Modeling of the Dammam outcrop fractures: Case study for fracture development in salt-cored structures

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ABSTRACT

The exposed Cenozoic carbonates of the Dammam Dome are studied to: (1) characterize fractures and associated structures; (2) interpret the fracture mechanism; and (3) gain insights into fracture development within dome-like structures in the subsurface of the Arabian Gulf region. The fieldwork is integrated with structural analysis of the near-surface horizons mapped from interpretations of 3-D reflection seismic and borehole logs. Fractures are mapped from the outcrops of the middle limestone unit of the Eocene Rus Formation. The outcrops are concentrated in the central, northern and western areas of the Dammam Dome. The fractures are interpreted as opening-mode, bed-bounded joints that form orthogonal sets in most areas. The primary (older) joint set (J1) developed in long lineaments, some of which can be traced for over 300 m across entire exposures. The J1 set is found to be broadly consistent in its trend over the dome, indicating that formation of J1 fractures was systematic and not influenced by local structural anomalies (including karst collapse) formed during the Miocene to Recent. The trend of the J1 set does not correlate with the NE-SW compressional orientation of regional stresses associated with the Zagros Orogeny. Field data interpretation, allied with analysis of dome’s growth and curvature, suggest that the overall joint pattern reflects the growth of the strata as a dome. In addition, the joint density is controlled by structural position on the dome and mechanical stratigraphy. The study results provide a first-order conceptual fracture model for the subsurface reservoirs to guide future development.

INTRODUCTION

The role of fractures as fluid conduits within hydrocarbon reservoirs propelled research since the 1960s (e.g. Stearns and Friedman, 1972) to characterize the nature of fractures, 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 reservoir fractures relies on multidisciplinary approaches to integrate interpretations of reservoir static and dynamic attributes, from a wide range of geophysical and engineering detection methods. Data quality is frequently insufficient to adequately constrain 3-D models of reservoir fractures. Some fracture parameters cannot be observed in core samples or image logs (e.g. fracture length, crosscutting relationships), and observations from wells are also influenced by directional sampling bias for fracture density (e.g. Fouché and Diebolt, 2004). In addition, tensile fractures are sub-seismic geologic features in reservoirs. Despite observations that some reflection seismic attributes may add values for analysis of fracture zones (e.g. Al-Dossary and Marfurt, 2006; Chopra and Marfurt, 2007), rock joints and the faults with offset less than 10 m 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), so the impact of fractures on reservoir behavior can be evaluated separately from the role of original rock matrix and diagenesis. The data shortages encountered by researchers investigating subsurface fractures motivate studying fractures in outcrops that can be used as subsurface reservoir analogues. The study of outcrops should continue improving 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. This should be practical if outcrops share some elements of the geologic settings (e.g. structural history) imprinted in their deeper reservoirs such as this study’s case on the Dammam Dome.

The Dammam Dome is notable at the Earth’s surface from the outcrops that form a relatively high topography in the otherwise flat extent of the eastern Arabian Peninsula. Several studies have established the stratigraphy of the outcrops together with surrounding areas within the Arabian sedimentary basin (Steineke et al., 1958; Powers et al., 1966; Tleel, 1973; Jado and Johnson, 1983; Irtem, 1986; Weijermars, 1999). Other studies have focused on the structural and geomechanical characterization of the outcrops. Geotechnical studies on the area started in the 1980s, including the evaluation of potential geohazards caused by solution cavities in shallow limestone beds (Davies and Lord, 1980; Abu Taleb and Egeli, 1981; Jado and Johnson, 1983; Crosch et al., 1985; Abdullatif, 2010). Weijermars (1999) reported on fractures and joints in the Middle and Lower Rus units.

Hariri and Abdullatif (2004a, b, 2005) and Hariri (2006), in a series of technical reports and conference abstracts, used landsat images and surface mapping to classify three categories of fractures based on size, affects and possible causes: (1) extensional (Mode I) fractures that exceed 500 m and may be related to doming; (2) local fractures (Mode I and III – dip-slip) that are between 1 and 10 m long; and (3) small-sized fractures of mixed modes. Subsurface studies of fractures in the dome are limited to ground-penetrating radar (Al-Shuhail et al., 2004).

Our study adds to the characterization of the outcrop structures (e.g. fractures and karst features). It focuses on large fractures and proposes explanations for the fracturing mechanisms and the factors that may have influenced fracture distributions and patterns. The methodology integrates field data on outcrop fractures with structural analysis of the near-surface structures imaged by industry 3-D seismic methods. Possible causes for the development of these fractures include: (1) the tangential longitudinal stress associated with folding growth of strata in response to active deep-seated salt diapirism; (2) remote compressional stress associated with the Zagros Orogeny; (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 subsurface hydrocarbon reservoirs of the Dammam Dome and similarly folded horizons in the Gulf region.

GEOLOGIC BACKGROUND

Historical Significance

The Dammam Dome is located in the Eastern Province of Saudi Arabia (Figure 1). The area of Dhahran is located on the central region of the dome, which includes the headquarters of Saudi Aramco and the campus of King Fahd University of Petroleum and Minerals (KFUPM). At the Earth’s surface, the Dammam Dome is expressed in the mapping of Tleel (1973) as oval-shaped, relatively high topography extending about 9 miles (14.5 km) along its major northwest-southeast axis, which trends N35°W, and covering an area of approximately 60 square miles (155 sq km) (Tleel, 1973). From subsurface, the geometry of horizons appears to be less elliptical (i.e. more circular) with a ca. N8°W 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) (Figure 1).

The Dammam Dome was the first discovery of a hydrocarbon-bearing structure within the Arabian mainland. The Standard Oil of California (SOCAL) found economic oil from drilling the Dammam-7 Well in March 1938. The credit for the discovery goes to the SOCAL geologists who were, then, motivated by the oil findings in the Bahraini Awali Dome. SOCAL secured a concession with the Saudi Arabian King Abdul Aziz Al Saud in the 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 (unpublished Aramco report) 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 stratigraphic traps, that were found to be oil-bearing rocks in Bahrain, Iraq and Iran, had almost doomed the
Figure 1: (a) Map of Arabia with the Dammam Dome location (red square). (b) The geological map of the Dammam Dome outcrops, from Weijermars (1999) and after Tleel (1973).
continuity of the exploration program. But the company made a paradigm shift in the drilling program in response to Steineke’s insistence to drill wells into deeper rock strata. The deep drilling that penetrated the Jurassic strata established the roots of SOCAL in the Arabian Desert, and the company was later joined by other companies to found Aramco. We currently know 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).

**Structural Origin of the Dammam Dome**

The structural growth of the domes of Dammam in Saudi Arabia and Awali in Bahrain is attributed to deep-seated salt diapirism belonging to the infra-Cambrian Hormuz Salt, which underlies great parts of the eastern area of the Phanerozoic sequence of the Arabian Plate (e.g. Edgell, 1991; Beydoun, 1991; Weijermars, 1999). The salt intrusion below the Dammam Dome was first interpreted on the basis of structural geometry and a strong negative gravity anomaly (Powers et al., 1966). The Hormuz Salt series and their equivalents were deposited in a broad network of subsiding basins stretching from the Arabian Peninsula, through Iran, Afghanistan, Pakistan and India (Falcon, 1967; Stöcklin, 1968; Player, 1969; Gorin et al., 1982, Talbot and Alavi, 1996; Edgell, 1996; Al-Hussein, 2000; Konert et al., 2001; Peters 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 (Kent, 1958, 1979, 1987; Player, 1969; Edgell, 1996; Talbot, 1998).

The extent of the salt in the Zagros and the 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 NS-trending Arabian arches, inherited from Pan-African structures such as the Qatar Arch, which extends to the north up to the Fars domain in the Zagros and Dezful embayment region (Bahrudi and Koyi, 2003; Sherkati and Letouzey, 2004). The timing of salt emplacement and structural growth of the Dammam Dome is beyond the scope of this study. The dome’s uplift during the Cenozoic is relevant in the search for the role of the folding-associated tangential stresses on fracture development.

**Stratigraphy of the Dammam Dome Outcrops**

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; Weijermars, 1999). The Paleocene to the Early Eocene Umm er Radhuma (UER) Formation is the lowermost Cenozoic formation. The name of the formation was given by S.B. Henry and C.W. Brown in 1935 (unpublished Aramco report) and derives from Umm Radmah wells (28°41’N, 44°41’E), which produce water from the upper part of the formation. 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 3 m-thick section of vuggy dolomite located about 488 m east of Jabal Umm ar Ru’us 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, 1999). The regional stratigraphical sequence above the UER Formation includes the Rus, Dammam, Hadrukh and Dam formations (Figure 2). 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, particularly the Rus Formation as it dominates the surface exposures of the Dammam Dome. Within the sequence of the exposed rocks, two unconformities were documented in previous works at: (1) Jabal Umm ar Ru’us where the pre-Neogene angular unconformity underlies the Middle Miocene Dam Formation; and (2) Jabal Midra al-Janubi where the Dam Formation lies unconformably on top of Midra Shales of the Dammam Formation (e.g. Tleel, 1973). The unconformity at Jabal Midra was documented to be poorly recognizable from the jabal’s surface, but a new road cut into the base of the jabal has facilitated recognition of the unconformity during the course of this fieldwork.
Figure 2: (a) The Cretaceous and Cenozoic stratigraphic column of eastern Arabian sedimentary basin. (b) Stratigraphic column of the Dammam Dome outcrops (from Weijermars, 1999, and after Powers et al., 1969, Tleel, 1973). Pictures are from fieldwork. Ages from Geological Time Scale GTS 2012 (Gradstein et al., 2012).
The Rus Formation was dated as Eocene and named after its type section at Jabal Umm ar Ru’us near the dome’s central region. The type section was referred to as the “Chalky Zone” when it was first established by S.B. Henry and J.W. Hoover in 1934. R.A. Bramkamp, in 1946 (unpublished Aramco report), 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 (Tleel, 1973 from unpublished Aramco reports). Tleel (1973) reported that Thralls and Hasson (1956) were 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 Sander’s (1962) discussion. Powers et al. (1966) divided the Rus Formation into three lithologic units and noted that diagnostic fossils have not been recognized in it. 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 the Rus Formation was re-described by Tleel (1973) and divided into three informal zones selected strictly for mapping convenience and do not correspond to Powers et al.’s (1966) distinctions.

Table 1 summarizes the different subdivisions of the 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.

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<th>Table 1</th>
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<tr>
<td><strong>Subdivisions of the Rus Formation from different authors</strong> (from Weijermars, 1999)</td>
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<td>Upper Rus Formation</td>
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<td>Middle Rus Formation</td>
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<td>Lower Rus Formation</td>
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The Dammam Formation was named by Bramkamp in reference to its type locality in the rimrock of the Dammam Dome (unpublished Aramco reports, 1941, 1964; Powers et al., 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) (Figure 2). The lower four members are also exposed in the dome’s core area at a small ridge near Aramco’s hospital at 26°14’81”N and 50°08’15”E (Weijermars, 1999). The Midra Shale at the base of the formation was deposited conformably on the Rus Formation followed by the deposition of 0.6 m 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 during the last marine transgression to cover the Dammam Dome area. The formation was deposited in late early Miocene in several facies ranging from a coral-algal reef, which grades laterally into a molluscan-rich facies containing pellets, foraminifera, echinoids, and stromatolitic limestone (Tleel, 1973). The type locality of the lower part of the Dam Formation is at Jabal al-Lidam, which is located at 26°21’42”N and 49°27’42”E, about 50 km west of Jabal Umm ar Ru’us and outside the dome’s area.
Fracture development in salt-cored structures, Dammam Dome

(Tleel, 1973). The Dam unconformably overlies the Rus Formation at Jabal Umm ar Ru’us, 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 (Tleel, 1973). The Dam rocks probably range from upper Burdigalian to Neogene (Kier, 1972); therefore the unconformity between the Dam and Dammam formations corresponds to a time gap of some 22 Myr, extending from the end of the Ypresian (43.8 Ma) until the onset of the Burdigalian (21.8 Ma) (Weijermars, 1999). But as Weijermars (1999) 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.

Structures within the Dome Outcrops

The local exposed geological features noted in Tleel (1973) include slumps, local steeply dipping anticlines and synclines. These structural features were mentioned without geological mapping nor geographic references, except for a syncline referenced at 26°19'23"N and 50°06'37"E, and slumping at 26°18'34"N and 50°08'16"E. No faults were noted at Earth’s surface (Tleel, 1973). Tleel (1973) reports that some slumping blocks might be faulted, including the exposure of the Dammam Formation located directly east of Saudi Aramco’s hospital (26°18'41"N, 50°08'15"E). Our fieldwork documents the karst features developed within the exposure, but notes no clear evidence for faults.

Rock fractures were first documented by Weijermars (1999) from outcrops located within the KFUPM campus. He reported that jointing is irregular and rare in the Lower Rus unit due to the presence of the incompetent marls, whereas regularly spaced joints are characteristic for the Middle Rus unit. Hariri and Abdullatif (2004a, 2005) add to the description of the outcrop fractures, and conjecture that the large fracture lineaments are a consequence of the structural growth of the dome.

METHODS

The methods used in the study integrate fieldwork on fracture characterization and rock rigidity, with numerical analysis for strains associated with structural development of the dome and near-surface faults. In the field, we characterized the fractures and other structural elements (e.g. karst) within the mapped outcrop areas (Figure 3). We considered several aspects for fracture characterization and fracture genesis, such as age relationships of fracture sets, dome modeling, and potential influence of different local, near-surface and far-field regional stress regimes.

We used the geological map of Tleel (1973) to display the locations of outcrops and the boundaries of stratigraphical units (Figure 3). Exposed rock units are recognized from rock descriptions, and the presence of distinctive stratigraphical markers and unconformity surfaces reported in previous studies (e.g. Tleel, 1973). Images from Google Maps were initially used to delineate fractures from the visible linear vegetation that developed along open fractures. The presence and attributes of the fractures were ground-truthed from detailed field mapping for fractures.

Detailed Fracture Maps (10 m × 10 m)

Some areas were selected to map fractures from the flat top of the Middle Rus outcrops to show fracture orientations, density and crosscutting relationships from small areas that represent the outcrop fractures. The mapping was conducted on locations toward the central regions of exposures and reasonably far from cliffs to exclude or limit the number of slump-induced fractures. The map areas were defined as rectangles on the ground (10 m × 10 m), oriented to the north and marked at corners using outstanding small blocks, e.g. large stones or cones. The mapped areas were positioned to capture the maximum number of the large fractures. All fractures, which are longer than 30 cm, were mapped on gridded scaled papers, which were later scanned and digitized using a graphic editing application. Beyond the boundaries of the 10 m × 10 m maps, large fractures were traced from satellite images to analyze variations in fracture orientations and spacing across exposures.
We used the Schmidt hammer to measure rock rigidity to estimate the rock elastic properties (e.g. Young’s Modulus, E). Several rigidity measurements were collected for the Middle Rus unit at different locations. The Young’s Modulus is calculated from an average rigidity value and the following empirical formula (Katz et al., 2000):

$$ E = 0.00013 R_c^{3.09074} $$

where $R_c$ is the corrected rigidity reading of the Schmidt rebound hammer.

The rock rigidity readings are obtained using N-type Schmidt hammer following the suggested procedure of Aydin (2009). Every rebound hardness data is an average of 10 tests obtained from one location, at which the hammer is positioned perpendicular (+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.

**Flexure-Based Methods**

Three methods based on the concept of flexure, and its relation to fiber stresses, were used to assess the role of folding in fracture development.
**Curvature Analysis of 1-D Fold Model**

We used a 1-D curvature model of a folded rock layer 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 the 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 \((L_1)\) than the original length \((L_0)\), the folding associated longitudinal strain, \(\varepsilon\), at the top of the layer can be expressed as follows (e.g. Price and Cosgrove, 1990, p. 190; Roberts, 2001; Turcotte and Schubert, 2002; Hunt et al., 2011):

\[
\varepsilon = \frac{(L_1 - L_0)}{L_0}
\]

\[
\varepsilon = \frac{(h/2)}{R} = \frac{(h/2)}{k}
\]

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 osculating circle is the circle that approximates the fold curve at a given point. The 1-D strain \((\varepsilon)\) in formula (2) can be related to stress using Hooke’s law of elasticity:

\[
\sigma = E \times \varepsilon = E \times (h/2) \times k
\]

where \((E)\) is Young’s modulus.

We used 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 using the Schmidt hammer. The 1-D curvature model is based on the current geometry of the near-surface units of the Dammam Dome. The geometry of the dome could be inferred from 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 depth-converted and tied to well logging data. The use of such a near-surface horizon could serve the need of finding more accurate geometry for the overall dome than relying on the field mapping of Tleel (1973). To get curvature of 1-D fold model, one cross section that represents 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 shows the maximum curvature of folded layers.

To account for the potential presence of fluid in rock pores, the effective stress \((\sigma_{ij}^*)\) was 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 \((p)\):

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

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.

**Fracture Trends from 3-D Strain Model**

We derived a 3-D strain model to compute for trends of tensile fractures that potentially developed due to stresses associated with deformations in the shallow 1,200 m sedimentary section. The strain model was a product of volumetric structural restorations. The restorations were applied to a full model, which includes all mapped subsurface horizons of the Dammam Dome (Figure 4). This study focused on the strain developed within the shallow section. The deformational structures (folds and faults) are modeled utilizing interpretations of 3-D reflection seismic and well logs. The 3-D geological framework was discretized into tetrahedral finite elements, and assigned
机械性能来自于一个已经建立的地质力学模型，用于表土层的下部单位。这些建筑物的变形是通过gOcad的科研插件恢复的，该插件基于有限元方法，使用机械性能来引导恢复，使用体积保全和应变最小化约束（例如，Mueller et al., 2005；Muron, 2005）。

在沉积时恢复岩层中的褶皱和断层，以恢复到一个平坦的基准面，这可以记录当时的原始形状。模型被考虑为不可压缩材料（或岩层）的每一部分（或节点）在恢复过程中都会被移动到沉积时的位置（例如，Mallet, 2002）。恢复过程允许计算每个四面体网格的恢复向量。每个节点的每个网格单元的体积和形状会发生变化。这些变化的量被用来分析应变的主要成分。应变在三维空间中计算，但可以在地图视图中投影显示最大横向拉伸和收缩方向的向量。由于恢复技术是结构演变的逆向建模，恢复模型中的最大收缩向量的方向在前向意义上与拉伸方向相似。因此，恢复模型中垂直于最大收缩方向的潜在方向可以作为拉伸裂缝的方向。浅层部分被分为两个网格单元：上部单元（ARUM）和下部断层单元（PAMU）；遵循沙特阿美公司对阿鲁玛组（ARUM）和前-阿鲁玛不整合（PAMUS）命名的惯例。浅层部分不包括上部单元（ARUM）和中鲁斯之间的间隔，因为从地球表面没有准确的结构图。

**Fracture Trends from Typical Dome**

这种分析用于获取不考虑局部影响的典型穹隆所观察到的裂缝趋势。3-D模型中拉伸裂缝的趋势可以预测到穹隆顶部，并可以与达曼姆进行比较。该分析使用了数学软件（例如，Maple）来计算给定位移函数（w）的平面应力场（x, y）沿三维弯曲层的顶部，这与Cooke et al., 2000; Turcotte and Schubert, 2002：
Fracture development in salt-cored structures, Dammam Dome

Fracture development in salt-cored structures, Dammam Dome

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

(6)

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 that resembles 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 (\(\nu\)):

\[
s_{\max} = -z\mu \left( \frac{\partial^2 w}{\partial x^2} + \nu \left( \frac{\partial^2 w}{\partial y^2} \right) \right)
\]

(7)

\[
s_{\max} = -z\mu \left( 1-\nu \right) \left( \frac{\partial^2 w}{\partial y \partial x} \right)
\]

(8)

\[
s_{\max} = -z\mu \left( \frac{\partial^2 w}{\partial y^2} + \nu \left( \frac{\partial^2 w}{\partial x^2} \right) \right)
\]

(9)

As the fiber stresses \((x-y)\) vary throughout the thickness of the layer, only tangential principal stresses \((S_{\max})\) at the top of the layer are considered:

\[
S_{\max} = \frac{1}{2} s_{\max} + \frac{1}{2} s_{\max} + \frac{1}{4} (s_{\max} - s_{\max}) + s_{\max}
\]

(10)

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.

FIELDWORK RESULTS

The spatial areas of rock exposures are generally limited due to weathering, sand cover, and removal of a few outcrops due to urban development that followed oil discovery. The analysis of the 1958 aerial photographs indicates that the change in the outcropping landscape was limited as most areas of urban expansion were built on flat and low-relief land. The outcrop study is concentrated on the areas of well-exposed rocks mapped in Figure 3, in addition to some exposures studied from recent road cuts and human-made trenches. Fractures are abundant in outcrops, but are not present within outcrops located in further southern and eastern flanks. In the central regions, the fractures preferentially host vegetation, which brings attention to their long lineaments on satellite images, as Hariri and Abdullatif (2005) have previously noted.

Other significant structural elements include karst features, and a few small-scale reverse faults, which are presented in a separate section below. Fractures are observed within all exposed carbonate units (Figure 3), but mostly notable 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 (Figure 1). The fractures are opening-mode fractures (or joints) that mostly form orthogonal sets, and display no evidence of shear (Figure 5). The analysis of fractures focuses on systematic joints and dominant patterns within the Middle Rus unit, but also includes significant observations from other carbonate units.
Figure 5: Examples of joints from the top flat surfaces of the Middle Rus unit.
Fractures within the Middle Rus Outcrops

The unit outcrops are well exposed within the central, northern and northwestern regions, but mostly covered by the Upper Rus unit in the vicinity of Jabal Umm ar Ru’us at the dome’s center (Figure 3). The joints identified from the top flat surfaces of the Middle Rus are classified to two main systematic joint sets: the northwestern-trending set or J1, and the orthogonal northeastern-trending set or J2 (Figures 5 and 6). The classification is based on the dominant trends of joints and their abutting relationships. The joint abutting relationship suggests that J1 set is the primary (or older) joint set, hence, bound all other joints, including J2 – the joint set that forms a well-developed orthogonal pattern in some locations (Figure 5a). The orientations of the different joints measured from the field and from Google Maps are presented in rose diagrams in Figure 6.

Figure 6: Fracture trends (rose diagrams) from the Middle Rus outcrops. The numbers in the upper left squares refer to the field stations on the map, and the numbers on the lower right corner of the rose diagrams are the number of measured fractures. The average of the primary northwestern-trending joints (J1) is drawn as dashed brown lines on the outcrop map.
The through-going joint set (J1) has a dominant northwest trend (Figures 7a and 7b). The lengths of J1 set (as measured along bedding plane) are greater than outcrop extents. On some outcrops, joint lengths exceed 300 m. At field Stations 3 to 6, the J1 set can be traced for about 1,000 m from both field and Google Maps (Figure 6). The joints can be missed in other areas when the unit is absent or covered by aeolian sands. The average trends of the J1 set change slightly from one exposure to another. This is obvious in the exposures (Stations 2 to 5) that span from the central region to northwestern boundary mapped for the Lower Rus exposures (Figure 7b). Rose diagrams show
westerly increased trends for outcrops closer to the boundary (Figure 6). This apparent systematic deviation in trends is not present in other field stations. The spacing of the J1 set generally ranges from 3 to 7 m, with 6 m being the most frequent measured distance (Figure 7). Field mapping suggests that the different spacing can be found on the same outcrop, but spacing generally increases from Stations 3 to 5. This indicates that the spacing is relatively larger in the stations closer to the northwestern flank of the dome.

In the same northern and northwestern regions, the second identified joint set (J2) is always bounded by the J1 set and has a dominant northeast (NE) trend. The two sets, therefore, form an orthogonal pattern in most mapped areas. Between the orthogonal joints, other small, mostly curved, surficial cracks are abundant. These small joints are marked in black color in the detailed maps (Figure 7a). In general, small curved fractures are not systematic joints and seem resulted from local stresses induced by rock sliding due to weathering and/or karstification. This type of locally limited fractures is not likely to have significance as reservoir analogue, but had to be delineated from the main systematic joints.

**Fractures within Other Carbonate Units**

Joints are observed within the units of the Lower Rus, Upper Rus, Dammam and Dam. The Lower Rus unit occupies considerable area of the dome's 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 from the cliffs of some relatively high topography mesas. The best exposures of the Lower Rus are located at Stations 6 and 16 (Figure 3). At Station 6, the J1 set is developed with a radial pattern. At Station 16 (26°18'59"N, 50°06'45"E), the joints are developed with different spacing within the Middle and Lower Rus units (Figure 8). The joint spacings are apparently influenced by mechanical properties and thicknesses of the Middle and Lower Rus units. The Upper Rus strata are exposed from a road cut at Jabal Umm ar Ru'us, however, the fractures are only observed in the carbonate units from the side exposure (or cross-sectional view). It was neither accessible to measure fracture orientations, nor possible to observe fracture crosscutting relationships.
The Dammam Formation is present in two outcrops: one at the central area of the dome and the other at its further western boundary. Fractures are observed within the outcrop at the dome’s central region, but missing from the outcrop at the dome’s western flank. Fractures of the outcrop at the dome’s 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 are consistent with the joints of the Middle Rus unit.

The joints within the Dam Formation are abundant, but seem less consistent in their patterns than the joints observed in the Rus and Dammam formations. The joints found at the best exposure at Jabal Umm ar Ru’us are curved 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 curved and small, a few others seem perpendicular to bedding and systematically spaced.

Variations in Fracture Trends and Spacing

The J1 set is a systematic joint set, which means it mostly strikes in parallel northwestern trends in the well-exposed rocks. Considerable variations in their general trends and spacing (or density) are present at the western flanks of the Dammam Dome at Stations 6 and 8 (Figure 6).

At Station 6, the J1 set is developed with a radial pattern and its trend ranges from north-south to east-west. The joints appear to form a fan-like pattern departing away from the dominant northwestern trend observed from Stations 2 through 5 (Figure 9). The area 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 a fault, syncline or an anticline, but there is a small sinkhole in the nearby high outcrops of the Middle Rus unit. The radial fracture pattern is localized within the influence of a small circle (ca. 500 m radius). The general radius of the Dammam Dome exceeds 5 km, which indicates that the variation in joint trends is due to a local anomaly in geometry on the structure.

At Station 8, the spacing of the J1 set differs from that measured at other field stations (Figure 7a). The J1 set is inferred to have a large spacing due to the absence of the J1 set within these scattered outcrops. The J1 set apparently forms the edges of these elongated, 15–20 m-wide, and NW-trending outcrops. Therefore, joint spacing is estimated to range from 15–20 m. This makes the density of the 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 field Stations 1–5 (Figure 7).

Karst Features

Ten small and large karst feature areas are found at scattered localities (Table 2 and Figure 10a). 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 synforms within the Lower Rus unit at some areas. The small sinkholes are of a bowl-shaped morphotype, but larger ones have indefinite shape and are simply referred to as synforms.

The large synforms are identified from some exposed units that dip with some angle to the flat surface. 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 central region of the dome. Some sites (e.g. karsts (1), (4) and (7) in Figure 10) are observed with concave up strata, where strata dip toward karst features. The karstification is interpreted as the obvious mechanism for the development of the small and large synforms at the Earth’s surface.

Although some fractures seem to be gravity-driven due to rock collapse toward sinking areas, the systematic J1 joint set can be identified within and near sinkholes (Figure 10b). Field observations indicate that karst-related fractures 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, curved and lack linearity, the J1 set is found to follow the NW trends and to be...
Figure 9: (a) A satellite image (Google) shows vegetation along large joints developed in radial pattern within Lower Rus unit at ST#6. (b and c) The joints can be seen also from these two photos.
Figure 10: (a) Locations of the karsted areas (e.g. sinkholes) and small reverse faults, numbers used to reference the karst areas. (b) Google Map with bed dips for outcrop at karst # 7 in (a). The rose diagram is for joint trends. NW-trending (J1) set is ubiquitous and seem unrelated to the development of karst (outlined circles).
Fracture development in salt-cored structures, Dammam Dome

Fracture development in salt-cored structures, Dammam Dome

bed-perpendicular within the inclined rock units. Karst-related fractures are not systematic and may have developed in response to local stresses associated with rock sliding toward sinkholes.

Table 2 lists the geographic locations and other information on the karst structures observed from the outcrops of the Dammam Dome. More details can be found in Al-Fahmi (2012).

Small Reverse Faults

Small reverse faults are observed at three sites at: (1) 26°18'38.40"N, 50°09'55.10"E; (2) Jabal Umm ar Ru’us (within the Upper Rus unit); and (3) Jabal Midra al-Janubi (within the Dam Formation). The three sites are located far from one another; one in the eastern flank, the two others on the dome’s central region and northwestern flank, respectively (Figure 10).

The first site in the eastern region of the dome (Figure 11a) is an excavated area with exposed rocks belonging to the Upper Rus from the lithological description of both shale and carbonate units. The hanging wall of the reverse fault appears to have moved in the southwest direction (ca. S25°W), although it could be oblique by some degrees, see map in Figure 11d. The amount of slip is estimated to be 15 cm. The second reverse fault is exposed from a road cut made through Jabal Umm ar Ru’us (Figure 11b). The fault is found in the Upper Rus within 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 small and estimated to be about 15 cm. At Jabal Midra al-Janubi, several reverse faults are observed from the road cut within the Dam Formation (Figures 11c and 11d).

The hanging walls of these reverse faults appear to have moved toward the karstification domain. Apparent directions of fault displacements are in the same directions of the bed inclinations. Two faults located at one side of the outcrop (Figures 11c and 11d), about 10 m apart, and show apparent different displacement directions. One fault displays northeast slip while the other apparently moved toward the north. Orientations of fault slips are not consistent with the fold axis or far regional stress of Zagros (Figure 11d).

<table>
<thead>
<tr>
<th>No.</th>
<th>Karst Features</th>
<th>Location</th>
<th>Area (square meters)</th>
<th>Formation</th>
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<tbody>
<tr>
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<td>1,000</td>
<td>Dam</td>
</tr>
<tr>
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<td>Synform</td>
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<td>Rus</td>
</tr>
<tr>
<td>3</td>
<td>Synform</td>
<td>26°19'23&quot;N, 50°06'37&quot;E</td>
<td>Uncertain</td>
<td>Rus</td>
</tr>
<tr>
<td>4</td>
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<td>20,255</td>
<td>Rus</td>
</tr>
<tr>
<td>5</td>
<td>Sinkhole</td>
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<td>4,115</td>
<td>Rus</td>
</tr>
<tr>
<td>6</td>
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<td>26°19'03&quot;N, 50°07'58&quot;E</td>
<td>300</td>
<td>Rus</td>
</tr>
<tr>
<td>7</td>
<td>Sinkholes</td>
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<tr>
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<tr>
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<td>650</td>
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ANALYSIS

We investigate the fracturing mechanism from the joint characterization, their relative chronology, and their potential relationships with the major structural and depositional events of the Cenozoic. The established framework of tectono-stratigraphy of the Dammam Dome and surrounding regions allow us to assess different hypotheses for the joint genesis. The fractures may have developed due to one of the following: (1) remote (far-field) compressional stress associated with the Zagros Orogeny; (2) tangential stress associated with the dome’s growth; or (3) stresses induced by development or reactivation of local structures.

Far-field Regional Stresses

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 fractures (e.g. joints) that develop due to far tectonic stresses have trends that are consistent with the known far-field regional stress regime, and can be driven by applied compressive stresses, especially in the presence of fluid...
Figure 11: (a, b, and c) Pictures and sketches for the small reverse faults (red) found at locations (a, b, and c) on the map of the Dammam Dome in (d); (e) 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 (N20°E).
Fracture development in salt-cored structures, Dammam Dome

Overpressure conditions (e.g. Hodgson, 1961; Engelder and Geiser, 1980; Engelder, 1982; Engelder and Gross, 1993). The influence of the Zagros compressional regime is observed in the subsurface of eastern Arabia from reservoir data analysis of in-situ stresses. Also, 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 Orogeny (Ameen and Hailwood, 2008). Compressional directions of Zagros were identified to be NE–SW and N20° during the Neogene (e.g. McQuarrie et al., 2003; Lacombe et al., 2011; Figure 12).

The compression/shortening direction remained within the close range of N20° from the Middle–Late Miocene to present-day in the western Fars region. The N20° compressional direction is consistent with the current compressional direction from the focal mechanisms of basement earthquakes and the geodetic data (Walpersdorf et al., 2006). The regional compression was generally constant across the Zagros collision zone during Late Neogene, consistent with the stability of the Arabia–Eurasia convergence over the last 20 Myr (McQuarrie et al., 2003; Mouthereau et al., 2012). If the rock joints of the Dammam Dome outcrops resulted from the regional stresses associated with the Zagros compression, the joint trends are expected to develop in systematic NE-SW trends (Figure 12b). This is a trend 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 the Zagros.

Local Structures: Karsts and Small Reverse Faults

Stresses associated with development of deformational structures may induce fractures within the influence of the deformations. We account for fractures that may develop in association with rock failure due to karstification or faulting process. Observations of karst features within the Rus, Dammam and Dam formations suggest that karstification was active within all the carbonate units of the Dammam Dome outcrops at some time. The limited spatial distributions of karst features and the abundance of the J1 set across exposures indicate that the J1 set cannot be attributed to stresses associated with local rock collapse due to karstification. In addition, the J1 set is found to be systematic (within and near sinkholes and within locations without sinkholes; Al-Fahmi, 2012).
This observation indicates that joints may have developed prior to karst development. If karst features predated the development of the J1 set, the joints would lack the systematically linear patterns that existed in outcrops. In karsted areas, the joints are expected to display concentric patterns that 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 the J1 set. The process of karstification is beyond the scope of this study, but karst development can be controlled by rock fractures and antecedent topography (e.g. Guidrey et al., 2007).

The presence of some small reverse faults indicates that compressional stress acted on the rocks. These faults are found within units younger than the Middle Rus unit, within the Upper Rus unit and Dam Formation. No evidence that the stress associated with development of these faults influenced the pattern of the J1 set, as these faults are not observed within or nearby to the outcrops of the Middle Rus (Figure 11d). 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 locally or regionally consistent with compressional trends; they are neither consistent with the axis of the Dammam Dome, nor parallel to the regional stress of the Zagros Orogeny. The development of these faults may be attributed to soft-sediment deformation within karsted areas (Al-Fahmi, 2012).

Stresses Due to Dome Development

Fracture development is well-documented to be mechanically related to folding (e.g. Stearns and Friedman, 1972; Cooke, 1997; Cosgrove and Ameen, 2000; Ismat, 2008). Fold-related fractures are expected to propagate perpendicular to maximum tensile stresses within bending units. The fold geometry can be used to predict the stress patterns associated with fold structures. 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's growth, and the strain developed in the shallow section. 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 show failure of beds due to extensional stresses that may have influenced all exposed units. Among these outcrops, the Middle Rus limestone is 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. The outcrops generally display interesting 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 at Station 6. Some slight change in the general 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 unit, 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 defined. The J2 set may have developed due to local stress concentration between the developed J1 set. This could happen 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 and Pollard, 2000). Accordingly, the J2 set may have resulted after local normal stresses parallel to the J1 set had 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., 2011). Weijermars (1999) interpreted that the tectonic style of the Dammam and Bahrain domes to be dominated by vertical rather than lateral displacement. The exposed carbonate units of the Dammam Dome gently evolved vertically, and without lateral growth. The joint density may increase with increasing stress of tightening dome, but the primary trends may still generally reflect the similar dome's geometry. This situation allows correlating the trends of primary joint (J1 set) with the dome's geometry.
The relative age of the J1 (the older set) may be interpreted from the stratigraphic 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 Jabal Umm ar-Ru’us, whereas the formation has a maximum thickness of 32.5 m 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 120 m, whereas the formation is missing in the area of the Dammam Dome (Weijermars, 1999). Accordingly, the Oligocene Orogeny may constrain the relative time of the older J1 set developed within the Middle Rus unit, if it is related to the dome’s growth. The structural growth of the Rus and Dammam formations may have started shortly after their deposition. The dome’s uplift during Oligocene was the last event in the series of uplift episodes mostly observed from the subsurface horizons. As a major structural event, the Oligocene uplift may have driven the thin (10 m) Middle Rus to fail in tension to accommodate ongoing stretching, producing the observed long J1 set.

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 widespread. The three methods analyzed in the following sub-sections are based on the use of flexure 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 joint patterns.

Stress from 1-D Curvature Model

The 1-D 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 13. The curvature is calculated from the inverse of the radius (R). The radius is obtained using the following mathematical formula:

\[ R = \frac{h}{2} + \frac{c^2}{8 \times h} \]  \hspace{1cm} (11)

where h is the elevation, and c is the chord length (Figure 13b). The thickness (h) of the Middle Rus unit is used, which is documented to be 10 m (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 et al. (2000):

\[ E = 0.00013 R_c^{3.09074} \]  \hspace{1cm} (12)

where \( R_c \) is the corrected rigidity reading of the Schmidt rebound hammer.

The calculated tangential stress ranges from 1.9 to 2.2 MPa. The stress estimate is compared with tensile strengths of limestone found in the literature. One experimental study on a limestone formation in Saudi Arabia provides a range for tensile strength between 2.13 and 2.39 MPa, with 2.31 MPa as an average value (Khan and Al-Shayea, 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 and Al-Shayea (2000) lack detailed geological description of the tested limestone that may differ in its rock properties with that of the Middle Rus limestone. Some consideration is given to the possible wide range of lab results due to lack of constraints on the effects of specimen size, shape and testing methods on strength measurements. Also, the fact that lab specimens are intact makes up-scaling from lab to field 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 within this context. For example, the Middle Rus unit hosts some scattered vuggy texture (Tleel, 1973), hence, it reduces the total rock strength. The vugs are mechanically rock flaws and their effects on rock...
mechanical properties are similar to that of pre-existing joints (Exadaktylos and 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 and Bombolakis, 1963), joints may initiate due to stress concentration at rock flaws (e.g. vugs) and propagate according to local principal stresses acting on the rock.

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 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, and calculated from the overburden of the 75 m thicknesses of the Upper Rus and the Dammam formations. 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 4 consider poroelastic effects at the bottom of the burden assuming a relaxed tectonic region and a hydrostatic pressure of fresh water. The density (2.56 g/cm³) and Poisson ratio (0.21) are average values for the Middle Rus (Abdullatif, 2010), and used here 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, 1998). 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, and helped the tangential stress driven by the dome’s uplift to generate the joints within the Middle Rus unit.

**Joint Trends from 3-D Strain Model**

The fracture trends computed from the 3-D strain model are compared with the trends of the observed primary joints (J1 set) from outcrops (yellow lines; Figure 14). 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’s crest. The variations in computed trends partially reflect local geometries due to fault displacements, therefore, produced joint trends that are different from the one observed in outcrops.

![Figure 14: The structural map of the PAMU surface with the predicted tensile fractures from 3-D strain model (black vectors) and average trends of outcrop joints (yellow lines). In the white frame, the correlation displays lack of agreement in general trends except toward the dome center. The trends of computed fractures are highly influenced by local variations in structure and appear with a dominantly north-south strike within the fault zone in the frame. Numbers and circles refer to field station locations.](image-url)
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 the faults mapped in the subsurface 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 (Figure 14). 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 (Figure 14). Accordingly, the analysis results show the potential influence of the fault geometry (the fault displacements) if faults were to extend 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.

**Joint Trends from a Typical Dome**

The idealized dome model is introduced to predict fracture trends without local influence of faults observed in the 3-D strain model. 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: 11 km; length: 13.5 km; amplitude: 290 m). The dimensions generally resemble that of the Dammam Dome. The computed joint trends from analytic function are superimposed on the Dammam Dome map (Figure 15), to correlate computed and observed joint patterns. Figure 15 displays that the lack of observed well-developed radial pattern joints, as the 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. In central regions, the trends slightly deviate from the predicted trends, possibly due to some local variations. Hariri and Abdullatif (2004a) noted that fracture trends from the KFUPM area (central region) can match a predicted pattern over a dome's shape. The lack of match in trends in western flank suggests local deviation of the dome's geometry from the idealized one used in this analysis. The geometry of the Dammam Dome is not an idealized oval-shaped dome, but agreements in trends support the relationship between joint trends and dome's 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.

**Variations in Joint Trends**

The dome's geometry from subsurface horizons (e.g. the PAMU) is not symmetrical (Figure 14). It displays local curvatures, some from the fault escarpments, and others that may reflect noisy seismic data. The location map of the J1 set is presented with respect to the dome's 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 Stations 6 and 8. Both field stations are located within the dome's western periphery (Figure 14). At Station 8, the primary joints (J1 set) are developed with a larger spacing range from 15–20 m, while the spacings at other stations (e.g. toward the dome's central region) range from 3–7 m. The joint spacings (density) could be attributed to variations in the tangential stresses from folding of the Middle Rus.

The density of the J1 set may reflect the structural position on the dome, with higher joint density toward the dome's central region and lower joint density toward the flanks; where the curvature is gentler in the flank than that of areas located toward the dome's central region. The geometry of the PAMU also shows a local fold coinciding in location with the Station 6, where the joints developed in local radial pattern. It is not clear from seismic interpretation if it is related to a fault at depth. It is important to consider the potential stresses from the western tip of the observed fault (Figure 14) 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 Station 6. The other possible explanation for the radial pattern of Station 6 is a large subsidence due to karstification beneath the Earth's surface (e.g. within the UER Formation).

CONCLUSIONS

We presented the characterization of the fractures observed within the exposed carbonate units of the Dammam Dome. Within the Middle Rus, the fractures are interpreted as opening-mode, bed-bound joints that form orthogonal sets in most areas. The study focused on the J1 set, which was interpreted from crosscutting relationships to be the primary joint set. The concluding points and implications of 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 Orogeny. The Zagros compressional trends were previously identified to be NE–SW (N20°) during the Neogene and remained within the close range of N20° 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 Orogeny.
(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, which 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 to overcome the tensile strength of the Middle Rus unit and, consequently, produced tensile fractures, as per the suggestion of the simple analysis of the 1-D curvature. The potential presence of pore fluid may have enhanced the fracturing process.

(4) Agreements in correlation between most of the J1 trends with the computed trends from typical dome’s geometry suggest that the J1 set may have developed due to the tangential stresses associated with the dome’s growth during the Oligocene uplift. This observation 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 or less idealized dome’s shape.

(6) The difference in the joint spacing 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 spacing 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’s 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 be correlated with the fold geometry, if folded rock units lack pre-folding fractures. The results also indicate that joint density may increase with increasing curvature.

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Fracture development in salt-cored structures, Dammam Dome


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