Evolution of fractures in a highly dynamic thermal, hydraulic, and mechanical system – (I) Field observations in Mesozoic Carbonates, Jabal Shams, Oman Mountains

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ABSTRACT

We studied an exhumed high-pressure cell in outcrops of Cretaceous carbonates on the southern flank of Jabal Shams in the Oman Mountains. This more than 2 km thick sedimentary pile contains reservoir and source rocks in northern Oman and the United Arab Emirates. It develops a complex and rapidly changing anisotropy, due to mechanical stratigraphy and several generations of pervasive regional fault and fracture sets. Calcite cement healed faults and fractures before the next sets were formed.

Burial extension within a high fluid-pressure environment led to the formation of four fracture generations by an anticlockwise rotating stress field. This was followed by bedding-parallel shear under lithostatic fluid-pressure conditions at a minimum temperature of 134–221°C deduced from primary and pseudosecondary fluid inclusions in quartz. The high pressure cell was drained along dilatant normal faults that were also repeatedly cemented and reactivated.

The rapidly changing mechanical anisotropy, in combination with a chemically reactive system formed a complex feedback system in which the mechanical strength, strain and the permeability underwent major changes in this coupled thermal, hydraulic, and mechanical (THM) system.

INTRODUCTION

The Oman Mountains offer exceptional outcrop quality over large areas allowing access to structures at a variety of scales (Figure 1). Our study is located on the southern flank of Jabal Shams exposing Mesozoic carbonates with several generations of regional vein sets (Hilgers et al., 2006a). The structural inventory incorporates veins, joints and normal faults as a result of a multiphase deformation at a depth of several kilometers (e.g. Glennie et al., 1974; Breton et al., 2004; Glennie, 2005; Al-Wardi, 2006; Hilgers et al., 2006a; Searle, 2007). We carried out a detailed structural study in the field and interpreted satellite images (Holland et al., in press) for a regional study of the meso-scale features and their spatial distribution. The main aim of this study is to describe and classify the structural elements of the field area. These micro- and meso-scale field observations are used to obtain detailed structural analyses and the temporal sequence attempting to extend the work of Hilgers et al. (2006a).

The information is further used to discuss aspects of thermal, mechanical and hydraulic (TMH) processes in what we interpret as a high-pressure cell (Bradley, 1975; Barton et al., 1985; Engelder, 1990; Bradley, 1994; Ortoleva, 1994; Ortoleva, 1995; Nguyen and Selvadurai, 1998; Tsang et al., 2000; Olsson and Barton, 2001; Tsang et al., 2004).

GEOLOGICAL OUTLINE

The study area is located on the southwest flank of Jabal Shams (Figures 2 and 3), the highest peak of the Al Jabal al Akhdar domal structure. The Al Jabal al Akhdar dome defines the central part of the Oman Mountains, which extends from the Musandam Peninsula in the north of the Sultanate of Oman, to the Batin coast in the southeast (Figure 1).

This mountain belt is part of the Alpine-Himalayan chain that formed during northeast-directed subduction and accretion of the Arabian Plate below the Eurasian Plate (e.g. Glennie et al., 1974; Beurrier et al., 1986; Loosveld et al., 1996; Breton et al., 2004; Glennie, 2005; Al-Wardi, 2006; Hilgers
et al., 2006a; Searle, 2007). Details of this major geodynamic event such as the extent and number of microplates, the timing of deformation, the partitioning of strain, the direction of subduction as well as details on the exhumation are still subject of controversial discussions (e.g. Glennie et al., 1974; Pillevuit et al., 1997; Miller et al., 1999; Gray and Miller, 2000; Wilson, 2000; Miller et al., 2002; Warren et al., 2003; Breton et al., 2004; Searle et al., 2004; Glennie, 2005; Gray et al., 2005a, b; Searle et al., 2005; Al-Wardi and Butler, 2006; Searle, 2007; Warren and Miller, 2007).

Figure 1: False color Landsat image illustrating the complex geology of the Oman Mountains (Images from Global Landcover Facility).
The orogenesis of the Oman Mountains started with intra-oceanic subduction (Searle and Malpas, 1980; Pearce et al., 1981; Searle and Malpas, 1982; Lippard, 1983) in Cenomanian, which led to the emplacement of two major nappes (e.g. Glennie et al., 1974; Breton et al., 2004). These nappes (called the ‘Allochthonous’) comprise the volcano-sedimentary Hawasina Complex and Semail Ophiolite as well as exotic blocks of distal origin (Figure 2) (Glennie et al., 1974; Searle and Graham, 1982; Pillevuit et al., 1997; Breton et al., 2004; Searle, 2007). The so-called ‘Autochthon’ comprises the strata below these nappes that were deposited prior to the thrust sheet emplacement and consequently have been affected by the deformation. The ‘NeoAutochthon’ defines the strata deposited after the nappes’ emplacement (Glennie et al., 1974; Breton et al., 2004; Glennie, 2005; Al-Wardi and Butler, 2006; Searle, 2007).

The studied field area exposes the youngest members of the autochthonous unit (Figure 2), which was deposited during the breakup of Gondwana on the passive margin of the Arabian Plate (Glennie et al., 1974; Loosveld et al., 1996; Breton et al., 2004; Sharland et al., 2004; Glennie, 2005; Searle, 2007). These members reflect a relatively continuous sedimentation in the region of the Oman Mountains (Hughes Clarke, 1988; Ziegler, 2001; Sharland et al., 2004; Searle, 2007). From Tithonian to Turonian a transition from a deepwater facies to an open-marine carbonate shelf and shallow-marine carbonate platform took place forming the Kahmah and Wasia groups (Figure 4). These hold predominantly carbonates and minor shales (Hughes Clarke, 1988; Ziegler, 2001; Sharland et al., 2004). The carbonate sequence (Kahmah and Wasia groups) was uplifted in response to the flexural bending of the foreland associated with the ongoing subduction. This uplift in Cenomanian – Turonian (the ‘Wasia-Aruma break’) is documented by incised valleys in the Natih Formation (Patton and O’Conner, 1988; Warbuton et al., 1990; Loosveld et al., 1996; Grelaud et al., 2006; Filbrandt et al., 2007; Searle, 2007).

The subduction in the north led to shallow thrusting and the emplacement of the two nappes. The gravitational load induced renewed burial of the shelf carbonates and the deposition of the Aruma Group until the 2.5 km thick carbonate stack was subsequently overthrusted by the Hawasina and
Thrust Faults N 0 5 km Semail nappes (Figure 2). The southwest-verging nappe emplacement ended either in the early Campanian or Maastrichtian (Glennie et al., 1974; Nolan et al., 1990; Searle, 2007) as the thrusting processes ceased when buoyant continental crust stopped the subduction process (e.g. Goffe et al., 1988; Searle et al., 2004).

The timing of uplift and folding of this part of the Oman Mountains is unclear and subject to debate. Some claim that it is restricted to the Late Cretaceous (e.g. Bernoulli et al., 1990; Hanna, 1990), to the Tertiary (e.g. Glennie et al., 1974) or a two-phase culmination and uplift in latest Cretaceous and middle Tertiary (Searle, 1985, 2007). The ongoing uplift due to the subduction beneath the Makran continental margin of Iran (Figure 1) leaves a juvenile topography (Kusky et al., 2005).

The regional metamorphic grade in the Oman Mountains, as a result of the collision and obduction, rises towards the northeast with the highest grade exposed in the region of the Saih Hatat culmination (Figure 2) with carpholite, blueshist and eclogite facies rocks (Miller et al., 2002; Breton et al., 2004; Searle et al., 2004; Searle, 2007; Warren and Miller, 2007). The southern flank of Jabal Shams, as a distal part, is however situated in the anchizone (Breton et al., 2004). It shows incipient cleavage in argillaceous units and the onset of pressure solution processes in the carbonates (Breton et al., 2004; Al-Wardi, 2006).

Figure 3: (a) Simplified geological map showing study area (rectangle) together with interpreted faults (red lines). The lithology of interest spans primarily the Wasia Group with the Nahr Umr and Natih formations as well as the Kahmah Group (Figure 4).

(b) Simplified stratigraphic column with allochthonous Semail and Hawasina nappes. Map and column changed after Beurrier et al. (1986).
LOCATION AND PHYSIOGRAPHY

The field area is located in the Oman Mountains on the southern flank of its highest peak, Jabal Shams. Jabal Shams is a part of the Al Jabal al Akhdar domal structure; one of several large anticlinal culminations in the Oman Mountains (Figures 1, 2 and 3).

Our primary working area is 17.5 km in an east-west direction and 5.5 km in a north-south direction, covering about 75 sq km. Morphologically the area is located on the dip-slope of the southern limb of the Al Jabal al Akhdar dome and cut by several deep canyons in a predominantly north-south direction. These sub-parallel cuts offer impressive vertical profiles of which the tallest section at Wadi Nakhr offers a continuous vertical exposure of approximately 1 km with rocks of the Wasia, Kahmah and Sahtan groups (Figures 3, 5, 6, 23 and 26a).

The good outcrop quality in the area is a result of massive flash floods from late Miocene to early Pleistocene (Rodgers and Gunatilaka, 2003) as well as the recent arid conditions. The differential erosion of ‘soft’ rocks leads to the exposure of predominantly competent units on the surface, so that softer rocks are exposed only in profiles along the wadi walls (Figure 6).

LITHOSTRATIGRAPHY

The strata exposed in the study area are mainly mechanically competent carbonates with minor shaley intercalations belonging to the autochthonous Mesozoic Sahtan, Kahmah and Wasia groups of the Hajar Supergroup (Figures 3, 4 and 5) (Glennie et al., 1974; Beurrier et al., 1986; Glennie, 2005). Outcrops of the younger Muti Formation of the Aruma Group can be found just outside the study area (Figure 3).

The lithological column is exposed starting with the Sahtan Group at the base, followed by the Berriasian Rayda, Salil, Habshan, Lekhwair, Kharaiib, Shu’aiba and Nahr Umr to the Natih Formation (Albian to Turonian) at the top (Hughes Clarke, 1988); Sharland et al., 2004. Spanning more than a kilometer, the complete column is exposed at the western wall of Wadi Nakhr (Figures 3, 4 and 5).

Figure 4: Simplified lithological column of the strata exposed on the western wall of Wadi Nakhr showing the resistance to weathering as a measure for relative strength. The stacking pattern impacts the cliff profile of many wadis (simplified representation of the bed stacking; not to scale).
Sahtan Group

The oldest strata exposed in the field area belong to the Sahtan Group: rust-brown shaley units of the Dhruma Formation and bluish carbonates of the Mafraq Formation are found in the cliffs of the deepest sections of the wadis and in a footwall section of a large fault in the northeast of the study area (Figures 4 and 5) (Hughes Clarke, 1988).

Kahmah Group

More common throughout cliff and surface outcrops are, however, the Kahmah and the Wasia groups. The Kahmah Group is a thick carbonate sequence. In its upper part it holds a transition from deeper marine pelagic to shallow-marine limestones (Hughes Clarke, 1988; Al-Wardi, 2006) interpreted as a “regressive mega-sequence” comprising a highstand systems tract (Pratt and Smewing, 1993). It is the lateral equivalent of the economically important Thamama Group of the United Arab Emirates with some differences in the lower parts (Hughes Clarke, 1988; Pratt and Smewing, 1993; Sharland et al., 2004).

Resistant to weathering and erosion, the upper formations of the Kahmah Group make up the bulk of the surface exposures of the eastern part of the study area (Figures 3 and 6).

Rayda Formation

The Rayda Formation (oldest unit of the Kahmah Group) can be recognized in the cliff profile above the steep cliffs of the Sahtan Group. The Rayda Formation forms prominent stacks of thinly bedded bright, porcellanitic limestones and argillaceous carbonates (Figure 25d) (Hughes Clarke, 1988; Al-Wardi, 2006) It displays a condensed deep-water unit with pelagic biota abundant in radiolaria (Pratt and Smewing, 1993). Its elements are similar in

Figure 5: Collage of photos taken from the east flank of Wadi Nakhr with the complete lithological column exposed at the western wall of the canyon more than 1,000 m high. Note how the stacking of the formations influences the cliff profile (view towards the west; perspective distortion applies).
thickness forming a regular stack of thin predominantly weathering resistant beds. This formation is exposed in deeper parts of several wadis, as well as on the northeastern part in the footwall block of a major normal fault (Figures 25d, e).

**Salil Formation**

Compared to the regular bedding of the Rayda Formation, the overlying Salil Formation is more heterogeneous. The alternating thin limestones, argillaceous limestones and marls that dominate the Salil Formation are interpreted as a periplatform facies by Pratt and Smewing (1993). The differences in the weathering characteristics lead to an irregular cliff profile bound to the top by the “clean” carbonate of the Habshan Formation (Figures 4, 5 and 26b).

**Habshan Formation**

The Habshan Formation consists of predominantly bioclastic grainstones that form prominent, more than 100 m high cliff faces in the lower Kahmah Group (Figure 5). The Habshan Formation can be easily recognized due to the weathering contrast to the underlying and overlying formations. Outcrops of the Habshan in the study area are limited to cliff faces. The Habshan Formation represents a regional platform carbonate (Hillgärtner et al., 2003) with massive beds.

**Lekhwair Formation**

The facies changes in the next-younger Lekhwair Formation to heterogeneous bed assemblages (Figures 4, 5 and 26b). The Lekhwair Formation represents sedimentary cycles of three main facies comprising argillaceous limestones, marls but also cleaner wackestones and grainstones (Hughes Clarke, 1988). The meter-to-decimeter stacking pattern has a shallowing upward trend (Hillgärtner et al., 2003). The relative strength of the individual materials, as well as the thickness of the single beds, strongly varies.

**Kharaib Formation**

An additional distinct cliff face is formed by the Kharaib Formation. Consisting of an essentially clean carbonate, the Kharaib holds two almost equally sized massive beds (Figures 4, 5 and 27). It was deposited in shallow water on a low-angle carbonate ramp. Similar to the Shu’aiba, the formation is characterized by the benthic foraminifera *Orbitolina* and abundant rudists (van Buchem et al., 2002).

**Hawar Member and Kharaib Formation**

The few meter-thick argillaceous carbonate of the Hawar Member is the mechanically weak interlayer separating the Kharaib cliff from the overlying Shu’aiba cliff (Figures 4, 5 and 6b): the Hawar Member was interpreted as a protected lagoon facies by van Buchem et al. (2002). Its low resistance to weathering leads commonly to a gentle slope in the otherwise steep cliff faces of the underlying and overlying formations.

The overlying Shu’aiba Formation, in contrast, consists of dominantly bioturbated packstone (Pratt and Smewing, 1993), and represents an aggradational carbonate platform (Hillgärtner et al., 2003). The Shu’aiba’s resistance to weathering creates a homogeneous appearing cliff approximately 100 m high (Figures 5, 6 and 23). This massive element is easily recognized in the overall cliff profile. The Shu’aiba Formation forms most of the surface outcrop in the eastern part of the field area. On a regional scale, the Shu’aiba Formation is a reservoir rock in the Middle East region and is therefore well characterized (van Buchem et al., 2002).

**Wasia Group**

The Wasia Group (Figure 4) was deposited in shallow-water conditions of a subtidal environment. It is described by some authors as an highstand systems tract after a transgression event that separates it from the older Kahmah Group (Pratt and Smewing, 1993). The Wasia’s contact with the underlying Shu’aiba Formation consequently shows local evidence of subaerial exposure during the stratigraphic break (van Buchem et al., 2002).
Figure 6: (a) View across Wadi Nakhr towards the east with exposures of the Shu’aiba Formation. In the cliff profile, the Hawar Member and lower part of the Kharaib Formation are exposed below the Shu’aiba. The height of the topmost Shu’aiba cliff is approximately 100 m. In the distance are outcrops of the softer Nahr Umr Formation (view towards the east; thickness of the Shu’aiba Formation is approximately 100 m).

(b) More detailed view onto the Shu’aiba Formation exposed on the eastern flank of the mapping area. The dense fracture pattern is visible by slightly brighter streaks.
**Nahr Umr Formation**

The boundary between Kahmah and the younger Wasia Group is defined by the sharp contact of the Shu’aiba to the prominent Nahr Umr Formation (Figures 5 and 6b). The Nahr Umr is known as a prominent clay-bearing seal for a number of reservoirs throughout the Middle East, whereas the formation here comprises marls and argillaceous limestone with minor intercalations of more competent beds (Figures 5, 6b and 23) (Hughes Clarke, 1988; Sharland et al., 2004). The depositional setting of this formation is described as a moderately deep-shelf environment (Pratt and Smewing, 1993). The Nahr Umr is one of the thickest formations exposed in the field area. Its low resistance to weathering however reduces the outcrops to a relatively small area protected from erosion by a footwall block of a major normal fault (Figure 6b). Other outcrops of this formation are limited to gentle slopes between the steep cliff faces of the overlying Natih and underlying Shu’aiba Formation (Figure 23). The slope exposures are however often covered by debris and provide limited structural information.

**Natih Formation**

The youngest strata within the field area belong to the massive Natih Formation (Figures 5 and 23). The Natih is several hundreds meters thick and divided into informal members: ‘g’ at the base to ‘a’ at the top (Hughes Clarke, 1988). The Natih Formation consists of argillaceous wackestone, bioclastic packstone and grainstone deposited in a shallow shelf environment (Pratt and Smewing, 1993). The members ‘e’ and ‘a/b’ form impressive cliffs of many 10s of meters, whereas the ‘c’ and ‘d’ members are prone to erosion leading to gentle slopes. The bulk of the surface outcrops of the western part and the southernmost margin of the field area expose members of this formation. Its rather homogenous appearance in the field limits the ability to distinguish its members.

**METHODS**

In this study we used multispectral Landsat scenes as well as a high-resolution Quickbird satellite image that provided the basis for the field work. From these data sets we interpreted the overall distribution of strata and the structural elements (Holland et al., in press). The field work focused on the visit of pre-selected areas and transects.

Structural measurements, overprinting relationships, macroscopic observations, as well as the documentation of the surface and profile views with sketches and photographs, were incorporated into a database. Micro- and macro-scaled observations on the fracture population were carried out to derive the temporal relationship of structures (Figures 11, 14 and 18a). The observations on the internal structure of the fractures and faults like offset relationships, fragmentation, and segmentation, as well as the types of cement, are vital for understanding the temporal relationships.

The notation used in this study for strike directions are such that North-South striking features have a 000°, East-West a 090° and Northwest-Southeast striking features a 135° strike.

**STRUCTURAL ELEMENTS**

The emphasis of this study is the characterization of the structural elements. These are predominantly brittle deformation fractures and faults (Figure 6b) of which we find the fracture density throughout the entire field area to be very high (Holland et al., in press). The massive population incorporates hairline fractures, joints, shear fractures, shear veins, veins and faults.

We use the term “fracture” in a general sense to describe any discontinuity within a rock mass formed as a response to stress (Bonnet et al., 2001). If an isolated fracture has a very small “opening” component of less than one mm, we use the term “hairline fracture” (Figure 30b). Systematic fractures with a pure opening mode component are called “joints” and can be cemented (Figure 7) or uncemented (Figure 29). A clear distinction between joint and fault is not always possible as we observe reactivated joints and hybrid fractures (Hancock, 1985). The term “vein” is used to generally describe a fracture filled with mineral (Bonnet et al., 2001) (Figure 7). If a shear component (a small in-plane movement) is present, the feature is labeled as a shear fracture (Figures 8 and 9), whereas it is considered a fault when the in-plane movement exceeds the aperture of the fracture by several factors.
Figure 7: Collection of outcrops with veins perpendicular to the bedding:
(a) Isolated competent bed within the Nahr Umr Formation shows veins with apertures over 10 cm. The layer-confined fractures have a spacing of approximately 2 m.
See facing page for continuation.
Figure 7 (continued):

(b) Small-scale layer-confined veins in a small competent bed sandwiched between argillaceous materials. Note the short length of the fractures as well as their dense spacing.

(c) View onto a Natih C bedding surface showing sub-parallel fracturing within a stromatoporid. Hydraulic overpressures presumably in combination with the higher porosity of the stromatoporid led to selective fracturing.

(d) Exposed carbonate bed with different sets of veins and joints. Cementation, spacing and apertures differ between the different sets.

(e) Profile view of layer-confined veins in competent units sandwiched between argillaceous units (coin for scale).

(f) Overview of previous image showing differences in the spacing between neighboring layers (Natih Formation).

(g) Bedding surface with systematic and non-systematic veins. The massive veins are sub-parallel and differ in spacing among the different exposed beds in the middle left of the picture (Nahr Umr Formation).
The vast majority of the fractures show an open-mode component, in most cases cemented with white calcite. As this bright cement forms a high optical contrast to the overall dark-colored carbonates, the cemented fractures are easy to recognize in the field as well as on the Quickbird satellite image (Holland et al., in press). The observations incorporate satellite image interpretations, as well as profile and surface data from virtually the entire area to form an extensive data set to study the orientations of the stress field (Holland et al., in press). The classification we use is, however, based on field observations using temporal relationships obtained by cross-cutting relationships and fracture morphologies described in the following section.

**Veins, Normal-to-Bedding Veins**

A prominent group of fractures comprises veins of different strike directions that are oriented normal to the bedding. These predominantly dilatant fractures are cemented with bright calcite. They are most frequent in massive carbonate beds.

**Veins in Vertical Segments of Stylolites**

One group of veins is formed in the steep limbs of stylolites. Described in detail by Hilgers et al. (2006a), these bedding-perpendicular veins have rather small dimensions, dictated by the morphology of the stylolites. This group is rare within the field area and found only in rocks of the Sahtan Group, exposed in the deepest sections of Wadi Nakhr.

**Veins with Straight Segments**

A more common type of vein is characterized by straight segments and apertures that can be as large as 10 cm (Figure 7). These veins are filled with coarse-crystalline calcite cement. Thick veins of this group are commonly sub-parallel to each other and up to few 10s of meters long. The majority of these veins are found in massive carbonate beds that are intercalated in weaker strata (Figure 7b) such as individual competent layers in the Nahr Umr Formation. The vertical dimension of the fractures is, in many cases, limited to the bed thickness as they terminate at the bedding interfaces. Within a single bed, the spacing of these veins appears to be rather constant (Figure 7a), whereas the spacing in the adjacent layers can be much different (Figures 7c, e, f), even if they are similar in thickness. The same applies for the apertures of the veins, suggesting that there is no consistent relationship of vein spacing to the bed thickness (Bai and Pollard, 2000). Layers with similar thickness may have distinct fracture patterns as, for example, spacing may differ by a factor five among similar beds within a single outcrop (Figures 7e, f).

The veins of this group are entirely cemented with white calcite, forming blocky crystals. In some veins broken lensoid host-rock fragments are embedded in the cement (Figure 9a). The cement of these regular veins is predominantly white but occasionally yellowish on the scale of an outcrop. The latter may be a result of a later staining; for example, due to the weathering of iron-bearing material of adjacent beds. The morphology and spacing pattern of this group of veins is the most regular aspect when observed in outcrop scale.

**Shear Veins**

A range of different vein terminations was identified. Some veins have straight segments over a large distance but terminate with splays, wing cracks or they transfer into *en-échelon* segments (Figure 8). This proves the presence of an additional in-plane displacement component. Although these shear veins may form regular arrays they are commonly solitary structures parallel to regular veins (Figure 8b, c). In the latter case, the shear veins are more pronounced due to larger apertures and longer traces in contrast to the other veins. The larger aperture veins of this group are not necessarily stratabound; they can cut across several beds. The cement of these veins is similar to the previously described type: white blocky calcite with common inclusions of host rock flakes.

**Branching and Braided Systems**

Branching and braided systems of joints form another group, found usually within a sub-parallel population of more regularly distributed veins or cemented hairline fractures (Figures 8d, e, f). The apertures of the braided veins are in the order of centimeters or smaller. The cement of the braided
system is similar to the blocky cement described earlier. Due to the braided character, the spacing and the aperture of the irregular veins are highly variable (Figure 8e, f). This group shows – as an effect of the branching – variances in strike directions as well as non-linear segments. The fracture walls are less regular as compared to the previous groups.

A significant increase in complexity within this group is seen in some cases at step-over segments between adjacent fractures. Here the veins are broken down into numerous small strands (Figures 8f and 9e). Similar shapes are seen at vein terminations, as the vein may feather into arrays of irregular shaped strands. The termination may also gradually taper into the rock.

**En-échelon Systems**

The *en-échelon* veins form separate systems in a more organized fashion. The individual *en-échelon* segments are commonly aligned over distances of several meters (Figures 8c and 9c). These segments may form isolated strands or conjugate sets of strands (Figure 9d), both in the horizontal as well as in the vertical directions. The aperture of the individual segments rarely exceeds 3 cm.

**Joint Orientations**

The orientation of the previously described veins were measured in the field and interpreted on the satellite image (Holland et al., in press). Plotted into a rose diagram, a distribution into four major sets is apparent. The mean strike directions of the sets are approximately 000°, 045°, 090° and 130° (Figure 10).

The 130° striking fracture set is the most prominent on the satellite image and in the field. Sub-parallel straight joints and cemented hairline fractures commonly belong to this group, having also the longest fracture traces. In contrast the 000° and 090° sets display the sharpest distribution. The 000° set is however commonly altered as the fractures commonly strike down-slope leading to preferential physical erosion of this group.

**Overprinting Relations**

A relative chronology of the fractures perpendicular to the bedding is not always entirely clear (Figures 11 and 12): abutting is not observed among all systematic veins and the cross-cutting relationships are not always easy to interpret (Figure 12). Curving of a fracture set towards other sets was not observed in the field area. Since the temporal relationship cannot be based on abutting, we used offset relationships along shear veins and the relationship of crosscutting cements to determine the chronological order (Figures 11 and 12). The offset across shear veins is unambiguous. The cement generations are more difficult to interpret (Figure 12a).

If a rock body with veins is fractured and filled with a homogenous material that is optically distinct from the previous veins the relationship is easy to recognize (Figure 12b). It seems, however, that some newly cemented fractures show an effect where the precipitated material mimics the fracture walls. This heterogeneous precipitation makes it, in some cases, difficult to determine the temporal relationship (Figure 12a).

Figure 12a shows such an example. At first glance at the overview picture the white horizontal vein seems to cut the vertical one. The detailed view in Figure 12a shows, however, that the reddish rim of the vertical vein is continuous contradicting the first observation. A robust distinction is in this case not possible. Similar examples are common among the vein sets and may easily lead to a misinterpretation of the relative chronology.

We determined the offset relationships of the joints from photographs and field observations displayed in Figure 13. Listed per line, the upper part of the figure shows measurements on photographs, the lower part those of field measurements. The fracture strike readings of an outcrop are plotted per row into the graph with a color marker in the corresponding strike column.
Figure 8: Unsystematic veins occur either in bundles or in an isolated manner: the cemented features commonly have long continuous, linear segments. Terminations are commonly splays, branches or *en-échelon* segments indicating in-plane movement.  
(a) Long linear veins with variance in spacing.  
(b) Linear vein segment with splays at its termination. Note the presence of subparallel hairline fractures.  
(c) Massive vein subparallel to hairline fractures with *en-échelon* termination.  
(d) Branching vein network with massive apertures along individual strands.  
(e) Complex vein network on polished surface with multiple strike directions.  
(f) Vein arrays with braided terminations. See facing page for continuation.
The observations from one outcrop pertain two or three generations of fractures at the same time at most. The relative succession or generation of fractures within the individual outcrops is shown in the left part of Figure 13. Colors indicate the relative age, while the location/column of the colored patches shows the strike direction of the corresponding fracture.

None of the studied outcrops displays all generations necessary to define a consistent temporal relation. For this purpose the second part (Figure 13b) uses five instead of three age classes. The five classes use the same relative chronology but a different grouping, resulting in a much more ordered pattern.

Based on this division, the oldest veins commonly strike in the 000° direction (Figure 13, dark green). The second set strikes into the 130° direction, followed by the 090° and then the 045° directions. Offset is common within the latter two groups marked with the letter ‘o’. The youngest members (Figure 13b, red) are distributed among all the previous groups and might represent reactivation features or interpretation errors.

**Bedding Parallel Veins**

Non-stratabound veins of the previously described set are overprinted by shear zones parallel to the bedding (Figure 14). Striations and offset relationships indicate a top-east and top-to-north movement (Breton et al., 2004; Al-Wardi, 2006; Al-Wardi and Butler, 2006; Searle, 2007). The overall distribution of these shear zones within the vertical column is rather heterogeneous. It is developed locally either on the interface of competent layers or within the incompetent layers themselves.
Shear at Bedding Interfaces

Bedding interfaces in many stratigraphic levels acted as slip planes where blocky calcite formed layer-parallel veins up to several centimeters thick (Figures 14 and 15b). In other cases, these veins are fibrous, with quartz and calcite fibers, indicating a different mode of precipitation. These sub-horizontal veins have offset relationships and sense-of-shear indicators with a top-to-north to top-to-east (Al-Wardi, 2006; Al-Wardi and Butler, 2006; Hilgers et al., 2006a). Local imbrications of these veins occur together with host rock fragments that are oriented parallel to the bedding (Figures 15 and 18a). Locally, the shear movement is also observed along more irregular bedding surfaces or along the clay seams of incipient stylolites (Figure 15a). The slip on these irregular surfaces leads to the formation of dilatant
The jogs are cemented and hold embedded host rocks fragments (Figures 15a, b). The formation of these slip planes at bedding interface is commonly linked to cleaner carbonate beds, whereas the argillaceous beds tend to localize the slip within the beds themselves.

**Shear Within Beds**

Within argillaceous units (Figures 15c to 15h) the bedding-parallel shear develops additional deformation structures. The clay-rich layers may form s/c textures (Figure 15g) or disjunctive cleavage (Figures 15c, d). Additional elements of the shear zones include sigmoidal clasts incorporating quartz (Figures 15e, f), pyrite cubes with pressure shadows, as well as rotated pinch and swell veins (Figures 15c, d). Although the strain is largely concentrated in the argillaceous layers, overlying more competent layers may locally show boudinage (Figures 15e, f).

Most of the layer-parallel shear was observed in the profiles of the central Wadi Nakhr within the lower part of the stratigraphic column as well as in the topmost Natih Formation. The localization within the column seems to be influenced by layer succession: pure carbonate stacks commonly develop multiple shear beds at the interfaces of the layers (Figure 15a, b), whereas argillaceous members localize the deformation more strongly towards single planes resulting in a higher degree of damage.

We performed detailed analysis of fluid inclusions (Muchez et al., 1994) in vein-filling quartz from samples of the shear zones, which show homogenization temperatures from 84°C–141°C (Figure 16). These temperatures are not pressure-corrected. Accounting for 3–5 km overburden, temperatures from 134°C–221°C seem valid. The Appendix discusses the methodology of the measurements in detail.
Figure 11: Examples for overprinting relationships:
(a) A thin vein striking approximately 045° offsets two 130° striking veins.
(b) Clear overprinting relationships on this outcrop due to the offset of numerous veins.
(c) Example of surface outcrop with three visible joint directions.
Figure 12: Example of unclear overprinting relationships:
(a) Two veins cut each other. Even at higher magnification it is not clear which fracture predates the other. The brighter cement of the horizontal fracture is continuous but at the same time the reddish rim of the vertical vein can be seen in the intersection.
(b) This effect could be explained by preferential cementation that mimics the material of the wall (lower case).
(c) Example of another unclear overprinting relationship: the bounding white rims of the horizontal vein are continuous. In the intersection however are remnants of the oblique vein.
Figure 13: Table showing organization of the temporal overprinting relationships of the veins derived from more than 40 outcrops. The individual outcrops are listed by row. (a) The relative age is presented by three colors in strike bins of 10°. ‘O’ indicates if an offset is apparent. Since more absolute groups are present than relative groups, a second figure is necessary for the absolute temporal relationship. (b) The order of the left figure is maintained but more classes are introduced. Five absolute classes are necessary for a consistent pattern. Its temporal relationship suggests the 000° class to be oldest, followed by the 130° set, the 090°–100° set and the 045° set. The red color shows the youngest set scattered into different strike directions (see text for details).
Normal Faults

The study area exposes a large number of normal faults with offsets of up to approximately 500 m (Figure 17). Although these are predominantly normal faults, oblique slickensides are commonly observed indicating strike-slip components (Al-Wardi, 2006; Al-Wardi and Butler, 2006; Filbrandt et al., 2006; Hilgers et al., 2006a; Searle, 2007). On the cemented fault planes striations from several generations as well as different directions indicate a complex history.

The vertical offset on the faults reaches up to several hundreds of meters as estimated for the largest fault in the northeastern part of the field area.

A temporal relationship of the normal faults to the previously described structures is derived from outcrops in Wadi Nakhr, where a number of small-offset, normal faults cut and offset the layer-parallel shear veins (Figure 18a).

The fault orientation from the interpretation of the satellite image (Holland et al., in press) shows a prevailing strike of the fault segments from 090° to 120°. The directions of these mature faults are sub-parallel to the fold axis of the Jabal al Akhdar dome. In the following section we describe and discuss the faults divided into groups related to the throw magnitude.

Incipient Faults (throw < 0.5 m)

The non-systematic joints perpendicular to the bedding striking 090° and 130° and incipient faults closely relate to each other (Figure 18e). Both the joints and the faults have an identical strike direction. Both are largely dilatant and cemented thus limiting a clear distinction. With fault nucleating along the joints, the steep joint segments within the competent units become interconnected and increased throw forms trough-going fault strands. These strands commonly refract at bedding interfaces.
(Hancock, 1985; Ferrill and Morris, 2003). Observed in thinly bedded units, the incipient faults with up to a few centimeters throw may develop dilatant jogs (Figure 18f) (Hancock, 1985; Ferrill and Morris, 2003), which are similar to the joints and entirely filled with coarse-grained cement.

Other structures in incipient faults are tension gashes (Figure 18b, c) or en-échelon segments and conjugate sets (Figures 18b, d). These structures indicate the reactivation of previous structures or the impact of a mechanical anisotropy within the system. The en-échelon systems are commonly observed in massive carbonate beds closely associated with normal fault zones. The en-échelon structures form in some cases as conjugate sets (Figures 18b, d) and are commonly found in zones of low displacement. With progressive offset these structures form normal faults.

**Small to Medium Offset Faults (0.5 to 10 m throw)**

With larger offsets in the order of 0.5 to 10 m the internal structure of the fault zone changes. The two end members of this group can be described as follows:

**Fault segments with “localized” displacement:** Often observed in profile view, medium-offset normal faults have sharp linear fault planes as the first end-member (Figure 19). These straight segments are predominantly exposed in massive cliff sections. The fault cores of these sections are commonly narrow; they are cemented and show intense fragmentation of the cement. Embedded fragments consist of blocky calcite or broken calcite rhombohedra. With more intense fragmentation the fault core can hold calcite-cemented breccias (Figure 19b).

In contrast to the uniform white calcite cement of the previously described veins, the cement of the faults can have brown, gray, yellow or red colors suggesting other genetic conditions or other fluid sources (Hilgers et al., 2006a). Incorporated host rock and angular cement fragments are common within the fault’s cement (Figure 21).

With this end-member the fault core (zone with fragmentation and cementation) is usually a few centimeters to 10s of centimeters thick concentrating the throw. This leaves the damage zone very narrow, as the surrounding host rock remains virtually intact.

**Fault segments with “distributed” throw:** In plane view on competent carbonate beds another kind of morphology is common (Figure 20). Here the fault throw seems to be distributed over a wider zone comprising an anastomosing network of fractures or a fracture corridor. Sometimes a single strand may concentrate the throw and show characteristics of a fault core accompanied by a large number of associated fractures that define a wide deformation zone (Figure 20a). The fault core strands have larger apertures compared to the other fractures in the system, as well as a larger degree of damage and greater variety in color. The aperture of the fractures can be several 10s of centimeters and filled with calcite cement.

The major fault strands of such a zone run sub-parallel and may branch to interconnect gradually with the less prominent fractures of the accompanied deformation zone (Figures 20b, d, e). The latter fractures of the deformation zone have smaller apertures and white blocky calcite cement without the discoloring or the intense fragmentation (Figure 20a). These fractures are formed predominantly in the direction of the previously described joints. The spacing of the fractures within the “fault corridor” is dense and irregular. Shear indicators and reactivation features are frequently present. These incorporate splays and horsetail fractures, en-échelon segments, riedel structures and conjugate sets of riedels. Flakes of host rock material are also found throughout these sets (Figure 21).

**Calcite Rhombohedra**

Indirectly associated with these intermediate fault zones are occurrences of large calcite rhombohedra (Figure 22), which we find along the traces of such faults. These massive idiomorphic crystals with lengths of more than 60 cm are found in different parts of the field area. The rhombohedra commonly have different zonation of clear calcite, yellow, white or gray colors. In some specimens stylolites developed parallel to the crystal shape.
Figure 15: Features of the bedding-parallel shear all with a top-to-north movement. Marked images (M) are mirrored for dextral impression:
(a) Horizontal pull-apart structures due to bedding-parallel shear along an irregular clay seam of an incipient stylolite. Image is mirrored for dextral shear.
(b) Stack of cemented segments formed within horizontal pull-apart.
(c) Array of pinch-and-swell veins in an argillaceous unit with the development of cleavage.
(d) Close-up image of the latter formation.
See facing page for continuation.
Figure 15 (continued):
(e) This clay unit localizes the strain; note the boudinage of the overlying carbonate.
(f) Close-up image of the latter with sigmoidal quartz clasts and intense deformation.
(g) Cleavage/Shear (S/C) textures within clay-rich unit.
(h) Heavily deformed and cemented deformation zone within a horizontal shear zone. Image is approximately 70 cm across.
Large Offset Faults

The largest vertical offsets are observed at two major fault zones, one in the northeast and one in the southeast of the study area (Figure 17). Both fault systems strike approximately 100° and are oriented sub-parallel to the fold axis of the Jabal al Akhdar domal structure. The largest stratigraphic offsets within the study area occur at the eastern boundary, and are in the order of several 100s of meters, diminishing towards the west.

The Large Southern Fault

In the surface exposures in the eastern part of this southern fault zone, the Natih Formation is offset against the Shu’aiba and Nahr Umr formations. The throw is mainly localized in a major fault zone until it crosses Wadi Nakhr and branches towards a number of strands on the western side of the canyon (Figures 17 and 23). The throw is distributed and the total offset diminishes towards the west where the southern fault dies out.

In a profile view exposed at the Wadi Nakhr’s western wall, the fault system is characterized by prominent horst and graben assemblages (Figure 23). A major horst structure can be seen in the deeper-lying Khammah Group. The throw distribution is more complex in the upper Natih Formation where the fault zone is spread to an array of horst and graben structures. The Nahr Umr Formation in-between forms more a monocline rather than an array of faults. The general, outcrop conditions in
the east along this major fault zone are poor due to the easily eroded Nahr Umr Formation exposed or offset by this fault.

Numerous wadis pond against the Natih Formation on the hanging wall block and accumulate soil and debris onto the eroded fault zone. Some wadis are redirected by the fault, cutting deep into the exposed Nahr Umr Formation or cut into the fault zone itself. Some sections in the eastern part of the fault are however preserved and exposed along a road cut (Figure 24). Here a fault zone with extensive deformation is several 10s of meters wide. The massive zone is made of a heterogeneous assembly of competent material “floating” in a clay-rich matrix; material probably derived from the argillaceous Nahr Umr Formation. The high degree of damage is linked to discoloring in reddish and yellowish colors.

The Large Northern Fault

The other major fault zone is sub-parallel and exposed a few kilometers to the north (Figure 17). It has the largest offset at the eastern boundary with a diminishing throw towards the west, where it seems to bifurcate into another system. Surface exposures in the east show the Kahmah Group offset against itself or against formations of the Sahtan Group (Figures 3 and 25). With the fault zone being located in more competent layers the deformation zone is narrower as compared to the southern fault.

The fault core in the eastern part consists of an heavily damaged and cemented zone of several meters width (Figure 25). With a higher resistance to weathering, the fault core forms a topographic ridge locally more than 6 m high (Figure 25a). Profile views on the large-offset section in the eastern part of the fault show a wide fault core spanning the entire exposed profile (Figures 25c, d). Figure 25d displays in contrast massive drag folds that are formed in the thin interbedded sequence of the Rayda Formation exposed in the footwall block.

Towards the west, the fault zone branches more prominently and the size of the fault cores diminish. The anastomosing character leads to a dense network of cemented fractures forming a wider damage zone within this fault system.

Towards Wadi Nakhr, the major faults split at the surface into smaller strands with offsets in the order of several 10s of meters as observed in the 1-km-high profile at the western wall of the canyon (Figures 26 and 27). Similar to the profile of the southern fault, the Nahr Umr Formation is deformed into a monocline (Figures 23 and 27). Throw is localized to single fault planes in the thick carbonate layers of the Kahmah Group. Within the uppermost section of the Kahmah Group, the single-strand fault splays towards the contact to the Nahr Umr to translate into the monocline structure (Figure 27).

Ramp Structures

Compression-related structures, like ramps and duplexes that are northwest-directed, are described by several authors in the surrounding areas (Al-Wardi 2006; Breton et al., 2004; Hilgers et al., 2006a; Searle 2007). These are reported to overprint the normal faults that were previously described. Within our field area we find only one example of a duplex structure (Figure 28), which is however directed southwest. Located within the Natih Formation on the southern part of the field area, the isolated structure forms a topographic ridge that can be traced a few kilometers. The ridge is oriented parallel to the slope and therefore parallel to the fold axis of the Al Jabal al Akhdar dome (Figure 28c). The temporal relationship, as well as the significance of this duplex structure, remains unclear because we did not study it in detail yet. The jointing pattern within the ramp remains normal to the bedding suggesting that the ramp was formed after the veins. More work is required to understand this southwest-directed ramp into the context of the structural framework.

Uncemented and Partly Cemented Joints

In addition to the cemented fractures, the area exposes a large amount of uncemented or partly cemented joints observed in profile view as well as in plane view (Figure 29). The orientation of these fractures is identical to the group of cemented joints that are approximately normal to the bedding as they encompass all four strike directions.
Figure 18: Low-offset normal faults and associated structures:
(a) Normal fault cutting the bedding-parallel veins. The fault plane is cemented.
(b) Aligned tension gashes show nucleation of incipient faulting.
(c) Tension gashes in a normal fault indicate the transition from brittle to ductile deformation.
See facing page for continuation.
Figure 18 (continued):
(d) Conjugate set of cemented fractures as a precursor of fault nucleation.
(e) Reactivation of joints as a sign for fault nucleation in an area with a distinct mechanical anisotropy.
(f) Dilatant jog as a result of fault-plane refraction.
Figure 19: Intermediate offset faults:
(a) Normal fault with a sharply localized fault plane.
(b) Detailed view of the latter with person for scale (circle).
(c, d) Normal fault with a sharply localized fault plane. The detailed view shows an increased degree of damage in the strong layers as the fault splays at the interface to weaker layers. In (c) the height of the yellow box is approximately 5 meters.
(e) Steeply dipping fault with sharp localization.
(f) Fault cutting the Natih Formation changes from a single-strand system to a braided system within the central interbedded section.
See facing page for continuation.
Figure 20: Normal fault systems with wide deformation zones:
(a) This fault has a thick fault core with a well-defined breccia in which the throw is localized. Some deformation is however distributed to neighboring joint planes or veins. Red discoloring is present among some of the strands.
(b, d, e) Massive deformation zone of a medium offset fault. Strain is largely delocalized to form a complex network of fractures using some of the preexisting joint planes.
(c) Fault zone with intense fragmentation and cementation.
In places where this jointing is developed systematically, the spacing of the joints is smaller than the spacing of its massive cemented counterparts. Plane-view observations display dense joint patches (Figures 29 and 30). Within the heterogeneously distributed patches the spacing can be as little as a few centimeters. Abutting within the patches is present but without a clear relationship suggesting that the joints were formed simultaneously (Figures 29 and 30).

**Faulted Fluvial Deposits**

An additional stage of fracturing is evident by small-scale offsets observed in the cemented gravels of fluvial terraces within Wadi Nakhr indicating recent tectonic activity (Figure 31). The observed fracture network strikes approximately in a north-south direction following the orientation of the large canyon.

**Interpretation of the Field Data**

This carbonate stack of the Autochthon shows evidence for a multiphase deformation visible by different sets of fractures and deformation structures.

**Vein Sets Normal to Bedding (d1)**

The first generation of structures are veins normal to bedding (Figures 33b, c, d, e, 7 and 8), with large apertures and mostly clean blocky calcite cement. Fibrous veins that could indicate a slow fracture opening were not found. The blocky calcite suggests that the calcite precipitated in open voids.

Abutting was never observed among veins of this group and none of the fractures are systematically curved. This indicates that cementation healed the fractured rock repeatedly, restoring most of its mechanical strength prior to the next fracturing event. A cyclic fracturing-healing model is suggested as a mechanism to produce joint spacings much smaller than bedding thickness (Figure 7). We interpret that these super-saturated beds were formed by many different stages of fracturing and healing events. An alternative explanation of the formation of the joints involves large differential stresses. The conditions of such an environment would promote the lack of mechanical interaction such as curving.

The age relationships of in total four strike direction classes are reasonably consistent. We interpret the data presented in Figure 13 on overprinting relationships from 42 outcrops. It implies four vein generations of which the oldest strikes north-south. This set is overprinted by the most prominent set that strikes approximately northwest-southeast dominated by long, wide and straight veins. This, in turn, is overprinted by an east-west striking and then a northeast-southwest striking group. The east-west striking group commonly offsets older veins and is interpreted to be partly reactivated by the normal faulting processes at a later stage. The systematic anticlockwise rotation of progressively younger veins is interpreted to represent a corresponding rotation of the minimum principle stress, from east-west, to northeast-southwest, to north-south towards northwest-southeast by in total 135°. Since the age relationship presented in this study is based only on a small sample size (<50 outcrops) a second interpretation cannot be ruled out. The four fracture groups may alternatively form conjugate sets. Grouping the north-south and east/west, as one set, and the northwest-southeast and northeast-southwest, as the other, would relate to a 45° rotation of the minimum principle stress. To test the latter interpretation, a much larger regional study on the overprinting relationships is required.

The apertures and spacing of the straight, sub-parallel veins are reasonably consistent within one layer on the scale of an outcrop, but can be quite different in neighboring layers of equal thickness (Figure 7e), thus suggesting that layer thickness is not the only parameter controlling the spacing and aperture. Additional parameters could be (1) tensile strength of the layer, (2) rheological contrast to neighboring weak layers, and (3) permeability structure of the system to affect the buildup and release of local fluid pressures (Zoback, 1978; Pollard, 1979; Engelder, 1987; Pollard, 1987; Engelder, 1990; Bai and Pollard, 1998; Bai, 2000; Bai and Pollard, 2000).
Figure 21: Detailed images of fault structures:
(a) Broken and re-cemented calcite crystals forming a breccia with dark, host-rock fragments and reddish cement (scale with centimeter increments).
(b) Small normal fault with multiple cement materials.
(c) Dextral shear vein with blocky calcite in the central part documenting a stage with a massive open-mode component.
(d) Thick cemented zone with numerous embedded rock flakes indicating repeated failure and healing stages.
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(c) Dextral shear vein with blocky calcite in the central part documenting a stage with a massive open-mode component.
(d) Thick cemented zone with numerous embedded rock flakes indicating repeated failure and healing stages.

Figure 22: (a, b) Along the traces of medium faults we find zones with poor outcrop conditions that expose massive calcite rhombohedra with more than half a meter length. The mostly idiomorphic crystals commonly show color zonations and occasionally stylolites. (c) Massive calcite-cemented block in a normal fault segment of a small graben system.
Many of the veins contain indicators for repeated fracturing and sealing, under progressively changing stress (Figure 9). Wall rock flakes are commonly embedded in the veins, with their long axis predominantly parallel to the vein wall in agreement with the model of a fast restoration of the strength (Holland et al., in press).

The orientation of the fractures perpendicular to the bedding as well as the prominent open-mode component indicates that the veins have formed in response to low differential stresses and tensile minimum effective stress.

Figure 23: View across Wadi Nakhr onto the western cliff face that exposes the Southern Large Fault. With a single horst structure at the base (Shu’aiba and Khaaraib formations), the fault segments into a number of horst and graben structures in the Natih Formation at the surface. The intercalated Nahr Umr Formation shows less defined fault planes (view to west; cliff face is approximately 400–500 m high).
**Duplex Structures (d*)**
The surface exposure of the duplex structure (Figures 33f and 28) on the southern flank needs more study. We interpret this ramp to postdate the bedding-perpendicular veins as these are rotated by the ramp.

**Structures Parallel to Bedding (d2)**
Veins and deformation structures that are sub parallel to bedding (Figures 33g and 14) overprint those that are perpendicular, indicating a change of the stress field. Fluid pressures close to lithostatic, were proposed for this phase by Hilgers et al. (2006a). The strain accumulated in this stage is partitioned heterogeneously in the vertical column. Argillaceous units and bedding interfaces tend to localize strain (Figure 15). In contrast to the southwest-directed emplacement of the Hawasina and Semail Ophiolite, the striations, S/C textures, the rotation of pinch-and-swell veins as well as offsets all document a top to north, and top to east movement (Breton et al., 2004; Al-Wardi, 2006; Al-Wardi and Butler, 2006; Searle, 2007) The cleavage seen within the argillaceous units indicates the transition towards ductile behavior.

**Normal Faulting (d3)**
Small offset normal faults exposed in the walls of Wadi Nakhr overprint the veins, indicating another major change of the stress field (Figures 33h and 18). The faults commonly start with arrays of en-échelon veins, a prominent opening-mode component and massive cementation, pointing to high fluid pressure conditions and a chemically reactive environment in the early stages of the normal faulting.

Incipient normal faults offset these arrays of en-échelon veins (Figure 18c). Isotope measurements by Hilgers et al. (2006a, b) show until this stage a rock-buffered isotope signature, whereas with progressive normal faulting meteoric signatures become more common indicating the formation of effective fluid conduits (Hilgers et al., 2006a).

Fault nucleation is also present on the veins of the 090° and 130° striking sets of the first-generation veins. This is based on the observation of some normal fault zones consisting of long, parallel veins, with brecciated vein cement (Figures 20a, d), and on the presence of long, straight veins in the complex damage zone of normal faults with a few meters offset (Figures 20b, d). Therefore, we infer the presence of a weak mechanical anisotropy during nucleation of the normal faults, both in horizontal (veins) and vertical directions (due to mechanical stratigraphy).

Progressive (normal to strike-slip) motion on these faults led to the formation of dilatant jogs (Figure 18f), to zones of extensive fragmentation (Figures 20b, d, e) and re-cementing. This organizes the damage zone into a mature fault zone that strikes at 100°–110°, at a 10–20° angle to the first-generation veins.
Figure 25: Images related to the Large Northern Fault that cuts and offsets the Rayda Formation.
(a) Topographic ridge consists entirely of the massively cemented deformation zone of the Northern Fault.
(b) View along the backside of the deformation zone. Note that the background shows the drag folds of the Rayda Formation where no weathering-resistant ridge is developed.
(c) View towards the west onto the massive deformation zone of the Northern Fault. The zone of drag folds and large deformation is some 10s of meters wide. Note how the density of the vegetation increases within this zone suggesting a higher permeability and loose substrate. Height of the image is approximately 45 meters.
(d) Drag fold of the Rayda Formation at the Northern Fault. Height of the image is approximately 50 meters.
(e) Quickbird subset to indicate the location of the images (UTM-40N, WGS-84).
The evolution of such a mechanical system can be expected to be very complex as the fractures are rapidly cemented, restoring mechanical strength and re-sealing the fracture for fluid flow. Cemented aggregates of host rock fragments, broken and re-cemented calcite crystals indicate that the mechanical properties, as well as the transport properties of the fault system, changed frequently throughout time (Figure 21). Progressive movement on these faults, up to offsets of several hundred meters, tends to make the fault zones wider and more complex but without major change in structural elements.

Figure 26: (a) Multi-dimensional image set on the Major Northern Fault on the western wall of Wadi Nahr.
(b) The normal fault has an offset of approximately 60 m branching to a few strands in the bottom part. Photo width approximately 450 meters.
(c and d) Here the fault shows sub-parallel fault planes, rotated blocks, deformed intercalated layers with drag folds and intense fragmentation. (c) Photo width approximately 40 meters and (d) person for scale in the right fault strand.
Many observations indicate a systematic change in fault zone structure as a function of position in the mechanical stratigraphy, and are therefore dependent on where the observations have been made. Massive carbonate layers commonly contain single, steep fault planes and very narrow damage zones in the center (Figures 19 and 32). When this layer is in contact with thick argillaceous (weak)
Figure 28: (a,b) Small-scaled ramp structure on the southern flank of the anticline. The ramp forms a topographic ridge, with can be braced a few hundred meters. (c) This aerial photograph draped onto a DEM shows very same ridge stretching several hundreds of meters. The yellow box marks the position of figure b. (Image is approximately 2 km wide, data was kindly provided by Petroleum Development Oman).
beds, these often develop a gradual monocline rather than localized offset. The transition between the monocline, in the soft layer, and the single fault plane, in the hard layer, contains a number of splays (Figures 19d, 23 and 27). Outcrop observations, in profile view, are commonly made on hard cliffs of wadi walls (Figures 19 and 32) exposing the single-plane section (except the relay structure of Figure 26d), whereas map view observations come from the top surfaces of hard layers on which the splayed faults are exposed (Figures 20 and 32).

**Calcite Rhombohedra**

The growth of the massive calcite rhombohedra (Figure 22) is interpreted to have taken place in dilatant jogs of up to 60 cm length, in open space. Changes in color and growth zonation indicate changes in fluid composition or other external conditions (Nollet et al., 2005; Hilgers et al., 2006a; Hilgers et al., 2006b; Nollet et al., 2006).

**Un- and Partly Cemented Joints and Neotectonics (d4)**

The uncemented joints exposed in plane and profile views all strike into the directions of the first vein group perpendicular to the bedding (Figures 33i, 29 and 30). The uncemented joints generally have higher densities and locally much higher densities. In some cases, beds with open joints are on top of beds with cemented hairline fractures with the same orientation. This indicates that some open joints have formed as a result of dissolution and weathering. Another explanation could be that the joints were formed as relaxation fractures at exhumation, which would explain their ubiquitous presence. In the latter case, the denser spacing could reflect a change of the elastic properties of the rock as an effect of its P/T path. The influence of the neotectonic movements is a possible contributor to the joints as well (Figure 31). Fractures in cemented terraces inside Wadi Nakhr indicate recent tectonic movement that presumably guided erosion of the Wadi Nakhr canyon in the Pleistocene (Rodgers and Gunatilaka, 2003; Kusky et al., 2005).

**SUMMARY**

In summary, detailed field observations in excellent exposures provide the basis for a model of the multiphase evolution of the Jabal Shams high-pressure cell in accordance with the work of Hilgers et al. (2006a). This evolution is illustrated by the schematic drawing shown in Figure 33. The earliest structures v1 are a series of anticlockwise rotating tension veins. The first of these formed in a north-south trending direction (Figure 33b), followed by a set striking approximately 130º (Figure 33c), 090º (Figure 33d) and 045º (Figure 33e). All vein sets are perpendicular to the bedding, have large apertures with blocky calcite cement. The geometry of the fracture shows no signs for interaction between the fracture sets in terms of abutting or curving. Rapid sealing of the fractures and thereby a restored tensile strength is interpreted to be the major cause for the dense spacing of this pattern. Veins of this stage hold a rock-buffered isotopic signature (Hilgers et al., 2006a) consistent with the limited vertical extent and the rapid sealing of the fractures. The tensile effective stresses required for the formation of this regional vein system may have been formed in response to overpressure build-up during burial, perhaps in combination with outer-arc extension during emplacement of the Hawasina and Semail nappes.

The position of the isolated ramp structure (d*) is not yet understood in detail. The joints in the ramp are normal to bedding, suggesting that the ramp postdates the jointing process. The south to southeast vergence of the ramp could indicate its relation to the emplacement of the Hawasina and Semail nappes. Figure 33f is our best guess of the evolution of the ramp.

The next stage is bedding parallel shear (d2), which indicates a major change of the effective stress tensor (Hilgers et al., 2006a). Bedding-parallel veins indicate fluid pressures close to lithostatic. Arrays of re-cemented rock flakes also suggest, in this case, cementation repeatedly restored the strength during deformation. The shear movement is top-to-north and top-to-east (Figure 33e). This direction – opposite to the nappes’ emplacement – suggests that these shear zones were formed after the nappe emplacement. An event like this is discussed in detail by Al-Wardi and Butler (2006).
Figure 29: Partly cemented and uncemented joints. Within the field area, a large number of joints with no or only little cement are found. Abutting relationships are common among these fractures. The strike directions correspond to the early veins.

(a) Irregular joint set with different strike directions in a carbonate bed with cemented fractures. Photo width approximately 11 meters.

(b) Cliff exposures with intense jointing in virtually every layer. Note that the spacing is smaller than the bed thickness.

(c) Orthogonal joint set of only two strike directions. Photo width approximately 10 meters.
See facing page for continuation.
Figure 29 (continued):
(d) Densely jointed cliff faces.
(e) Patch with high-joint density. Note three dominant strike directions and the remnants of cement.
(f) Outcrop surface with dense joint pattern with three strike directions (view to the west).
Figure 30: (a) Within some of the high-density joint patches remnants of cement are found. (b) The irregular patches in this case are accompanied with deeper lying beds that are not jointed. In the latter material cemented hairline fractures suggest that the overlying joints were formed exclusively by dissolution or insolation (sun-related surface temperature fluctuations).
Figure 31: Neotectonic features:
(a) Fracture cut the cemented terraces in Wadi Nakhr indicating recent tectonic movement (coin for scale).
(b) The orientation of the fractures corresponds with the axis of Wadi Nakhr, suggesting that the formation of this large valley was dictated by these fracture systems (Kusky et al., 2005).

Figure 32: The normal faults develop single-strand systems in thick competent layers (bottom) and monoclines in softer layers (top). Between these end-members a splayed system develops. Field observations on the normal faults are commonly made within the wadis exposing predominantly the competent layers, whereas the surface observations are made on the exposed top of the latter layers (compare with Figure 23).
Based on fluid inclusion analysis, precipitation temperatures were in the range of 134°–191°C, accounting an overburden load of 90 MPa. No independent pressure data is available that would strengthen the data.

The next major change in effective stress, under continuously high fluid pressures, led to strongly dilatant normal faults with strike-slip components that offset the bedding-parallel shear zones (Figure 33g). These have a distinct isotopic signature indicating meteoric influence, draining the high-pressure system (Hilgers et al., 2006a). The faults nucleated as en-échelon vein sets or along the pre-existing veins in the 090° and 130° strike direction. This means that these faults cannot be simply used to infer the principle stress directions, because of the anisotropy.

Figure 33: The evolution of the regional fracture network is interpreted to result from multiphase deformation: the predominantly carbonate rock material (a) forms sets of joints with prominent apertures. (b, c, d, e) These fractures are formed perpendicular to the bedding probably as a response to high fluid pressures. The open-mode fractures are effectively cemented with white calcite. (f) An isolated ramp structure is interpreted to have formed next with a top-to-south-southwest movement. The role and the temporal relationship are not yet clear. (g) Bedding parallel shear with a top-to-north and northeast movement postdates the bedding-parallel veins forming layer-parallel veins and argillaceous shear zones. Normal faults (h) develop in the next stage. The faults nucleate partly along the weak anisotropy of the 090° and 130° striking veins. The normal fault system forms anastomosing networks to develop a strike of approximately 110°. (i) Exhumation and exposure to weathering lead to the opening of joints (simplified sketch, not to scale; arrow points north).
This weak lateral mechanical anisotropy, combined with the prominent mechanical layering, produces distinct fault zone structures as shown in Figure 32. Important elements are refraction at bedding planes and splaying of single fault strands towards the contact with weaker material (Figure 32). This led to a heterogeneous distribution of fault properties as the morphology of the faults changes.

At the stage of the normal faulting, the environment was still chemically active and led to healing of the fault gouge and several generations of deformed, brecciated fault cement, cemented in turn by less-deformed calcite.

The high-pressure cell of Jabal Shams proves to be a natural example of thermal, hydraulic, and mechanical processes (Bradley, 1975; Zoback, 1978; Noorishad et al., 1984; Bradley, 1994; Noorishad et al., 1996; Tsang, 1999; Olsson and Barton, 2001). The high fluid pressures and the repeated cementation of the fracture system led to the formation of a complex fracture network. Its transport properties, as well as the mechanical strength of the system, were constantly changing as the calcite cement sealed the fractures.

**APPENDIX**

**Methodology Fluid Inclusion Measurements**

A microthermometric analysis of fluid inclusions has been performed on the vein-filling quartz from one of the bedding-parallel shear zones. A detailed description of the sample preparation technique is given by Muchez et al. (1994). Homogenization temperature, followed by phase transitions occurring during heating after completely freezing of the inclusions, were measured on a Linkam THMSG 600 heating-cooling stage mounted on an Olympus BX 60 microscope. The stage was calibrated between -56.6 and 374.1°C with synthetic fluid inclusions provided by Syn Flinc. Reproducibility was within 0.2°C for temperatures between -56.6 and 30°C, and 1°C for total homogenization temperatures. The fluid inclusions occur in growth zones (primary fluid inclusions) and in trails (pseudosecondary and secondary fluid inclusions). The pseudosecondary fluid inclusions occur in first vein-filling quartz generation. All fluid inclusions are two-phase aqueous inclusions and the size of the studied inclusions is between 6 and 20 µm. First melting of the fluid inclusions was clearly observed from -19°C, indicative for the H₂O-NaCl system with a eutectic temperature of -21.2°C. The range of final melting temperature of ice, within the primary and secondary fluid inclusions, varies between -2.3 and -3.7°C, corresponding to a salinity of 3.8 to 6.0 eq. wt% NaCl (Figure 16). This reflects once to twice the composition of sea water. The temperature values of primary and secondary fluid inclusions overlap and are between 84 and 130°C. Within one growth zone, or within one trail homogenization, temperature of the fluid inclusions is within a few degrees. The temperature values of an assemblage of pseudosecondary inclusions are between 134° and 141°C (Figure 16). The homogenization temperatures reflect the minimum temperature of precipitation. A pressure correction to obtain the trapping temperature is difficult since an independent paleogeothermometer or paleogeobarometer is lacking. Accounting for a 3–5 km thick cover of high-density ophiolites, the corresponding correction for lithostatic fluid conditions would raise the temperature for all inclusions by approximately 50–80° from 84–141° to 134–191° at 90 MPa or 186–221° at 150 MPa.

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