

The strain is typically computed in three dimensions, but can be projected on map views to display vectors for the maximum directions of horizontal stretching and contraction. As restoration technique is reversal to the structure evolution, the directions of maximum
contraction vectors in restoration models resemble that of stretching in forward sense. Thus, the directions perpendicular to the maximum contraction in the restored model can be presented as potential directions for tensile fractures (Fig.16).

3.2.3. Fracture Trends from Typical Dome

For prediction of tensile fracture trends on top of folded strata, the 2D curvature-based stress analysis is performed on idealized dome. The analysis used a mathematical softwater (e.g. Maple) to compute for in-plane stress field \((x, y)\) along the top of a 3D bending layer using a given deflection function \((w)\), (e.g. Turcotte & Schubert, 2002, & Cooke at al, 2000):

\[
w := (x, y) \rightarrow amp \left( 1 - \tanh \left( \frac{4x^2}{hw^2} + \frac{4y^2}{hl^2} \right) \right)
\]

where, \(hw\), and \(hl\), are the width (along \(x\)) and length (along \(y\)) of the bending layer, respectively. The dimensions along \((x, y)\) describe a general oval shape resamples that of the Dammam Dome, while the amplitude is considered from PAMU, which describes the difference in structural height between the apex of the Dome and its boundary.

The analysis investigates in-plane stress components within the bended layer (with Young’s modulus \((\mu)\) of the Middle Rus and 0.25 for Poisson’s ratio \((\nu)\):

\[
sigxx := (x, y, z) \rightarrow -\frac{z \mu \left( \frac{\partial^2}{\partial x^2} w(x, y) + \nu \left( \frac{\partial^2}{\partial y^2} w(x, y) \right) \right)}{1 - \nu^2}
\]

\[
sigxy := (x, y, z) \rightarrow -\frac{z \mu \left( 1 - \nu \right) \left( \frac{\partial}{\partial y} \frac{\partial}{\partial x} w(x, y) \right)}{1 - \nu^2}
\]
As the fiber stresses (x-y) vary throughout the thickness of the layer, only tangential principal stresses \((\text{maxPrinc})\) at the top of the layer are considered:

\[
\text{maxPrinc} := (x, y, z) \rightarrow \frac{1}{2} \text{sigxx}(x, y, z) + \frac{1}{2} \text{sigyy}(x, y, z) + \sqrt{\frac{1}{4} (\text{sigxx}(x, y, z) - \text{sigyy}(x, y, z))^2 + \text{sigxy}(x, y, z)^2}
\]

The tensile fractures can be computed from directions perpendicular to the trends of principal maximum stress. The computed trends can be plotted on the map of the Dammam Dome and compared with observed fracture trends from outcrops.
Figure 14: A diagram shows the shallow section considered in this study. The 3D structural restoration is performed for the complete model. The figure is not to scale.

Figure 15: The lower unit (PAMU) of the shallow section of the Dammam Dome model; at left, the gOcad FEM model with current geometry (fold + faults), at right, the restored model. Vertical exaggeration: ×3.

Figure 16: The restored model in (Fig. 15) shows the vectors of the maximum shortening directions, which in forward sense resembles the maximum elongation (e1) in the inserted figure of strain ellipsoid. The vectors perpendicular to maximum horizontal stretching of the ARUM & the PAMU beds are computed as potential trends to form tensile fractures.
CHAPTER

4. FIELDWORK RESULTS

The Dome is partly covered by sand and dikakah (bush- and grass covered sand). This cover is predominant on the north and eastern flanks of the Dome. Tleel (1973) noted that the presence of sand, gravels and dikakah have reduced bedrock exposures. In addition, urban development that followed oil discovery may have reduced exposures in the southern areas of the Dome. Nevertheless, analysis of the 1958 aerial photographs indicates limited change in the outcropping landscape. With the exception of the KFUPM area, most areas of urban expansion were limited to flat and low relief areas. The outcrop study is concentrated on the areas of well-exposed rocks mapped in Fig. (11), in addition to some exposures studied from recent road cuts and trenches.

The most ubiquitous structural features of the Dammam Dome outcrops are the fractures. The fractures preferentially host vegetation, which brings attention to their presence on satellite images, as Hariri (2004) has previously noted. Most large fractures (with long lineaments) can be traced on Google maps and high-resolution aerial photographs from the well-aligned vegetation developed within their apertures. Typically, vegetation appears as dark lineaments in the light color of the Dome semi-barren surface. Other significant structural elements include scattered karst features, and a few small-scale reverse faults.

4.1 Fractures

Fractures are observed within all exposed carbonate units (Fig.11), but predominantly within the Middle Rus unit due to the vast exposures of this unit. Other units seem to display the same degree of fracture distribution, but their exposures are restricted to a few and small
outcrops over the large Dome area, Fig.1, & 11. The fractures are opening-mode fractures (or joints) that mostly form orthogonal sets, and display no evidence of shear, see Figures (17 through 20). This study focuses on the large-scale joint and dominant patterns. However, this study also reports the presence of three small-reverse faults within units younger than the Middle Rus unit. These reverse faults will be described in a separate section of this document. We also report the presence of other small fractures. Those fractures are mapped within detailed maps on the 10*10m areas, where indicated in black color lineaments (Fig. 21). These fractures are apparently resulted from local stresses induced by rock sliding due to weathering and/or karstification. This type of locally limited fractures are not likely to have significance as reservoir analogue, but should be delineated from the main systematic joints.

4.1.1. Fractures within the Middle Rus Outcrops

The exposed areas of the Middle Rus unit are enclosed in the dashed-line area in Figure 11. However, the unit outcrops are limited and mostly covered by Upper Rus unit in the vicinity of Jabal Umm ar-Rus and adjacent outcrops in the Dome eastern and northeastern region. This limited exposure prevented us from characterizing fracture trends and spacing on the center of the Dammam Dome. Where the unit is well exposed within the northern and northwestern regions, the joints are classified to two main systematic joint sets (J1 and J2), but a third joint set (J3) was observed in some limited localities, Fig. 17 & 21. The classification is based on the dominant trends of joints and their abutting relationships. The joint abutting relationship suggests that J1 is the primary (or older) joint set, hence, bound all other joints, including J2—the joint set that form well-developed orthogonal pattern in some locations, Figures (17 through 19). The orientation of the different joints measured from the field and from Google Maps is presented in rose diagrams in Figure (20). Fracture orientation data is listed in Appendix A.
The earliest through-going joint set (J1) has a dominant northwest trend (NW) and their lengths (as measured along bedding plane) are greater than outcrop extents, Fig. 18. On some outcrops, joint lengths exceed 300m. At field stations from 3 through 6, the J1 set can be traced for about 1000m from both field and Google Maps, Fig. 20. Joints can be missed in other areas when unit is weathered or covered by aeolian sands. The average trends of J1 set change slightly from exposure to another. For the series of exposures (stations 2, 3, 4, and 5) which span from central Dome region to its northwestern contact between Lower and Upper Rus, the compiled rose diagrams of J1 trends show a relatively systematic decrease in azimuth degrees toward more westerly trends, Fig.20. However, this apparent systematic deviation in J1 set trends is not present in other field stations.
Figure 17: Example of Joints (J1, J2 & J3) within the Middle Rus unit, NW indicates northwest trend of J1, a) a sketch for joints in (b), b) a photograph of the joints (notice the campus and person’s leg for scale). For spacing measured from these, see ST#5 in Fig. 21.

Figure 18: Other examples of joints from field stations # 2, see joints on Google Map.

Figure 19: The orthogonal joints of the Middle Rus unit.
Figure 20: Fracture trends (rose diagrams) from the Middle Rus outcrops. The numbers in the black squares refer to the field stations on the map, and the numbers on the lower corner of the rose diagrams are the number of measured fractures. The average of the primary northwestern trending joints is drawn as dashed brown lines on the outcrop map.
The spacings of the J1 set generally ranges from 3 to 7 meters apart with 6 meters being the most frequent measured distance (Fig. 21, 22). Field mapping suggests that the different spacings can be found on the same outcrop, but spacing generally increases from stations 3 to 5, see Fig. 21. This indicates that spacings are relatively larger in the stations closer to the northwestern flank of the Dome.

In the same areas within the Dome northern and northwestern regions, the second identified joint set (J2) is always bounded by J1 set and has a dominant northeast (NE) trend. The two sets, therefore, form orthogonal pattern in most mapped areas. Between these orthogonal joints, other small, mostly curvy, surficial cracks are abundant. These small joints are marked in black color in the detailed maps (Fig.21). Among these small joints is a third set (J3) with a northwest trend, but only occurs in a few places. The J3 set is parallel to J1 set and bounded by J2 set. In general, small curvy fractures are not systematic joints and seem limited to the upper surface of the Middle Rus unit.
Figure 21: Fracture maps (10m*10m) from the Middle Rus unit. Locations are indicated by numbers on the map.

Figure 22: Google Maps for some outcrops (Stations: 1, 2 & 4 and interpretation for the large joints traced from vegetation lineaments to measure spacing for J1 set. (See caption inside).
4.1.2. Fractures within Other Carbonate Units

Joints are observed within the units of Lower Rus, Upper Rus, Dammam and Dam. The Lower Rus unit occupies considerable area of the Dome central region, but only a few well-exposed areas are available to study fractures. Most of the Lower Rus outcrops are capped by the Middle Rus unit. The Lower Rus is only exposed along the sides of some of relatively high topography mesas. The best exposures of the Lower Rus are located at Station 6 and Station 16; refer to reference map in Figure 20. At Station 6, the J1 set are developed with radial pattern that will be described below in section (4.1.3.). At Station 16 (26° 18' 59"N, 50° 06' 45"E), the joints are developed with different spacings within the Middle and Lower Rus units. The different spacings are observed from two large outcrops, one is photographed in Figure 23. The difference in joint spacings is attributed to the different thickness and mechanical stratigraphy of the Middle and Lower Rus units. These field observations suggest that joints are controlled by bed mechanical properties. The observations of joint sets and their relations to mechanical units are summarized in a simple conceptual diagram, Fig. 24.

The Upper Rus strata are exposed from a road cut at Jabal Umm ar-Rus, however, the fractures are only observed in the carbonate units from the side exposure (or cross sectional view). This view has limited the ability to measure fracture orientations and observe fracture types (tensile or shear) and their abutting relationships.

The Dammam Formation is present in two outcrops: one at the central area of the Dome and the other at the further western boundary of the Dome. Fractures are observed within the outcrop at the dome central region, but missing from the outcrop at the dome western flank, giving a hint for the role of structural growth on joint development. Fractures of
the outcrop at the Dome central region, (at the Station 12, at 26° 18' 41"N, 50° 08' 15"E), are observed with northwest trending set. The observed fractures are open-mode joints, which appear to be consistent with fractures of the Middle Rus unit. Joints have the same trends of J1 set and seem to be bed-bound to the upper carbonate unit.

The joints of the Dam Formation are abundant, but seem less consistent in their patterns than the joints observed in the Rus and Dammam Formation. This is based on observations from the best exposure at Jabal Umm ar-Rus. The joints also seem to be curvy joints on the rock surface and without clear intersection relationship. At Jabal Midra al-Janubi, some open-mode fractures are also observed near the karstification domain. While some fractures are curvy and small, a few others seem perpendicular to bedding and systematically spaced. The small reverse faults found at the same location are discussed below.
Figure 23: Photo of outcrop at ST#16 (with sketches made on picture) to show the role of mechanical stratigraphy on fracture spacing in both Middle (MR) and Lower Rus (LR) units.

Figure 24: Sketch for the dominant joint pattern; J1 set is the large primary NW trending joints (in red), J2 set is the bounded NE trending joints (in green). Some of J1 & J2 joints found to propagate through the beddings of the Lower Rus unit but display different spacing.
4.1.3. Variations in Fracture Trends & Spacings

The J1 set is systematic joint set, which means they mostly strike in parallel northwestern trends. However, considerable variations in their general trends and spacings (or density) are present at the western flanks of the Dammam Dome at Stations 6 & 8, see Fig. 20.

At Station # 6, the J1 set are developed with a radial pattern in their trends range from north-south to east-west trends. The joints appear to be a fan-like pattern departing away from the dominant northwestern trends observed from Stations 2 through 5.

The area of St#6 is a run-off bed for seasonal rain and gently dips toward the west. There is no evidence of local deformation such as presence of fault, syncline or anticline. However, a very small sinkhole is noticed in the nearby high outcrops of the Middle Rus unit, invoking the idea that it may be channeling to deeper and bigger cave system. The Radial fracture pattern is localized within influence of a small circle (~500m radius), centered as shown in Figure 25. The general radius of the Dammam Dome exceeds 5 km, suggesting that the variation here is due to a local anomaly in geometry on the structure.

At Station 8, the spacingss of J1 set are different from that measured at other field stations, Fig. 26. The J1 set is inferred to have large spacings due to the absence of J1 set within these scattered outcrops. The J1 set apparently form the edges of these elongated, 15-20m wide, and northwesterly trending outcrops (Fig.26). Therefore, joint spacings are estimated to range from 15 to 20 meters. This makes the density of J1 set range between (0.05-0.06) fracture/meter. It is much lower than the dominant averaged density of 0.16 fracture/meter, which is obtained from other field stations (1-5) and presented in Figures 20, & 21.
Figure 25: A satellite image (Google) shows vegetation along large joints developed in radial pattern within Lower Rus Unit at ST#6 in Fig. 9. The joints can be seen also from the inserted two photos (lower right).

Figure 26: Figures to demonstrate the large spacing between J1 set at station 9 in western flank of the Dome area, a) photograph for the top surface of one of the small outcrops for the Middle Rus with sketches below it for the fractures (solid black, looking northwest), b) Google Maps of the outcrops with sketches for the visible lineaments and their measured spaces (sketched on Google Maps).
4.2. Karst Features

10 small and large karst feature areas are found at scattered localities; see Table 2 and Figure 27. The karst features are found within the limestone and dolomite units of the Rus, Dammam and Dam Formations. The presence of karst within the UER Formation can be inferred from synclines within the Lower Rus unit at some areas.

The small sinkholes are of a bowl-shaped morphotype, Fig. 28, but larger ones have indefinite shape and are simply referred to as synclines. The large synclines are identified from some exposed units that dip with some angle to the flat surface (Fig. 29, a). It is also identified from the bedding inclination measurements for some rock strata dipping in an opposite direction to the general gentle dip of the Dome--at locations where bedding is expected to dip away from the Dome central region. The development of the highly inclined units was attributed to sinking, although the presence of some buried faults cannot be excluded. However, some sites (e.g. karst (1), (4) and (7) in Fig. (27)) are observed with concave up strata, where strata dip toward karst feature.

The karstification is interpreted as the obvious mechanism for the development of the small and large synclines at the Earth’s surface. Some fractures seem to be gravity-driven due rock collapse toward sinking areas. However, the systematic J1 set can be identified within and near sinkholes, Fig. 28, 29, b. Field observations indicate that karst-related pattern can be distinguished from the dominant pattern of joints recognized within the northwestern areas of the Dome. While the karst-related fractures seem very limited in space, curvy and lack linearity, J1 set found to follow the NW trends and to be bed-perpendicular within the inclined rock units, see Figures 28, b, 29. Karst-related fractures, however, are not systematic and may have
developed in response to changing local stresses associated with rock sliding toward sinkholes, Fig. 30. Some details are included in Appendix B for more information and figures for the karst areas.

The following table lists the geographic locations and other information on the karst structures observed from the outcrops of the Dammam Dome.

Table 2: Karstification Data of the Dammam Dome Surface

<table>
<thead>
<tr>
<th>No.</th>
<th>Karst Feature Morphology</th>
<th>Location</th>
<th>Appr. Area</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>E</td>
<td>Sq. Meters</td>
</tr>
<tr>
<td>1</td>
<td>Filled cave</td>
<td>26° 18' 52&quot;</td>
<td>50° 04' 47&quot;</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>syncline</td>
<td>26° 18' 48&quot;</td>
<td>50° 05' 56&quot;</td>
<td>8987</td>
</tr>
<tr>
<td>3</td>
<td>syncline</td>
<td>26° 19' 23&quot;</td>
<td>50° 06' 37&quot;</td>
<td>Uncertain</td>
</tr>
<tr>
<td>4</td>
<td>syncline</td>
<td>26° 18' 59&quot;</td>
<td>50° 06' 45&quot;</td>
<td>20255</td>
</tr>
<tr>
<td>5</td>
<td>Sink Hole</td>
<td>26° 19' 12&quot;</td>
<td>50° 07' 05&quot;</td>
<td>4115</td>
</tr>
<tr>
<td>6</td>
<td>Sink Hole</td>
<td>26° 19' 03&quot;</td>
<td>50° 07' 58&quot;</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>Sink Holes</td>
<td>26° 18' 43&quot;</td>
<td>50° 08' 19&quot;</td>
<td>400</td>
</tr>
<tr>
<td>8</td>
<td>Sink Hole</td>
<td>26° 18' 17&quot;</td>
<td>50° 07' 23&quot;</td>
<td>16323</td>
</tr>
<tr>
<td>9</td>
<td>syncline</td>
<td>26° 18' 16&quot;</td>
<td>50° 06' 24&quot;</td>
<td>14020</td>
</tr>
<tr>
<td>10</td>
<td>Sink Hole</td>
<td>26° 18' 21&quot;</td>
<td>50° 06' 07&quot;</td>
<td>650</td>
</tr>
</tbody>
</table>

52
Figure 27: Map of karst and reverse fault locations. Numbers used to reference karsts.

Figure 28: Google Map with bed dips for outcrop at karst # 7 in Fig. 22. The rose diagram is for joint trends. NW trending set is ubiquitous and seem unrelated to the development of karst (outlined circles).
Figure 29: Syncline at Karst#2 in Fig. 22, a) outlines of outcrops (A, B & C) from Google Maps, photos for outcrop (B) looking SE, and outcrop (C) looking SW, b) sketch made on a photograph for fractures of outcrop (B) with interpretation for J1 set (red) and J2 set (green).

Figure 30: Idealized conceptual diagrams for the fractures described within karsted areas.
4.3. Small Reverse Faults

Small reverse faults are observed at three sites at: 1) Jabal Umm ar-Rus (within the Upper Rus unit), 2) Jabel Midra al-Janubi (within the Dam Formation), and 3) a third site at (26° 18 38’.40” N, 50° 09 55’.10”). The three sites are located far from one another; one in the Dome eastern flank, the two others on the Dome central region and northwestern flank, respectively (Fig. 31).

The first site in the Dome’s eastern region (Fig. 31, a) is an excavated area with exposed rocks belong to the Upper Rus from the lithological description of both shale and carbonate units. The hanging wall of the reverse fault (thrust) appears to be moved in the southwest direction (~S25W), although could be oblique by some degrees, see map in Fig. 31, d. The amount of the slip is estimated to be 15cm. The second reverse fault is exposed from a road cut made through Jabal Umm ar-Rus at the Dome central region (Fig. 31, b). Similar to the first location, the fault is in the Upper Rus within an alternating shale and carbonate units. The hanging wall block of this small reverse fault appears to be displaced toward the west. The amount of the slip is also small and estimated to be about 15cm.

At Jabal Midra al-Janubi, several reverse faults are observed from the road cut within Dam Formation (Fig. 31, c, d). The hanging walls of these reverse faults appear to have moved toward the karstification domain. Apparent directions of fault slips are in the same directions of the bed inclinations. Two faults located at one side of the outcrop, see Fig. 31, c, d, and within a few ten of meters apart show apparent different directions for their displacements. One fault displays northeast slip while the other apparently moved toward north. Orientations of fault slips are not consistent with the fold axis or far regional stress of Zagros, see map in Fig. 30, d.
Figure 31: a, b, & c) Pictures and sketches for the small reverse faults (red) found at locations (a, b, & c) on the map of Dammam Dome in (d), d) different view for the faults at (c) which seem to be soft-sediment deformation driven by rock sliding toward the domain of karstification. Arrows in the map point to the propagation of the hanging walls. Orientations of slips are not consistent with fold axis of the Dome or the regional stress of Zagros (N20E).
CHAPTER

5. ANALYSIS

The fracturing mechanism that produced the outcrop joints are investigated in the light of the joint characterization, their relative chronology, and their potential relationships with the major structural and depositional events controlled (or influenced) the Dome outcropping carbonates during the Tertiary period. The established framework of tectonostratigraphy of the Dammam Dome and surrounding regions allow me to assess different hypotheses for the joint genesis. Possible causes for the development of the joints include: 1) the remote compressional stress associated with the nearby Zagros uplift, 2) the tangential stress associated with folding growth during Oligocene due to the active deep seated salt diaprim 3) the stress induced by development or reactivation of local faults, and 4) a combination of these previous mechanisms.

5.1. Far Regional Stress

In some geologic settings, fractures (e.g. joints) may develop due far tectonic stresses (e.g. Hodgson, 1961, Engelder 1982, 1993), such fractures have trends that are consistent with known far-regional stress regime. Tensile fractures of this type can develop due to applied compressive stresses, especially in presence of fluids, which can yield overpressure conditions (e.g. Engelder & Geiser, 1980).

The proximity of the Dammam Dome to the fold-thrust belt of Zagros raises the possibility that regional stresses may have produced the outcrop joints. The development of the hydrocarbon-bearing anticlines of Eastern Arabia is not related to Zagros compressional regime; refer to section (1.2 & 1.3). However, open natural fractures in some Saudi Arabian reservoirs (e.g. Wudayhi structure) are interpreted to be consistent with the regional stress associated with the Zagros uplift (Ameen et al, 2008).
The Zagros mountain belt is defined as a NW-trending orogen stretching 2000 km from the East Anatolian fault in eastern Turkey to the Makran subduction in southern Iran (e.g. Mouthereau et al., 2012). It is associated with Arabia/Eurasia convergence, and belongs to the Alpine–Himalayan orogenic system that resulted from the closure of the Neotethys Ocean during the Cenozoic (Dercourt et al., 1986; Dewey et al., 1973; Stampfli and Borel, 2002). Recent studies suggest that the collision between Arabia and Eurasia initiated at 35 Ma, when the continental margin of the Arabian plate was underthrust beneath the Iranian plate (e.g. Mouthereau et al., 2012).

The uplift of Zagros folding and exhumation across the Zagros, and throughout the Arabia/Eurasia collision zone, started later at 15–12 Ma (e.g. Mouthereau et al., 2012). The shortenings in the basement and cover are absorbed within the collision zone by ongoing thrusting and accretion (e.g. McQuarrie et al., 2003, Walpersdorf et al., 2006, Oveisi et al., 2009), with absence of evidence for shortening and flexure in the eastern part of the Arabian Shelf.

Compressional trends were identified to be NE–SW and N020° during the Neogene (e.g. McQuarrie et al. 2003, Lacombe et al., 2011), see Fig. 32. The compression/shortening direction remained within the close range of N020° from the Middle-Late Miocene to present-day in the western Fars region. Deviation of the pre-folding local paleostress trends from the N020° has been related to stress perturbations induced by locally underlying basement faults (Lacombe et al., 2011).

Regardless, the N020° compressional trend is consistent with the current compressional trend from the focal mechanisms of basement earthquakes and the geodetic shortening axis (Walpersdorf et al., 2006). The regional compression was generally constant across the Zagros
collision zone during the late Neogene, consistent with the stability of the Arabia–Eurasia convergence over the last 20 Ma (McQuarrie et al., 2003, Mouthereau et al, 2012).

If the Joints of the Dammam Dome result due to the regional stresses associated with Zagros compression, the joint trends are expected to develop in systematic NE-SW trends, Fig. 32, b. But this trend is almost perpendicular to the northwestern trends of the observed primary joint set. The primary joint trends, therefore, seem unrelated to the compressive regional stress of Zagros.
Figure 32: Correlation between the trends of the J1 set and the trends of the remote regional stress associated with the Zagros uplift: a) map shows the location of the Dammam Dome in Eastern Arabia, the location of cross section in (c) figure, and directions of in situ stresses (from World Stress Map, 2008), which may locally change due to partitioning in the crust, but generally consistent with N020° paleostress presented as lines in (b), b) the map of the Dome with the paleostress trends to display the NE potential trends for the joints may result from the far compression stress of the Zagros uplift, c) a NE-SW cross section for the Zagros Fold Belt and Thrust systems (from McQuarrie, 2004) to display the general NE-SW compressional trend, d) the average trends of the primary joints (J1 set), b &d) show that Dome fractures are not consistent with the regional stress trend.
5.2. Joints Relationship with Local Structures (Karst & Small Reverse Faults)

The observation of karst features within the limestone and dolomite units of the Rus, Dammam and Dam Formations suggest that karstification was active within all the carbonate units of the Dammam Dome outcrops at some time. However, the limited presence of karst features as well as the ubiquity of the main joint pattern indicates that the joints are not related to stresses associated with the rock collapse due to karstification. In addition, the J1 set found to be systematic (within and near sinkholes and within locations without sinkholes), see Appendix (B). These observations indicate that joints may have developed prior to karst development. If karst features predated the development of J1 set, J1 set may lack systematic patterns, and develop in concentric pattern reflect the local geometry of sinkholes and/or subsidence. These findings suggest that the associated loading stresses (e.g. gravity) on karsted rocks are not linked to the development of systematic trends of J1 set. The development of karst is beyond the scope of this study, but the karst development may have been facilitated by two factors: 1) the presence of joints (e.g. J1 set), and 2) the dissolution of carbonate and sulfate deposits under Middle Pleistocene wet climatic conditions that were regionally recognized elsewhere, refer to text in Appendix (B).

The other local structural elements found within the Dome outcrops are the three small-reverse faults; refer to description in section (4.3.). These faults are found within units younger than the Middle Rus unit; within the Upper Rus Unit and Dam Formation. The influence of the stress associated with these faults on the pattern of J1 set is not visible, as these faults are not observed within or nearby the outcrops of the Middle Rus; see the location map in Fig. 27. These faults are developed within units (e.g. Upper Rus) that contain interbedded shale and gypsum. The age of these faults is difficult to constrain, but their propagation trends are not consistent
with compressional local or regional trend; they are neither consistent with the axis of the
Dammam Dome, nor parallel to the regional stress of Zagros. The development of these faults
may be attributed to soft-sediment deformation within karsted areas, see Karst (1) as an
example in Appendix (B).

5.3. Local Stress Due to Dome Flexure

Fracture development is well documented to be mechanically related to folding (e.g.
expected to propagate perpendicular to the maximum tensile stress within the bending units.
The fold geometry can be used to predict the stress patterns associated with fold structures.
Herein, the structural growth of the Dammam Dome forms the foundation to analyze the
mechanism of the joint development. The approach of this study is based on the relationships
between the joint characterization (e.g. trends) and the general geometry of the Dammam
Dome. Also, the study considers the relative chronology of the dome growth, and the potential
strain from near-surface faults.

The exposed units of the Dammam Dome dip away from its central region where
exposures of the less weathered rocks form relatively high topography (Tleel, 1973). The Joints
observed within all carbonate outcrops are opening-mode joints that represent failure of beds
due to extensional stresses that may have influenced all exposed units. Among these outcrops,
the Middle Rus limestone found to offer the best exposures to study the distribution of joints,
despite the exposures are limited with respect to the large area of the Dammam Dome.
However, the outcrops generally display interestingly regular joint trends, especially for the
through-going J1 set, which is interpreted, from crosscutting relationships, to be the older joint
set developed within the Middle Rus unit.
The patterns of the J1 set are systematic within most outcrops except at the western flank; however, some slight change in their trends does exist from one exposure to another. The general northwestern trends of the J1 set and the slight variations in their trends may reflect the folding shape of the Middle Rus bed, and not regional stresses. Propagation of other joint sets (e.g. the J2) is controlled by presence of the J1 set, and, hence, their timing and origin is not well established. The J2 set may have developed for the local stress concentration between the developed J1 set. This could happen when after the ratio between spacing of developing fractures and layer thickness reach a critical value and further sequential infilling is inhibited (e.g. Gross, 1993, Bai et al, 2002). Accordingly, the J2 set may have resulted after the local normal stress parallel to the J1 set has become the maximum tensile stress.

The Dammam Dome may differ from other tectonic settings, where the effects of early and laterally transitional fold shapes on joint development invalidate correlation of joints to fold shape (e.g. Fischer and Wilkerson, 2000, Savage et al, 2010). The exposed carbonate units of the Dammam Dome gently evolved vertically, and without lateral growth (Weijermars, R. 1998). The joint density may increase with increasing stress of tightening dome, but the primary trends may still generally reflect the similar dome geometry. This situation allows correlating the trends of primary joint (J1 set) with the dome geometry.

The relative age of the J1 (the older set) may be interpreted from the stratigraphical record of the outcrops. The domal growth of the outcrops, which was initiated in Oligocene is suggested by: 1) the erosion of the Dammam Formation from the central area of the Dome at Jebel Umm-Er-Rus, whereas the formation has a maximum thickness of 32.5m at the rim of the Dome, and 2) the deposition of the clastic Hadrukh Formation beyond the boundary of the Dome with a maximum thickness of 120m, whereas the formation is missing in the area of the
Dammam Dome (Weijermars, R. 1998). Accordingly, the Oligocene uplift may constrain the relative time of the older J1 set developed within the Middle Rus unit, if it is related to the dome growth. The structural growth of the Rus and Dammam Formations may have started shortly after their deposition.

The dome uplift during Oligocene was the last event in the series of uplift episodes mostly observed from the subsurface horizons. The interpretation of the subsurface data for the shallower horizons confirms the dome geometry, although it seems less elongated dome than that expressed from the Earth’s surface (Tleel, 1971), Fig. 33. As a major structural event, the Oligocene uplift may have driven the thin (10m) Middle Rus to fail in tension to accommodate ongoing stretching, producing the observed long J1 set.

5.3.2. Curvature Analysis

The gentle folding of the Dammam Dome requires an assessment of the role of fold-associated stress in the development of the joints. The observation of widely spaced regular joints suggests that the fold was everywhere. The three methods analyzed in the following subsections are based on the use of curvature and its relation to fiber stresses. Despite the difficulty of using curvatures for evolving structures, the joint pattern observed within outcrops can be still compared with the predicted joint pattern from current fold curvature to reveal whether the folding alone can account for the observed pattern of jointing.

5.3.2.1. Stress from 1D Curvature Model

The 1D curvature is estimated from an east-west cross section of the PAMU structure. Several cross-sections are used in the direction sub-perpendicular to the hinge line of the
Dammam Dome. One example is presented in Figure 33,d. The curvature is calculated from the inverse of the radius (R). The radius is obtained using the following mathematical formula:

\[ R = \left( \frac{h}{2} \right) + \frac{(c^2)}{8h} \]

where \( h \) is the elevation, and \( c \) is the chord length, Fig. 33.d. The thickness (h) of the Middle Rus unit is used, which is documented to be 10m (Tleel, 1973, Table 1). The Young’s Modulus (E) is estimated to be 24 (±4) Gpa from field measurements (Table 3), and the following empirical formula from Katz at al (2000):

\[ E = 0.00013 \cdot R_{\text{corrected}}^{3.09074} \]

where \( R_{\text{corrected}} \) is the corrected rigidity reading of Schmidt rebound hammer.

<table>
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<th>St#3</th>
<th>St#4</th>
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<td>53.3</td>
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<td>48.0</td>
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<td>24.6</td>
<td>28.3</td>
<td>19.1</td>
<td>20.4</td>
<td>24.6</td>
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The calculated tangential stress ranges from 1.9 to 2.2 MPa. The stress estimate is compared with tensile strengths of limestone found in literature. One experimental study on a limestone formation in Saudi Arabia provides a range for tensile strength between 2.13 and 2.39MPa, with 2.31MPa as an average value (Khan et al, 2000). This average value is slightly higher than our obtained stress above, but used for comparison in our analysis considering the possible variations in tensile strengths of limestone rocks of the region.
Khan et al (2000) lacks detailed geological description of the tested limestone that may differ in its rock properties with that of the Middle Rus limestone. However, some consideration is given to the possible wide range of lab results due to lack of constraints on the affects of specimen size, shape and testing methods on strength measurements. Also, the fact that lab specimen are intact makes up-scaling from lab to field is not always successful. The measurements carried out on intact samples likely overestimate the actual tensile strengths of natural rocks (e.g. Mandl, 2005). Moreover, some geological observations can be added with this context. For example, the Middle Rus unit hosts some scattered vuggy texture (Tleel, 1973), hence, subtracts from the total rock strength. The vugs are mechanically rock flaws and their affects on rock mechanical properties are similar to that of pre-existing joints (e.g. Exadaktylos & Stavropoulou, 2008). According to the principles of fracture mechanics (e.g. Griffith, 1924; Cottrell and Rice, 1980) aided by observations from laboratory experiments (e.g. Brace et al 1993), joints may initiate due to stress concentration at rock flaws (e.g. vugs) and they propagate according to local principal stresses acting on the rock.
Figure 33: Geometry of the Dammam Dome from surface and near-surface, a) surface geology map (after Tleel, 1973), b) subsurface map of the (PAMU) horizon based on reflection seismic and well data, c) Tleel’s cross section (A-A’) in (a), d) cross section (B-B’) in (b), in addition to Digital Terrain Map (DEM) in the same location. B-B is one of 1D curvatures obtained along E-W cross-sections for the PAMU.
Although the calculated stress from overall folding seems high and may have produced the tensile fractures, the potential presence of fluid may have enhanced the fracturing process. There is no available information if fluid was present, or whether fluid was overpressured during the joint development. Abnormal pressure, however, is not considered, as the developing conditions for high pore pressure may have not been available in such a very shallow column of sediments. The shallow overpressured sediments are not common, but found in young basins with high sedimentation rate (e.g. delta), and from about 1.0 to 2.0 km downwards. Therefore, only the normal fluid pressure is considered. It can be calculated from the overburden of the 75m thicknesses of the Upper Rus and the Dammam Formation. It is the thickness of the rocks deposited on the top of the jointed Middle Rus unit and assumed to be present during the Oligocene uplift.

Calculations for the stresses in Table 3 count for poroelastic effects at the bottom of the burden assuming a relaxed tectonic region and a hydrostatic pressure of fresh water. The density (2.56g/cm³) and Poisson’s (0.21) are average values for the Middle Rus (Osman, 2009), and used here as averages for the carbonate overburden. For the Biot-Willis constant (α), 0.32 is used, which can be used for strongly cemented sandstone with clay (e.g. Berge, 2005).

Accordingly, the calculated internal fluid pressure is 0.7344 MPa. The pore pressure is greater than the calculated total horizontal stress (S_h), but is much lower than the tensile strength of the Middle Rus unit. The pore pressure may have reduced the rock strength, however, and helped the tangential stress driven by the Dome uplift to generate the joints within the Middle Rus unit.
Table 4: Properties used for the carbonate overburden above the Middle Rus Unit

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<td>Bulk Density (d)</td>
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<tr>
<td>Young’s Modulus</td>
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<td>Poisson’s ratio (v)</td>
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<tr>
<td>Biot’s Constant (α)</td>
<td>0.32</td>
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<tr>
<td>Internal Fluid Pore Pressure (P_p)</td>
<td>0.7344 MPa</td>
</tr>
<tr>
<td>Total vertical stress (S_v) = d g z</td>
<td>1.88 MPa</td>
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<tr>
<td>Total Horizontal stress (S_h) = (v/1-v)S_v</td>
<td>0.498MPa</td>
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5.3.2.2. The Geometry of Near-Surface Horizon

The dome geometry from subsurface horizons (e.g. the PAMU) is not symmetrical, Fig. 34, a. It displays variations in location curvatures, some from the fault escarpments, and other may reflect noisy seismic data. The structures of the near surface are studied from: 1) correlating the exposed dome geometry of Tleel (1973) with the dome of near-surface horizons, 2) applying volumetric structural restorations for the shallow section to restore the dome and faults and predict trends of joints due to bed stretching, and 3) comparing strain patterns from the dome restoration with that from faults above the tips of the faults; at the top surface of the shallow section.

5.3.2.2.1. Near-Surface Dome

The location map of the J1 set is presented with respect to the dome geometry from the map of the near-surface PAMU. The two-map correlation is useful for the observed interesting trends and spacings of the primary joints at ST#8 and at ST#6. Both field stations are located within the dome western periphery, Fig. 34, b.
At ST#8, the primary joints (J1 set) are developed with larger spacings range from 15-20m, while their spacings in other stations (e.g. toward the dome central region) range from 3 to 7m. The joint spacings (density) could be attributed to variations in the tangential stresses from folding of the Middle Rus. The density of J1 set may reflect the structural position on the Dome, with higher joint density toward the dome central region and lower joint density toward the flanks; where curvature is gentler in the flank than that of areas located toward the dome central region.

The geometry of the PAMU also shows a local fold coinciding in location with the ST#6, where the joints developed in local radial pattern, see section (4.1.3). However, it is not clear from seismic interpretation if it is related to a fault at depth. It is to consider the potential stresses from the western tip of the observed fault (Fig. 34.b) that can be extrapolated to the Lower Rus at surface. The fault dips toward the north and its extrapolated trace would be further south where the location of ST#6. The other possible explanation for the radial pattern of ST#6 is a large subsidence due to karstification beneath the earth’s surface (e.g. within UER Formation).

5.3.2.2.2. Joint Trends from Near-Surface Dome

The structural restoration method is employed to compute for extensional strain produced by the development of the dome and fault structures. The strain components can be analyzed to identify the maximum directions of contraction and stretching from restoration vectors, after restoring the tetrahedrons of a deformed unit to its depositional flat status. Here, I only consider the bed parallel (horizontal) strain, as strain is typically computed in the 3D space of the restored model. Tensile fractures (joints) are predicted to develop in trends perpendicular to the maximum horizontal stretching (in forward sense). Therefore, the main strain
components are used to predict the trends of tensile fractures from directions perpendicular to maximum shortening.

The strain (dilation) is computed from the sum of the restoration vectors of the two units forming the shallow section. The results are presented in lines (vectors) and superimposed on the structural map of the PAMU for georeference, Fig 34, a. These trends are compared with the trends of the observed primary joints (J1 set) from outcrops (yellow lines), Fig. 34, b. The model suggests that the computed joint trends (vectors) are not consistent (parallel) with the observed joints despite some agreement in trends toward the dome crest. The variations in computed trends partially reflect local geometries due to fault displacements. The local variations in structure produced joint trends that are different from the one observed in outcrops, and also from a typical dome geometry. Therefore, the use of the analysis to predict joint trends from the general dome of the near-surface units is reduced due to local geometries.

Nevertheless, if faults are assumed to have extended to the Earth's surface, the model suggests that joints mostly strike in north-south trends within the fault zone, Fig. 34, b. As the faults are restored along their dip slips, the analysis computes for the horizontal components of layer stretching due to faulting. If the shallow section is fractured due to that horizontal stretching (strain), the model displays that predicted joint trends are not parallel with the observed joints, Fig.34, b. Accordingly, the analysis results show the potential influence of the fault geometry (the fault displacements) if faults were extended to the Earth’s surface.

The results from strain analysis do not indicate if there is a relationship between buried faults and the development of joints within the outcrops. The faults are not observed within the outcrops, nor the computed trends within their zone of influence match the observed trends. Also, the faults are (dip-slip) normal faults, and without evidence for strike-slip components.
One should consider, however, the potential lack of mapping precisions inherited from the seismic data interpretation and the method sensitivity to mapped structural irregularities on surfaces.
Figure 34: a) the structure map of PAMU surface with black vectors for trends of tensile fractures computed from directions normal to maximum shortening within the 3D restored model of the shallow section of the Dammam Dome, the area of interest (yellow) is enlarged in (b), b) outcrop joints (J1 set) (yellow) are superimposed on map to correlate their trends with computed ones. Computed trends reflect local geometrical variations (e.g. fault cutoff geometry), hence, generally lack agreement with J1 trends except toward the dome center. Within fault zone, the model suggests sub north-south trends for tensile fractures. See text for some details on ST#6 & ST#8.
5.3.2.2.3. Analysis of Strain Patterns

Strain patterns (dilation) are computed from the 3D structural restoration method. Two restoration scenarios are performed for the ARUM unit. The main difference between the two restoration scenarios is that fault displacements within the PAMU unit are locked in one model, and freely restored in the other one. This should allow observing the difference in strain distribution from both folds and faults. Figures 35 & 36 display the influence of displacements from the top surface of ARUM, and from cross sections through the ARUM and PAMU units.

Only one of the faults causes considerable strain, Fig. 35, b. The similarity of strain patterns from both model scenarios suggests that the influence of the other faults is absent on the top surface of the upper unit within the framed area in Fig. 35, a, b. This area is the area of interest, which outlines the location of joints observed at surface. In addition, folding-associated strain seems to dominate the near-surface section of the Dammam Dome from the pattern of strain at the top of the upper unit, Fig. 35. This result is due to 1) small displacement of faults within the bottom of the upper unit, 2) the well-developed dome geometry. This finding implies that stress induced by slips on near-surface faults is generally localized compared with fold related stress. Despite the limitations of using strain magnitudes in relation to stress, it can be still inferred from strain patterns that influence of fault slips on the joints of the Middle Rus is not evident within the area of interest. The fault-associated stress may either have been absorbed within fault damage zones or diminished within the interbedded shale units and rock contacts of the 500ft section between the PAMU and surface.
Figure 35: Strain patterns (dilation) from two 3D restorations scenarios performed for complete 3D model to evaluate the influence of near-surface faults, a) model with locked fault slips, b) model with restored slips on faults. The strain similarity of both models (a & b) suggests that the influence of other faults is absent on the top surface of the upper unit within the frame area (where joints are observed from surface).

Figure 36: Different views for the strain patterns from the two scenarios (a), (b) in Fig. 35. The strain from the larger fault is localized at the bottom of the upper unit, suggesting that the influence of fault-associated strain is mostly limited to the lower faulted unit. See text.
5.3.2.3. Joint Trends from Typical Dome

Trends of predicted tensile fractures are computed from directions perpendicular to principal stress directions using an analytical formula for a typical dome. The dimensions used as follows: (width: 11km, length 13.5km, amplitude: 290m). The dimensions generally resemble that of the Dammam Dome; see Appendix C for more details.

The computed joint trends from analytic function are superimposed on the Dammam Dome map, Fig. 37, to correlate computed and observed joint patterns. Figure (37) displays that the lack of observed well-developed radial pattern joints, as model suggests, might be due to the concentration of outcrops toward central regions. Only the northern and northwestern outcrops of the Dome seem to offer reasonable coverage for observed joint data. But in general, some correlation can still be made with the situation of limited exposures. The joint trends in northwestern and southeastern outcrops are generally consistent with predicted trends. However, the lack of match in trends in western flank suggests local deviation of the Dome geometry from the idealized one used in this analysis.

The geometry of the Dammam Dome is not idealized oval-shape dome, but agreements in trends support the relationship between joint trends and dome geometry. Thus, observed joint trends in northwestern and southeastern areas of the Dome generally developed in the same orientation as the model, making the curvature analysis reasonably valid for general prediction.
Figure 37: Computed trends of predicted tensile fractures (green lines) from directions perpendicular to principal stresses on an idealized dome structure (using Maple Software). The dimensions generally resemble that of the Dammam Dome. The map of rock outcrops (light green color), Tleel’s map for unit surface contacts (black) and outcrop joints (black lines) are superimposed to show the positions of rock exposures and their limited areas in comparison to the large dome area. Exposures are limited to central, northern and northwestern areas of the Dome. Joint trends in northwestern areas are generally consistent with predicted trends. It is also true for the trends in the southeastern outcrops of the Dome. However, variations in trends in the northern areas and western flank suggest local deviation of the Dome geometry from the idealized one used in this analysis.
CHAPTER

6. CONCLUSIONS

In this study, I presented the characterization of the fractures observed within the exposed Middle Rus carbonate unit in the Dammam Dome. The fractures are interpreted as opening-mode, bed-bound joints that form orthogonal sets in most areas. The study, however, focuses on the J1 set, which is interpreted from crosscutting relationships to be the primary joint set. The conclusion points and implications from this study are summarized as follows:

1) The dominant NW-SE trends of the J1 set are not consistent with the remote regional stress associated with the Zagros uplift. The Zagros compressional trends were previously identified to be NE-SW (N020°) during the Neogene and remained within the close range of N020° from the Miocene to present-day in the western Fars region. Therefore, the development of the J1 set cannot be attributed to the compressional stress associated with the Zagros uplift.

2) The J1 set found to be systematic in their trends over a large area, indicating they have developed independently of the karsts found in limited locations. Stresses associated with karst development may induce joints that lack systematic patterns. Karst-related fractures may develop in concentric patterns reflect the local geometry of sinkholes and/or subsidence. In addition, the limited presence of karst features as well as the ubiquity of the main joint pattern suggests that the joints are not related to stresses associated with the rock collapse due to karstification.
3) The stress from the overall dome seems to have caused tensile stresses overcome the tensile strength of the Middle Rus unit and, consequently, produced tensile fractures, as per the suggestion of the simple analysis of the 1D curvature. The potential presence of pore fluid may have enhanced the fracturing process.

4) The geometry of the Dammam Dome is not idealized oval-shape dome, but agreements in correlation between most of the J1 trends with the computed trends from typical dome geometry suggest that the J1 set may have developed due to the tangential stresses associated with the Dome growth during the Oligocene uplift. This is consistent with the results from structural analysis of the subsurface faults. The computed trends from strain analysis within the zones of fault influence do not match the J1 trends.

5) Location deviations of the J1 trends from the dominant regular trends may reflect influence of local geometry such as local folding, or subsidence due to karstification.

6) The difference in the joint spacings observed between the Middle Rus and the Lower Rus units can be attributed to the effect of the mechanical unit thickness on joint sequential infilling, which resulted in higher joint density within the relatively thin (Middle Rus) than that of the thick (Lower Rus) unit. The Joint spacing also differs within the Middle Rus, especially when the flank outcrops compared with the central regions. This may indicate variations in the intensity of bending over different structural positions on the Dome.

7) Some insights from this study can be used to predict fracture occurrence at deeper hydrocarbon-bearing horizons. The deeper horizons had experienced
the same folding process. The folding-associated stress is expected to be high enough to produce joints at deeper horizons.

8) The results from fieldwork and curvature-based analysis provide a first-order conceptual fracture model for the Dome carbonate reservoirs. The quantitative attributes of curvature indicate that joints may develop in such gently folded strata. But also indicate that local variations may affect fracture trends. The fracture trends may reflect the general fold geometry, in geologic settings lack pre-existing fractures. The results also indicate that joint density may increase with increasing curvature. The main implications of this study are presented in Figure 38. These results should be integrated with the subsurface data to guide near-future reservoir development.
Figure 38: First-order conceptual model based on observations from outcrops for joint orientations and density, a) from idealized dome geometry, where fractures are systematically develop in radial pattern and their trends are perpendicular to maximum curvatures, b) from PAMU horizon where predicted fracture trends are calculated from directions perpendicular to maximum strain contraction in 3D restored model. Within fault zones (1,2 &3), fracture density and geometries may vary due to complexity of fault zones (grey areas) and their re-activation history, c) idealized cross section based on the curvature of PAMU and the joint spacings measured from the Middle Rus unit (10m).
APPENDIX A

DATA OF JOINT TRENDS

Trends of joints collected from the Dammam Dome outcrops. Data for field stations 9 and 10 is collected using Google Maps to trace fractures from vegetation lineaments.

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APPENDIX B

KARST DEVELOPMENT IN THE DAMMAM DOME

The Dammam Dome is part of the large eastern Arabian landforms and, therefore, shares some of the geological and morphological features. Among these features is the karst that was commonly found in the exposed carbonate formations of the Arabian Desert. Early investigations report most of the karst features from the Summan and Shedgum Plateaus. About 58 cavities were surveyed within the Summan Plateau, some of them leading to sub-horizontal cave system (Edgell, 1990a). Karst features are mostly developed within the Umm-Er-Radhma Formation (UER), which is a well-known near-surface aquifer in the region. In a recent technical report, Saudi Geological Survey (SGS) published maps and some information for some of the previously recognized caves to highlight their potential as touristic sites (Pint et al, 2002; Forti et al, 2003; Pint, 2003).

Previous studies highlighted the role of climatic factors, lithology and presence of fractures on karst development. The first study on Ghar An-Nashab, a famous cave in the region, published a map shows a series of 30 m-high, narrow, joint-controlled fractures containing 1.5 km of passages (Hötzl and V. Maurin, 1976). A recent study on the site re-emphasizes the role of joints in the cave development (Hussain et al, 2006). The recent study indicates that Ghar An-Nashab is unlike most of the caves reported from the As-Summan Plateau, which were formed by dissolution of limestone by ground water. It was rather developed due to sub-aerial weathering and enlargement of the well-defined fracture systems in the Hofuf Formation (Hussain et al, 2006). In the nearby State of Qatar, karst is widespread in central and northern region, and about 9700 large and small depressions, sinkholes and caves are reported (Sadiq et al, 2002). Karst is concentrated mainly within the limestone, dolomite, gypsum, and anhydrite
horizons of the Rus and Dammam Formations. The study indicates that rock type and the presence of joints and fractures played a major role in the development of karst in Qatar (Sadiq et al., 2002).

In addition to the role of fractures in karst development, previous studies highlighted the geological and climatic factors especially for karst features found within the UER (e.g. Hoetzel et al., 1995). The deposition of the UER formation was followed by a regression of the sea towards the current region of the Gulf. In this new depositional environment, the thick marls and evaporite of Rus Formation and limestone of Dammam Formation were deposited during the Eocene. The western part of the UER became land and was exposed to strong karstification (Hoetzel et al., 1995). Its latter sedimentary cover was produced by terrestrial accumulation processes during the Miocene. Since the upper Miocene, the recent landscape has been developed under prevailing arid climatic conditions and repeatedly intercalated short wet (semiarid) phases with erosion processes (Hoetzel et al., 1995). The humid phases may caused an exhumation and reactivating of the karst in the outcropping area of the UER, where nowadays a lot of collapse structures, dolines, open shafts and caves are to be found (Benischke et al., 1988; Edgell 1990a; Al-Saafin et al., 1990).

Previous works on the Dammam Dome lack significant information on the karst development and locations of karsted areas. This study collects new observations on the development of karst within the formations of the Dammam Dome outcrops. It is not a complete treatment for the subject of karstification development. However, some general geological description is required to consider the role of local structures that may have caused or affected the development of joints. For example, the role of ground subsidence on the development of fractures within the Dome outcrops.
The analysis of the field observations suggest that the primary large joints (J1 set) are developed prior to the development of karst, see section (5.2). Hence, the presence of the rock joints may have facilitated the karstification at some areas, despite the lack of direct relation between the shape of karsted areas and the joint trends. The following pages include some figures and photos for the 10 karsted areas found within the Dammam Dome. Some description is included for some sites.

The karst (1) is developed within Jabal Midra al-Janubi, which is located at the further northwest flank of the Dammam Dome. The mountain was a high-peak mountain, until recently has been partly excavated for a T-shape road that exposed some remarkable rock features on its 5 giant walls. Observations from these freshly exposed rock walls suggest that at least one large karst feature was developed within the Dam Formation. The geometry of this karst feature is roughly mapped, from observations and high-resolution photos taken from the road cut exposures. The map is sketched on a Google satellite image that shows the outlines of the mountain and the road cuts. Within the boundary of the karst, the carbonate stratification of the Dam Formation is mostly lost, but some large rock blocks seem to belong to the same Formation. Within the excavation rock remnants, gypsum crystals are observed in a block that has apparently sloughed off the roof of a cave developed within the karstification domain. The rock bedding dips from the flanks of the outcrop toward the karst at the center. The bedding of strata, outside the karst, is obviously concave up forming a syncline. With the absence of any potential mechanism that could make a syncline in a very limited area of about 150m diameters, the concentric bedding inclinations are apparently gravity-driven by subsidence within karstification domain. The subsidence is most likely responsible for the development of fractures, especially the reverse faults. The propagation trends of the reverse faults are
consistent with dip inclination directions toward the karstification domain. It seems that the reverse faults are developed within soft sediment.

At the second location karst (2), a seemingly karst-related syncline was identified from the highly inclined units of the Middle and Lower Rus within three outcrops. The outcrop locations and the bed dip directions suggest that these outcrops bound a large sink area of 8987 sq. meters, located at 26° 18' 48"N, 50° 05' 56"E. The exact syncline geometry is unknown, but approximately mapped from the three outcrops. Also, the presence of some buried faults cannot be excluded, although no sign can indicate their development. If sinking was due to karstification, this suggests that some karst feature(s) are developed within lower Rus or UER Formation. Similar to karst (2) is the location of karst (9), where the presence of a large sinkhole (or syncline) was interpreted from the bed inclinations of some exposed units of the Middle and Lower Rus members.

The location at karst (4) was found from bedding inclinations of the Lower Rus unit within a recently excavated trench within a low-relief area. The NE-SW trending trench offered a cross-sectional view for a syncline span in an area of about 200m diameter. The concave-up of Lower Rus unit and absence of apparent faults suggest that a sinkhole may have developed in the buried level of Lower Rus or the upper part of UER Formation. In the following pages, some photographs, Google maps and sketches are presented for the karsted areas found from the study of the Dammam Dome outcrops.
Map of Karst Features found within the Dammam Dome outcrops

Karst (1): Google Map for Jabel Midra Al-Janubi shows the T-shape road cuts.
Map view with some interpretations for the karstification domain and bedding inclinations. Pictures and sketches show the interpretation from three side-walls of the road cut. Arrows indicate the photographed side.
Karst (2): Google Map for the three inclined outcrops (a, b & c).

a) outlines of outcrops (A, B & C) from Google Maps, photos for outcrop (B) looking SE, and outcrop (C) looking SW, b) sketch made on a photograph for fractures of outcrop (B) with interpretation for J1 set (red) and J2 set (green).
Karst (3): Recent road cut shows bedding inclination of 4 degrees toward the northwest. Tleel (1973) reported the presence of a syncline at the same location.
Karst (4): A syncline identified from the bedding inclinations through a trench dug for pipes. The exposed parts of the rocks belong to the Middle Rus unit. It is probably developed due to subsidence within the lower part of Rus Formation or the upper part of UER formation.
Karst (5): Google Map for the location.

Karst (5): A syncline identified from bedding inclinations of exposed parts of the Middle and Upper Rus units.
Karst (5): Photos for the location shows the deformation for the Upper Rus carbonate and shale units.
Karst (6): Google Map for the location.

Karst (6): small sinkhole developed within the Lower Rus unit.
Karst (7): Google Map for the location and dip measurements. The rose diagram shows the trend of fractures.

Sinkhole at location (a) in the Google Map above. At location, there is no indication of faults. The photo also shows the north trending wind striations.
Karst (8): Google Map for apparent sinkhole.

Looking southeast

Karst (8): photos for the inclined rocks of the Middle Rus unit.
Karst(9): Google Map for a potential large sinkhole, from inclinations of outcrops. J1 set are present in northwestern trends, a & b are station 4 & 3 respectively. Inclination of beds are not consistent with the general dome geometry.

Karst(9): Bedding inclinations of the outcrop (a) are not consistent with that of the general dome. At outcrop (a), beds dip toward the southeast, whereas the general dome dip gently toward west and northwest.
Karst(9): photos for the inclined Middle Rus outcrops.
Karst (10): Google Map for the location.

Photos for the sinkhole area.
APPENDIX C

CALCULATION OF JOINT TRENDS FROM TYPICAL DOME GEOMETRY

The stress field along the top of a 3-D plate is computed from a given transverse deflection. The plate dimensions used as follows, width \((hw)\): 11000m, length \((hl)\): 13500m, and amplitude \((amp)\): 290m. The dimensions describe a general dome shape resamples that of the Dammam Dome. The analytic deflection function \((w)\) is defined in Maple Software as:

\[
w := (x, y) \rightarrow amp\left(1 - \tanh\left(\frac{4x^2}{hw^2} + \frac{4y^2}{hl^2}\right)\right)
\]

The method investigates stresses within the bended layer with 24MP for Young’s modulus \((\mu)\) (e.g. for the Middle Rus from Shimidt rebound measurements), and 0.21 for Poisson’s ratio \((\nu)\). The analysis, however, only considers the in-plane \((x-y)\) stresses due to flexure, and ignores in-plane stretching of the layer:

\[
sigxx := (x, y, z) \rightarrow -\frac{z\mu}{1 - \nu^2}\left(\frac{\partial^2}{\partial x^2} w(x, y) + \nu \left(\frac{\partial^2}{\partial y^2} w(x, y)\right)\right)
\]

\[
sigxy := (x, y, z) \rightarrow -\frac{z\mu}{1 - \nu^2}\left(\frac{\partial^2}{\partial y\partial x} w(x, y)\right)
\]

\[
sigyy := (x, y, z) \rightarrow -\frac{z\mu}{1 - \nu^2}\left(\frac{\partial^2}{\partial y^2} w(x, y) + \nu \left(\frac{\partial^2}{\partial x^2} w(x, y)\right)\right)
\]

As the tensile fractures \((J)\) form perpendicular to the maximum principal stress, the maximum principal stress \((\text{maxPrinc})\) is first required to be found from the stress components:
To plot the tensile fractures $(J)$, 90 degrees (e.g. $\pi/2$) are added to the trajectories of the maximum principal stress ($maxPrinc$). Also, the tensile fractures ($joints$) are computed from in-plane stresses along the top of the layer, as the x-y fiber stresses vary throughout the thickness of the plate. Stresses are maximum at the base and top of the bended plate and equal zero at the plate center (neutral zone). The thickness of the layer is 10m, similar to that of the jointed Middle Rus Unit. The stresses are examined where $z = h/2 = 5m$.

$\text{maxPrinc} := (x, y, z) \rightarrow \frac{1}{2} \text{sigxx}(x, y, z) + \frac{1}{2} \text{sigyy}(x, y, z) + \sqrt{\frac{1}{4} (\text{sigxx}(x, y, z) - \text{sigyy}(x, y, z))^2 + \text{sigxy}(x, y, z)^2}$

The joint plot is superimposed on the map of the Dammam Dome outcrops and rotated to match the Dome’s major axis.
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