Development of fault and vein networks in a carbonate sequence near Hayl al-Shaz, Oman Mountains

Simon Virgo, Max Arndt, Zoé Sobisch and Janos L. Urai

ABSTRACT

We present a high-resolution structural study on the dip slope of the southern flank of Jabal Shams in the central Oman Mountains. The objectives of the study were: (1) to test existing satellite-based interpretations of structural elements in the area; (2) prepare an accurate geological map; and (3) collect an extensive structural dataset of fault and bedding planes, fault throws, veins and joints. These data are compared with existing models of tectonic evolution in the Oman Mountains and the subsurface, and used to assess the applicability of these structures as analogs for fault and fracture systems in subsurface carbonate reservoirs in Oman. The complete exposure of clean rock incised by deep wadis allowed detailed mapping of the complex fault, vein and joint system hosted by Member 3 of the Cretaceous Kahmah Group. The member was divided into eight units for mapping purposes, in about 100 m of vertical stratigraphy. The map was almost exclusively based on direct field observations. It includes measurement of fault throw in many locations and the construction of profiles, which are accurate to within a few meters. Ground-truthing of existing satellite-based interpretations of structural elements showed that faults can be mapped with high confidence using remote-sensing data. The faults range into the subseseismic scale with throws as little as a few decimeters. However, the existing interpretation of lineaments as cemented fractures was shown to be incorrect: the majority of these are open fractures formed along reactivated veins.

The most prominent structure in the study area is a conjugate set of ESE-striking faults with throws resolvable from several centimeters to hundreds of meters. These faults contain bundles of coarse-grained calcite veins, which may be brecciated during reactivation. We interpret these faults to be a conjugate normal- to oblique fault set, which was rotated together with bedding during the folding of the Al Jabal al-Akhdar anticline. There are many generations of calcite veins with minor offset and at high-angle-to-bedding, sometimes in envelop sets. Analysis of clear overprinting relationships between veins at high-angle-to-bedding is consistent with the interpretations of Holland et al. (2009a); however we interpret the anticlockwise rotation of vein strike orientation to start before and end after the normal faulting. The normal faults post-date the bedding-parallel shear veins in the study area. Thus these faults formed after the emplacement of the Semail and Hawasina Nappes. They were previously interpreted to be of the same age as the regional normal- to oblique-slip faults in the subsurface of northern Oman and the United Arab Emirates, which evolved during the early deposition of the Campanian Fiq Formation as proposed by Filbrandt et al. (2006). We interpret them also to be coeval with the Phase I extension of Fournier et al. (2006). The reactivation of these faults and the evolution of new veins was followed by folding of the Al Jabal al-Akhdar anticline and final uplift and jointing by reactivation of pre-existing microveins. Thus the faults in the study area are of comparable kinematics and age as those in the subsurface. However they formed at much greater depth and fluid pressures, so that direct use of these structures as analogs for fault and fracture systems in subsurface reservoirs in Oman should be undertaken with care.
Figure 1: Geological map of the central Oman Mountains with major geologic tectono-stratigraphic groups. The central Oman Mountains comprise two tectonic windows namely Al Jabal al-Akhdar and Saib Hatat. The pre-Permian basement (Autochthon A) and platform carbonates deposited on the southern margin of the Neo-Tethys (Autochthon B) were overridden by the Hawasina (deep sea sediments) and Semail Nappes by a NS-directed obduction from Early Turonian until Early Maastrichtian. An Oligocene to Miocene orogeny led to the formation of large-scale folds, and subsequent erosion carved the present-day Oman Mountain geology (modified after Breton et al., 2004).

INTRODUCTION

The Oman Mountains have been the subject of intensive research because of their unique tectonic setting at the Arabian-Eurasian convergent plate boundary with hydrocarbon systems in northern Oman and United Arab Emirates (UAE) (Glennie et al., 1973; Hanna, 1990; Mann et al., 1990; Pratt and Smewing, 1993; Loosveld et al., 1996; Masse et al., 1997; Gregory et al., 1998; Fournier et al., 2001; Terken et al., 2001; Breton et al., 2004; Melville et al., 2004; Glennie, 2005; Johnson et al., 2006; Hilgers et al., 2006; Al-Wardi and Butler, 2007; Searle, 2007; Holland et al., 2009a). They also offer excellent outcrop analogs for the reservoirs in the subsurface (Borgomano et al., 2002; van Buchem et al., 2002; Hillgartner et al., 2003; Greselle and Pittet, 2005; Homewood et al., 2005, 2008; Filbrandt et al., 2006; Holland et al., 2009b; Droste, 2010; Gomez-Rivas, 2011).

The main tectonic elements and phases of the evolution of the Oman Mountains have been known for a long time (Glennie et al., 1973; Glennie, 2005; Searle, 1985). However, in recent years new research has revealed further details of the complex faulting, fracturing and fracture-sealing events in the Mesozoic platform carbonates (Hilgers et al., 2006; Searle, 2007; Al-Wardi and Butler, 2007; Holland et al., 2009b; Holland and Urai, 2010; Gomez-Rivas, 2011). In the southwestern part of the Oman Mountains, the studies of Hilgers et al. (2006) and Holland et al. (2009b) presented a high-resolution structural map over an area of more than 30 sq km, which is comparable to seismic surveys in the subsurface. The map is based on the interpretation of high-resolution satellite images and local ground-truthing and provides a model for the structural evolution of the area. This work...
opened the way for a similar map, covering a much larger area of about 450 sq km, covering the dip slope of the south flank of the Al Jabal al-Akhdar anticline, from Murri in the northwest, to Birkat al Mawz in the southeast (Figure 1). If properly validated, such a map could provide a uniquely large and detailed dataset and new insights into the structure of faults and fractures in carbonates (cf. van Gent et al., 2010a, b).

This paper provides the validation of the satellite-based interpretations of structural elements from a previous study by Holland et al. (2009b; see coverage in Figure 2). The study carried out a detailed ground-truthing test in a representative area, which is the basis for a regional follow-up study using remote-sensing techniques. The study prepared an accurate high-resolution geological map of the representative area based on detailed fieldwork. It also involved collecting an extensive dataset of orientations of fault and bedding planes, fault throws, vein overprinting relationships and vein strike orientations on bedding planes, together with orientations of joints. This dataset allows the inverse of the ground-truthing exercise, namely the mapping of all the structures that could be detected in remote-sensing images so as to improve future interpretations. This dataset was then used to build a structural model of fault and fracture networks in carbonates that can be compared with existing models. The evolution of the study area is also related to models for the tectonic evolution of the Oman Mountains and subsurface Oman. Finally, the dataset is used to assess the applicability of these structures as analogs for seismic to sub-seismic fault and fracture systems in the reservoirs in Oman and the UAE.

**GEOLOGIC SETTING**

The central Oman Mountains can be subdivided into four tectono-stratigraphic groups – the Autochthonous A and B and the Allochthonous nappes (Hawasina and Semail Nappes) (Breton et al., 2004; Glennie, 2005; Searle, 2007; Al-Wardī and Butler, 2007) (Figure 1). Sedimentary and volcanic rocks of Neoproterozoic to pre-Permian age characterize Autochthon A.
This is unconformably overlain by the sedimentary succession of Autochthon B (Permian–Upper Cretaceous, see Figure 1). Autochthon B consists of platform carbonates that were deposited during the Permian to Late Cretaceous onto the southern passive margin of the Neo-Tethyan Ocean after the break-up of Gondwana (Breton et al., 2004; Glennie, 2005).

With the opening of the North Atlantic Ocean during the Late Cretaceous the Neo-Tethys Ocean began to close. This led to the NNE-directed obduction of young and therefore hot and light oceanic crust, the Semail Ophiolite, on top of the autochthonous units, together with the Hawasina Nappes, which consist of deep-sea sedimentary rocks with intercalated volcanic rocks and massive blocks of shallow-water carbonates – the so-called Oman Exotics (Hanna, 1990; Pratt and Smewing, 1993; Breton et al., 2004; Glennie, 2005; Bernecker, 2007; Searle, 2007).

The southern slope of Jabal Shams in the central Oman Mountains is part of the Al Jabal al-Akhdar anticline, which forms a tectonic window into the pre-Permian basement (Beurrier et al., 1986; Breton et al., 2004; Glennie, 2005; Searle, 2007). The study area is located north of the village of Hayl al-Shaz, northwest of Al Hamra in the Oman Mountains, covering an area of ca. 6 sq km (Figure 2).

Stratigraphically, the area exposes rocks of Autochthon B, more specifically the Barremian–Lower Aptian Member 3 of the Kahmah Group (Kh3, Figures 3 and 4b), mapped by Beurrier et al. (1986). Parts of this group are the Shu‘aiba and Lekhwair formations, which form major oil and gas reservoirs on the Arabian Peninsula (Masse et al., 1997; Terken et al., 2000; Borgomano et al., 2002; van Buchem et al., 2002; Hillgärtner et al., 2003; Greselle and Pittet, 2005; Droste, 2010). The Kahmah Group is the equivalent of the Thamama Group in the UAE, which also contains several major reservoirs (Melville et al., 2004; Johnson et al., 2006).

The map of Beurrier et al. (1986) shows two faults in the study area. In the north a large fault with at least 500 m throw (here called Dar al-Baydhaa Fault; DAB) juxtaposes Kh3 rocks with both Kh1 and Sa (Jurassic Sahtan Group). In the south another large fault (called Hayl al-Shaz Fault) juxtaposes Kh3 rocks with rocks of the Natih Formation (Ws2; throw > 100 m) (Razin et al., 2005). Within the central part of the study area no faults were mapped by Beurrier et al. (1986) (Figure 4b). Hilgers et al. (2006), Holland et al. (2009b), and Holland and Urai (2010) prepared a much more detailed fault and fracture map, and presented a model of the structural evolution of the area based on overprinting relations of structures found in the field.

**METHODS**

The fully-exposed outcrop of clean rock cut by deep wadis presents world-class exposures of the Kahmah Group (Beurrier et al., 1986; Breton et al., 2004; Hilgers et al., 2006; Holland et al.; 2009b). This allowed the creation of a very high-resolution geologic map including measurements of fault throw. With this exceptional outcrop condition it is possible to create a geological map based exclusively on direct, verifiable field observations without interpolations across areas lacking outcrops.

**Positioning and Measurement**

The mapping was carried out based on a sub-meter resolution, multispectral Quickbird™ satellite image that offers a spatial resolution of 0.7 m in the panchromatic band (see Holland et al., 2009b). The first-order topography was derived from an ASTER digital elevation model with a spatial resolution of 30 m and a vertical accuracy better than ± 15 m (Hirano et al., 2003). Positioning in the field was very accurate against Quickbird™ imagery printouts at the scale 1:2,500 and aided by GPS.

Structural features such as bedding, joints and veins were measured with a Breithaupt geological compass. The orientation of faults was determined using photographs of fault exposures in wadi walls, taken with a spirit-leveled digital SLR Camera from the other side of the wadi while viewing direction is parallel to the strike of the fault. This produced accurate measurements of the orientation of a fault plane at a ten-meter scale. Ground-truthing and age relationship
Figure 3: Stratigraphy of the study area comprising rocks of the uppermost member of Early Cretaceous Kahmah Group (Kh3). The member contains the well-known Habshan, Lekhwair, Kharaiib and Shu‘aiba formations (Razin et al., 2005). The figure is compiled from Beurrier et al. (1986), Breton et al. (2004) and Searle (2007).
Figure 4: Figures showing results of geologic mapping and comparison to existing geologic maps and fault maps in the study area. Note: Basemap for all maps is a high-resolution Quickbird™ image (cf. Holland et al., 2009b). With the exception of map 4e all maps show the same area. The position of map 4e is indicated in map 4d.

(a) High-resolution geologic map based on eight lithostratigraphic units (see Figure 5) showing a dip-slope outcrop pattern with steeply incised wadis and faults showing a strong segmentation of the strata. See text for further explanation regarding accuracy and reproducibility. The anchor points of three geologic cross-sections (Figure 9) are marked with red dots. The stratigraphy to the north of the Dar al-Baydhaa Fault (DAB) has been adapted from Beurrier et al. (1986). The map is almost exclusively based on direct field observations. Areas (steep wadi walls) with interpretations are marked with a hatched shading.

(b) Geological map of the study area adapted from Beurrier et al. (1986). The study area between the Dar al-Baydhaa (DAB) Fault and the village Hayl al-Shaz exposes rocks of the Kh3 Member. According to formation thicknesses published by Razin et al. (2005) the DAB Fault has a minimum stratigraphic displacement of 500 m. The southern main fault has a minimum stratigraphic offset of 100 m.

See facing page for continuation.
observations were documented with geo-tagged photographs. With the use of the Quickbird™ image as a basemap all mapped structures and documented information were integrated into a GIS-system.

**Mapping Units and Structures**

The area exposes approximately 100 m of stratigraphic thickness. The stratigraphic units are laterally very continuous and easily recognized, with thickness variation of less than one meter. The thickness of lithostratigraphic units was measured at several locations by lowering a tape measure along the steep wadi walls. This allowed, for the purpose of structural mapping, definition of a local set of eight lithostratigraphic units named A to H. These are shown in Figure 5 and described later in the paper. In addition to mapping the eight lithostratigraphic units, we mapped faults, and in some cases fault gouge (Figure 4a).

**Geologic Mapping and Ground-truthing of Joints and Veins**

As a result of the exceptional exposure, this map is very accurate and reproducible. All unit boundaries and structures on the map were checked

---

**Figure 4 (continued):**

(c) Overlay of faults mapped by Holland et al. (2009b). This data should be compared with the data from the current study in Figures 4a and 4d.

(d) Fault map of the study area with visualized fault throw data. Circle size indicates the fault throw (see legend facing page). The white rectangle indicates the area shown in Figure 4e. Note the variability of fault throw along strike and the bifurcation of the fault network towards the east. The throw of the Dar al-Baydha Fault is estimated at 500 meters.

(e) Enlarged image of area shown in Figure 4d. Detailed section of the fault map with measured fault throw data. Note the fault throw ranging 1.5 m up to 35 m in this excerpt.
against direct field observations. The accuracy of mapped unit boundaries is estimated to be one meter in the reference frame of the QuickBird\textsuperscript{TM} image and better than 10 m in the global reference frame as shown by comparing locations identified on the QuickBird\textsuperscript{TM} image with the GPS location. An exception is the walls of the steep wadis where the map accuracy is less and interpolation is locally required (Figure 4a).

Mapping of faults was done exclusively based on field observations. Therefore, faults on the map are only shown when they can be directly observed in the field, by offset of layers and/or characteristic fault gouge. These results were then compared against the fault map based on satellite interpretation (Holland et al., 2009b). Mapping of the faults was facilitated by the fact that in the vast majority of faults, which can be clearly identified in a wadi wall (throw > 1 m) and followed on the dip slope, there is a characteristic set of white calcite veins and calcite vein breccia. In the mapping area faults without calcite veins are very rare.

Profiles were constructed based on the orientation data of bedding as well as the throw and orientation of all mappable faults (throw > 1 m). Comparing the constructed surface of the profiles with the topographic profile based on the Digital Elevation Model (DEM), it was shown that these independent data agree within the accuracy of the DEM (± 15 m).

Joints and veins were mapped in detail in a set of 17 selected, representative sub-areas based on practical considerations, where the correspondence of field structures and satellite lineaments was compared in detail.

**RESULTS**

**Outcrop Pattern in Local Topography**

The outcrop pattern is mainly controlled by four factors. (1) The regional topography (10\textsuperscript{3}–10\textsuperscript{4} m scale) can be characterized as a dip slope where the topography of the southern slope of Jabal Shams has the same dip as the outcropping strata. (2) WNW-trending faults produced stratigraphic offsets juxtaposing younger strata with older strata. A prominent and potentially confusing feature here is that in many cases the topographic slope is smooth
and parallel to the bedding across a fault. In other words, faults usually do not have topographic expression (Filbrandt et al., 2007), but wadis may change direction across faults (see also Holland et al., 2009b). (3) Wadis form windows into older stratigraphic units. (4) Local topography (10–100 m scale) is defined by weathering resistance of limestone layers and is reflected in the outcrop pattern (see Figures 4, 6 to 8).

**Lithostratigraphic Units A to H**

The approximately 100 m of stratigraphy exposed in the area is characterized by up to 15 m-thick massive limestone layers intercalated with argillaceous limestone layers of variable thickness. For the purpose of mapping, we defined a series of layers called lithostratigraphic units A to H (Figure 5), which are laterally very continuous and recognizable. The limestone beds are commonly made up of dark gray mudstone to wackestone that weathers to a lighter gray or light brown color. Within these, floatstone horizons made up mainly of rudist debris as well as bioturbation are common in all mapping units. In fossil-rich beds low-angle cross-bedding can be occasionally observed. Stylolites as well as iron-bearing concretions occur in several layers. Thicker fossil-rich layers are laterally continuous and recognizable. The argillaceous interlayers are commonly less
thick (< 2 m) and of a light gray to brown color. They consist of a marly to clay-rich limestone with a laminar or lenticular texture with pressure solution cleavage and lack macroscopically recognizable fossils.

**Unit H:** The lowermost unit H (light green in Figure 4a) has only its top defined. Its upper layer is a ca. 2 m thick argillaceous bed that tends to form a horizontal recess in the cliff leaving unit G overhanging. Especially near faults this layer is often washed out, forming small caves. Below this an erosion-resistant layer of 20 m thickness is present (Figures 5 and 8).

**Unit G:** This unit (orange in Figure 4a) consists of a single, massive limestone bed of 11.2 m thickness that forms a prominent cliff at wadi walls (Figures 5 and 8).

**Unit F:** This unit (blue in Figure 4a) appears in the wadis as a 16 m-high cliff composed of numerous, layers of equal thickness. Bioturbation and horizons of rudist debris are present in several layers of the unit. The bottom of the mapping unit F is marked by a gray mudstone bed, which is pervaded by reddish schlieren (Figures 4 to 8).

**Unit E:** The top layer of this unit (olive in Figure 4a) is a 10 m-thick, weathering-resistant limestone layer that comprises a horizon of iron bearing concretions. Below this there are five almost equally thick limestone beds of which four are usually clearly seen in wadi walls. The lowermost bed of unit E is a 5 m-thick limestone layer, which shows intensive bioturbation as well as bedding-parallel stylolites. Laterally discontinuous, fossil-rich horizons are common. These fossils are associated with small iron concretions (Figures 4 to 8). The overall thickness of unit E is 21 m.

**Unit D:** This unit (red in Figure 4a) has an overall thickness of 19.5 m and part of it forms a cliff in most wadis. It is bound at the top by a 70 cm-thick, solitary, massive limestone bed. The remainder of the unit is made up of a single massive and fossil-rich limestone bed. On the dip slope it is easily
recognizable by a horizon rich in rudist debris. In profile, the bed shows a southward dipping low-angle joint set, which is unique within the studied stratigraphic column. The lower half of the red unit contains frequent stylolites as well as bioturbation. The bottom of unit D is defined by an argillaceous bed of ca. 1.5 m thickness. Due to its recessing weathering, this layer usually does not crop out on the dip slope (Figures 4 to 8).

**Unit C:** This unit (brown in Figure 4a) is 4 m thick and consists of two weathering-resistant limestone beds separated by a 0.7 m-thick argillaceous bed with lenticular texture. The top of the unit is marked by bioturbation. The bottom of unit C is characterized by a 1.5 m-thick, argillaceous bed (Figures 5 and 7).

**Unit B:** The upper half of this unit (yellow in Figure 4a) is a 6 m-thick unit that is enriched in fossils while the lower half features a fossil-poor limestone bed with undulating laminations (Figures 5 and 6).
Unit A: The uppermost (light blue in Figure 4a) mapping unit has only its bottom defined. It is marked by a 40 cm-thick argillaceous limestone layer of light gray color. Above this, there is a succession of massive limestone beds, which were not further studied (Figures 5 and 6).

Geologic Map and Cross-sections

The map has two main elements: the outcrop pattern of the boundaries of the lithostratigraphic units, and the faults (Figure 4a). The boundaries of the lithostratigraphic units show the typical outcrop pattern of a dip slope, with the lower units cropping out in the northern part of the area. Faults are the most prominent structural feature in the mapping area. They are exposed in the wadi walls (Figures 8 and 12) and usually easy to follow laterally on the dip slope. Minor faults with throw of less than one meter were occasionally identified in the wadi wall profiles, associated with the larger faults (splays, branches), but these could not be followed on the dip slope.

Three geological cross-sections (A-A', B-B', C-C'-C''), Figure 9, see Figure 4a for location) illustrate the three-dimensional architecture. A few longer faults can be traced through all profiles showing variations in strike orientation (undulation) and fault throw (compare with van Gent et al., 2010a, b).
Structural Inventory and Overprinting Relationships

Faults
The orientation of faults was measured across the wadi walls with an accuracy of a few degrees. Figure 10 shows a lower hemisphere plot of faults and bedding in the mapping area, distinguishing the faults with hanging wall in the south and north. It can be seen that some N-dipping faults have the hanging wall to the south.

The throw of the mapped normal faults ranges from > 500 m (Dar al-Baydhaa Fault) to ca. 1 m (Figures 4d and 4e). Especially in faults with throws exceeding 10 m, very large calcite crystals often occur as shown by the cleavage rhombohedra (Figure 11e). In some cases the cemented fault gouge is brecciated and incorporates angular and elongated vein and host-rock fragments (Figure 11h).
Figure 11: (a–e) Fault core details of the Dar al-Baydhaa Fault (DAB); and (f–h) medium size faults with an offset of a few tens of meters.

(a and b) The DAB Fault is exposed in the westernmost wadi of the field area where it juxtaposes the rocks of the field area (Kh3) to equally competent rocks of the Kh2. The fault gouge reaches a width of more than 10 meters.

(c) On the slope, the cemented fault core stands out due to its high weathering resistance.

(d) In the east of the mapping area, where soft rocks of the Sahtan Group are present in the footwall, the cemented core is less wide. Bedding is rotated and dragged into the fault on the footwall side. Note that the density of vegetation increases in the vicinity of the fault.

(e) Volumes filled with large crystals of precipitated calcite are common along the DAB Fault and indicate dilatational sites.

*See facing page for continuation.*
Figure 11 (continued): (f–h) Fault zones of medium- and small-sized faults usually also feature calcite-cemented breccia with angular and elongate host-rock fragments (Photo f) besides large calcite crystals (Photo h) and an increase of vein density (Photo g).
Figure 12: Fault exposures in the subvertical section of wadi walls.
(a) Horst with nearly identical throw (10 m) on both delimiting faults;
(b) south-dipping fault with 16 m of throw branching into two synthetic fault strands;
(c and d) outcrop of a steep normal fault (hanging wall to south, north-dipping) in a wadi bed,
one of the few locations where direct measurement of a fault plane is possible;
See facing page for continuation.
Fault planes are rarely exposed (mainly along the massive gouge of the Dar al-Baydhaa Fault), but where visible, striations in dip-slip and oblique-slip orientation were occasionally observed (Figures 12c and 12d). The faults are usually not solitary but form an interconnected network that shows a trend of increasing bifurcation towards the east (Figures 4a, 4d and 4e).

**Open joints** occur sub-perpendicular to bedding in two predominant strike directions (NE-SW and NW-SE) forming an orthorhombic to orthogonal fracture network (Figures 13 and 14). The joints are usually straight, show varying apertures (mm-, cm- and dm-scale) and, in general, are spaced 10 cm to 1 m apart. Joint sets with a small spacing and a low aperture are usually confined to a single limestone bed. Wider joints, with a fairly constant and wide spacing, can penetrate through several beds. Abutting of joints is very common but the abutting relationships are inconsistent. Therefore a classification into systematic and non-systematic joint sets is not possible. A common observation is that joints reactivate microveins and macroscopic veins. In outcrop joints are often widened by erosion and filled with light brown fine-grained, carbonatic soil (Figure 13e).
Veins are referred to as microveins if their aperture is less than 1 mm. In the mapping area they occur with variable densities. In some locations they show a spacing of only a few millimeters and an aperture-to-length ratio significantly lower than that of macroscopic veins in the same area. The microveins have straight walls and a calcite cement that gives only poor contrast to the host rock. Nevertheless, they can easily be spotted in places where they separate rock volumes of slightly different color (Figure 16b). Most microveins are oriented sub-perpendicular to bedding and strike NW-SE. However many other orientations, including bedding-parallel, are common. Intersections between microveins are usually sharp and show no signs of curving or abutting. Microveins are often preferentially weathered and develop into open joints (Figure 16a). A common observation is microveins being reactivated by veins at high-angle-to-bedding (see next section) as well as joints (Figures 16c and 16d).

Veins at High-angle-to-bedding (VHAB)
Calcite veins are ubiquitous in the area, commonly at high-angle-to-bedding. These can be found with all strike directions in the mapping area (Figure 17). The overall vein density is the highest in the damage zones of faults. The ubiquitous occurrence of veins with high-angle-to-bedding away from faults however suggests that many veins are not fault-related. There are hints in the field that

**Stylolites**
All major stylolites found in the mapping area are parallel to bedding. Their teeth can be up to several centimeters long. Laterally they can be traced for long distances (order of several tens of meters) and also where they cross faults. Minor stylolites of mostly less than a meter length occur in various strike directions at a high-angle-to-bedding. Those can often be found interacting with subvertical veins (Figure 15b).

Figure 13: (a and b) Quickbird™ image excerpts.
(b) Image shows interpreted joints/fractures from Holland et al. (2009b). Quickbird™ image, band 4, 2, 1 as RGB, pan-sharpened. The image’s contrast was adjusted with ArcMap.
(c) Oblique view photo on same area as in Figure 13a. Open fractures with a well-distributed spacing of 3–5 m can be found here. The black frame indicates the position of Figure 13d.
(d and e) The previously mentioned open fractures have an aperture of 20–40 cm and are not only filled with fine-grained soil but also are densely inhabited by vegetation. Small grasses are predominantly growing in the soil, but small bushes and even trees with a height up to 3 meters are rooting into the fractures. No calcite veins with appropriate dimensions were observed.

See facing page for continuation.
Figure 13 (continued):
the vein density varies between layers, but this correlation is not very strong. The end-member, regularly spaced, bedding-confined veins (compare Holland et al., 2009b) has not been found in the area.

Normal-to-bedding veins are commonly in opening mode. In some cases indicators for mixed-mode opening and shear displacement along veins can be found, such as "wing vein" terminations and dilatant jogs (Figures 15c, 15g and 18a).

Veins at high-angle-to-bedding can be solitary with highly variable length-to-aperture ratios, vein bundles and en-echelon sets. Solitary veins feature straight walls and show apertures up to 5 cm and lengths ranging from less than one meter to several tens of meters (Figure 15a). Veins at high-angle-to-bedding are filled with coarse-grained calcite. Lenticular host rock inclusions and tip splay termination are indicative for crack-seal growth (Figure 15e). The zebra veins described in Holland and Urai (2010), occasionally occur in the area, as tip splays of larger veins (Figure 15f).
En-echelon vein sets sometimes occur as conjugate sets. In some cases they also form the termination of solitary veins. The en-echelon vein sets have lengths of several meters and consist of equally sized and distributed vein segments along their strike. The segments usually feature a high aperture-to-length ratio at lengths in the order of 10 centimeters (Figure 15d) (cf. Gomez-Rivas, 2011). The distribution of vein, joint, and microvein orientations in the area is shown in Figure 17.

**Bedding-parallel Veins**

Bedding-parallel shear veins are found at bedding interfaces (Figure 19). They can be found in the same stratigraphic position in outcrops several hundred meters apart, which suggests a large lateral continuity. Bedding-parallel veins show apertures between 1 cm and 3 cm. They contain host rock inclusion bands that are arranged sub-parallel to the vein wall as well as slickenfibers that indicate NNE to SSW striking shear direction (Figure 19b).

**Overprinting Relationships and Vein Orientations**

Veins at high-angle-to-bedding consistently crosscut major bedding-parallel stylolites. The interplay of veins and minor stylolites with high-angle-to-bedding suggests that those stylolites formed either contemporaneously with or later than the veins (Figure 15b). Overprinting relationships between the veins and the normal faults are inconsistent and complex in this area. Abutting of veins was never observed. Normal faults clearly offset bedding-parallel veins as well as bedding-parallel stylolites. Joints are interpreted as very recent since they crosscut all other structural features.

Over 100 overprinting relationships between veins at high-angle-to-bedding have been collected. To get more insight into the overprinting relationships between veins, strike directions were plotted in an X-Y diagram shown in Figure 20. In this diagram, each point represents one overprinting relationship where the strike direction of the intersected (older) vein is plotted on the Y-axis against the strike direction of the crosscutting (younger) vein.

Data from eleven outcrops with three mutual vein-overprinting relationships are shown also in this diagram (see Figure 21 for examples). Nine cases indicate anticlockwise rotation (taking acute angles) of the three subsequent veins, one clockwise, and one mixed. It is also seen in this diagram that vein intersections with clear overprinting relationships at angles below 30º are rare.

**Ground-truthing**

An unambiguous correlation of a lineament on the satellite imagery to a distinct feature in the field is not possible in all cases; i.e. in some cases one sees different structures on a satellite image than in the field. A comparison of the results of the satellite image interpretation by Holland et al. (2009b) to the direct field observations shows a consistently good correspondence of the faults mapped with remote sensing and faults mapped in the field (Figures 22 and 23). 60% of faults (measured by outcrop length on the map) appear on both satellite and the field map. 25% were directly observed in the field but have not been interpreted by remote sensing. The remaining 15% mapped by remote sensing could not be proven in the field, due to lack of lithologic offset and absence of a fault gouge (Figure 24). The sum of all (100%) refers to combined faults mapped from remote sensing and field observations.

Mapping of faults on the floor of deeper wadis could not be carried out with comparable quality to mapping on the dip-slope surface due to limited accessibility and recent sediments. These areas are excluded from comparison of fault outcrop lengths.

Ground-truthing of linear features (referred to as “fractures” and “joints” in the Holland et al., 2009b, dataset) revealed that these lineaments are in most cases joints filled with light brown soil or veins and vein arrays with bright (white) calcite fill (Figures 13 and 14). The open joints far outnumber calcite-filled veins in the area. Only a few lineaments in the immediate vicinity of settlements are of anthropogenic origin (i.e. point source mining of building stones or paths created by daily livestock movements).
Figure 15: Examples of veins oriented high-angle-to-bedding (VHAB).
(a) Long solitary veins with cm-scale aperture and lengths of several meters (compass for scale).
(b) Solitary veins interacting with minor, sub-vertical stylolites (compass for scale).
(c) Solitary vein with wing cracks and en-echelon veins as lateral termination (person for scale).
(d) Dextral en-echelon vein array (compass for scale).
See facing page for continuation.
In contrast to the fault interpretation, which showed a good agreement to field observations, the vast majority of joints and veins that can be found in the area are not directly resolved on the satellite imagery because their spacing is generally below the resolution of the Quickbird™ image. Regions with high gradients in the density of joints and weathered microveins appear as a recognizable linear pattern on the Quickbird™ imagery and even though the structures are too small to be resolved, the main strike directions are measureable.

DISCUSSION

Field Conditions and Map Quality

The unique outcrop conditions, which allowed the quality of mapping presented here, are a combination of a number of factors. Firstly, the dip-slope outcrops incised by deep wadis cutting into Member 3 of the Cretaceous Kahmah Group, allowed definition of the eight stratigraphic units for mapping purposes, encompassing 100 m of vertical stratigraphy; these units are easily recognizable across the mapping area. The same wadis allow for the measurement of the fault plane orientations, mapping of fault zones (Holland et al., 2009b, Figure 12) and measurement of fault throw.

Secondly, the full exposure of clean rock eroded sub-parallel to bedding allows for the precise mapping of the layer contacts and the fault zones. The bedding dip of around 20° is exceptionally well suited for this study because it is easy to access and at the same time is washed by rainfall. These exceptional conditions, in combination with the high resolution Quickbird™ image, allow producing a satellite-based map, which can be verified by direct field observations. The verification includes measurement of fault throw in many locations and construction of profiles, which are accurate to within a few meters. This method can be extended to the whole southern flank of the Al Jabal al-Akhdar anticline. The mapped faults might form an interesting dataset that can be used to constrain the faults commonly found in the Shu’aiba and Natih reservoirs (Filbrandt et al., 2006).
Figure 16: Photos of ubiquitously observed microveins.
(a) Densely spaced microveins are weathered forming comb-like, sharp ridges.
(b) Microveins form a polygonal tile-pattern by separating limestone with different rock color.
Recent joints are deflected by microveins as to be seen in the mid-right part of the image.
(c) Recent joints with interfering crack-tips reactivate pre-existing microveins. Coin for scale.
(d) Pre-existing microveins (white arrows) appear reactivated by macroscopic veins that show a sinistral in-plane displacement creating a dilatant jog. The jog itself is delimited by pre-existing microveins.

Figure 17: Rose diagrams displaying the strike directions of structural features obtained from different scales and methods on the southern slope of Al Jabal al-Akhdar. (a) Open (recent) joints measured in outcrop; (b) macroscopic veins (at high-angle-to-bedding) measured in outcrop; (c) microvein orientations obtained in a microstructural study by Meeßen (2011); and (d) orientation of linear features (respectively joints) from satellite image interpretation by Holland et al. (2009b).
An interesting and important aspect regarding the surface morphology of this part of the southern flank of the Al Jabal al-Akhdar anticline is that faults usually do not leave a topographic expression on the dip slope (see Figure 25). In the cases where a systematic topographic expression related to faults can be observed, it does not reflect the fault kinematics and fault throw but rather to the weathering resistance of the juxtaposed layers and/or fault gouge (Figure 25c).

The study of Filbrandt et al. (2007) documented several cases where a fault of the same system shows a topographic expression on the dip slope that corresponds to the throw of the fault. In these cases it is possible to extract the kinematics and throw distribution of the faults from the topography via remote sensing. We note that this is not possible for any faults within our study area.
Virgo et al.

Figure 19: (a) Stacked bedding-parallel vein at the interface of two argillaceous limestone layers in profile view. The vein contains bands of host-rock inclusions incorporated into the vein parallel to the interface (pen for scale). (b) The remnants of eroded bedding-parallel veins are often exposed on the surface of limestone layers. The orientation of stretched calcite crystals indicate the shear direction to be either NNE or SSW. The stretching lineation of the crystals is highlighted with red lines (length of arrow is 10 cm).

Figure 20: Age relationship observations organized in a scatter plot. For each observed vein overprinting the strike direction of the relatively older vein (green scale on y-axis) is plotted against the strike direction of the relatively younger vein (red scale on the x-axis). An anticlockwise rotation of subsequent veinings is indicated by the wedge-like shape of the point-cloud that widens to the left with respect to the y-axis. The top right corner corresponds to the oldest vein generation (1). Colors from green to red indicate subsequently younger veins. Data points in the blank area correspond to veins that have reactivated already existing vein strike directions after the rotation has exceeded 180°.

Faults and Fault Network

The fault map prepared in this study shows good correspondence to the satellite-based fault map of Holland et al. (2009b). All faults with a throw above 5 m were identified both in the field and in satellite images. However, there are also small but significant differences. Firstly, approximately 20% of the calcite-filled vein arrays interpreted as fault zones in the satellite images do not have throw (compare Figure 24). Secondly, about 30% of faults that were identified in the field contain calcite-filled vein arrays, which are not visible on the satellite images (Holland et al., 2009b).

These observations are interpreted as follows. The majority of the faults in the study area are exposed in the more competent carbonate units of the sequence. In these units the faults are commonly dilatant and develop the characteristic vein arrays. However, these vein arrays are sometimes too thin to produce sufficient contrast in the satellite images. Only a small fraction of the faults exposed in the outcrop are non-dilatant and without vein arrays. This can be seen in some of
Figure 21: Examples veins with three different strike orientations overprinting each other. Their corresponding data points are highlighted in the scatter plot on the right side (see also figure 20). (a) Based on the acute angle between the intersecting veins, this example is one of the rare indicating a clockwise rotation of veining direction. In our interpretation the youngest vein (NE-striking) reactivates a strike direction that was active before. (b) Triple overprinting indicating an anticlockwise rotation of the subsequent veins. Clear crosscuttings of veins at angles less than 30° (here: youngest and intermediate vein; nb. 1) are not common. (c) Example indicating anticlockwise rotation. The total amount of rotation recorded in this outcrop is 100°.
Figure 22: (a and b) Correlation of faults appearing on satellite-image with corresponding faults in the field.

(a) Satellite image showing the Dar Al-Baydhaa Fault (DAB, throw > 500 m) juxtaposing Member 3 rocks of Kahmah Group (dark color in the southern part) with bright colored rocks of the Rayda Formation (Kh1 Member) and Jurassic Sahtan Group (deeper in the wadi; see also Figure 4a, 4b).

(b) Corresponding outcrop in the field of the DAB Fault. The position and viewing direction of the photograph is indicated on the satellite image. The image width at its bottom is 2 meters.

Figure 22: (c and d) Correlation of faults appearing on satellite-image with corresponding faults in the field.

(c) Satellite image showing a fault (throw 44 m) in the central part of the study area. The fault’s appearance on the image is aided by the incisions into the wadi wall as well as massive calcite blocks and vein bundles. Furthermore the fault can be identified by aligned vegetation (in red). This can be compared to the field photo in Figure 22d.

(d) The photo’s position and viewing direction is indicated with a red marker on the satellite image in Figure 22c. The scale (black box; an abandoned house) is 8 meters.
Figure 23: Comparison of the faults mapped in the area by field observation and satellite image interpretation. Red lines indicate fault solely found by remote sensing. Blue fault traces indicate faults that are proven to exist in the field either by showing clear offset or a cemented fault gouge but are not identified in the satellite imagery. Faults that are identifiable in the field as well as on the Quickbird™ imagery are labeled green.

the excellent wadi wall exposures, where the amount of calcite veins in the fault zone clearly varies along the vertical profile. A detailed study of this vertical distribution of dilatant sections is the subject of a follow up study.

Many faults show a lateral continuation of the characteristic vein arrays beyond the sections where there is visible offset. They were interpreted by Holland et al. (2009b) as faults. In our interpretation, these arrays without visible offset represent the first stage of development of the dilatant sections of faults, which start out as a network of highly dilatant crack-seal veins (cf. figure 18 of Holland et al., 2009b). Similar faults, in highly over-pressured pegmatites, were also described in Schenk et al. (2007) and this interpretation is similar to the model shown in figure 35a of Filbrandt et al. (2006), and thus could be a general feature of this fault system which formed in a highly overpressured sequence. A sketch of our working hypothesis of this fault structure is shown in Figure 26. The network of faults mapped in the area shows a high connectivity such that the mapped rock volume is strongly segmented. Accordingly it is not possible to cross the study area from north to south on one horizon surface without crossing several faults.
The satellite image clearly suggests a fault line that runs from the relay in the upper left corner in ESE direction.

Alignment of trees and a light color contrast to the adjacent bedrock as well as the impact on the surface morphology (wadi wall incisions) indicate a fault. The red arrow illustrates position and view direction of profile photograph in Figure 24c. The white rectangle shows the approximate position of a map view photograph of this linear feature in Figure 24d.

Field photograph showing a profile view in strike direction of the fault (view to ESE). Position is marked in Figure 24b. The fracture corridor indicated by dashed line is characterized by an alignment of trees as well as by vein bundles (Figure 24d) that are running along. The outcrop does not show any visible vertical or horizontal offset that would be evidence for a normal or strike-slip fault.

See facing page for continuation.

The fault relays exposed in the area are invariably strongly deformed and contain high concentrations of veins. They would be classified as breached relays following the nomenclature of Childs et al. (1995).

The common occurrence of the brecciated veins in the exposed fault zones is interpreted as evidence for reactivation of the fault network. The reactivation may have occurred in a different
stress field, possibly a later event involving strike-slip movement as suggested for the area by Gomez-Rivas, 2011).

The fault-orientation data presented in Figure 10 are very accurate. From the two clusters of fault orientations the half dihedral angle is normal-to-bedding and the intersection direction of the average of both clusters is horizontal. This argues that the faults formed as a conjugate normal fault set with a WNW-strike, both sets dipping about 60°. Later, this horst-and-graben system was tilted southwards together with bedding. As a result some initially steep southward-dipping faults with their hanging wall to the south are now found dipping to the north. However, a few faults with low stratigraphic offset appear as reversed faults after the back rotation. Those faults possibly formed as late faults during the phase of strike-slip reactivation. A more detailed analysis of pairs of fault orientation data, from locations where the faults from both clusters are locally intersecting, shows that the local intersections are also horizontal (Figure 10). The analysis of fault plane orientations shows the same conclusion as drawn in the work of Al-Wardi and Butler (2007): the faults formed when bedding was horizontal and were rotated together with the bedding during the folding of the Al Jabal al-Akhdar anticline.

Because of the strong connectivity of the fault network the calculation of throw gradients and length-throw relationships in the study area is difficult. Nevertheless the data are consistent with similar faults in the area studied by Filbrandt et al. (2007). A full analysis of fault-throw distributions is the subject of an ongoing study.
Virgo et al.

Veins, Microveins and Joints

It is clear from the data presented above that the vast majority of the veins in the area are oriented at a high-angle-to bedding, and display a wide range of strike orientations. Exceptions are some of the en-echelon vein sets, which are oriented at variable angles to bedding. This means that where en-echelon vein sets are present in conjugate pairs the intersection of the two is plunging.

The damage zones of faults show a much higher vein density than the rest of the study area. However, even away from all outcropping faults, a place in the study area where no veins are present within a radius of 10 meters can hardly be found. Veins can therefore be regarded as a ubiquitous structure.

Figure 25: Surface expression of faults in profile view.
(a) The dip slope extends across a southward dipping normal fault (throw: 11 m) without a recognizable topographical change. The erosional surface is parallel to bedding.
(b) A gradual change of erosional surface dip in the vicinity of a southward dipping normal fault. The overall change in elevation associated to the normal fault does not reflect its actual throw.
(c) Surface expression of the Dar al-Baydhaa Fault (throw: > 500 m) in the eastern part of the study area. Away from the fault the erosional surface (highlighted with dashed line and triangles) on the footwall and hanging wall is parallel to bedding. The surface elevation of the footwall is lower than the surface of the hanging wall (vice versa case would be expected). The topographic expression is controlled by the weathering resistance of the juxtaposed layers and does not represent the fault’s kinematics.
of a pre-existing anisotropy formed by the microveins. It does not necessarily correspond to the
Therefore in our interpretation the joint network exposed in the area is formed as reactivation
microveins (Figures 16c and 16d). In agreement with this, the orientation distribution of microveins
studied limestone volume (Meeßen, 2011). It is also common to find macroscopic veins reactivating
observed. A microscopic study has shown that closely spaced microveins are common in the whole
area microveins parallel to veins and (micro) veins being reactivated by joints are commonly
becomes progressively filled with veins, the new veins will increasingly interact with the old ones
bedding-parallel and fault veins. This work should take into account that as the rock volume
is needed to fully understand the evolution of the veins, focusing on the relationship with the
sequence. The faults are therefore interpreted to overprint the earliest generations of veins, and
outside the fault zones can be both older and younger than the faults. This is in disagreement
with the interpretation of Holland et al. (2009b), who have interpreted the full set of anticlockwise
rotation of successive generations of veins. However, there are some exceptions and
more work is needed to fully test this model.

An important observation is that veins in the damage zone of faults are part of the overprinting
sequence. The faults are therefore interpreted to overprint the earliest generations of veins, and
are overprinted themselves by younger veins. This means that the veins at high-angle-to-bedding
outside the fault zones can be both older and younger than the faults. This is in disagreement
with the interpretation of Holland et al. (2009b), who have interpreted the full set of anticlockwise
rotating veins to have formed before the bedding-parallel shear phases. More detailed work
is needed to fully understand the evolution of the veins, focusing on the relationship with the
bedding-parallel and fault veins. This work should take into account that as the rock volume
becomes progressively filled with veins, the new veins will increasingly interact with the old ones
(Holland and Urai, 2010).

Another important point is the relationship of veins to microveins and joints. In the entire study
area microveins parallel to veins and (micro) veins being reactivated by joints are commonly
observed. A microscopic study has shown that closely spaced microveins are common in the whole
studied limestone volume (Meeßen, 2011). It is also common to find macroscopic veins reactivating
microveins (Figures 16c and 16d). In agreement with this, the orientation distribution of microveins
is the same as that of joints as measured in satellite images by Holland et al. (2009b) (Figure 17).
Therefore in our interpretation the joint network exposed in the area is formed as reactivation of
a pre-existing anisotropy formed by the microveins. It does not necessarily correspond to the
traditional interpretation of the orientation of the recent stress field.

Data of vein overprinting (veins at high-angle-to-bedding) has been plotted in a new type of
diagram (Figure 20) with strike directions of overprinting veins on the x and y-axis. One can see
that veins with strike direction between 150° and 155° are overprinted by veins with a large range
of strike orientation. Thus they are interpreted to be the oldest veins. An anticlockwise rotation of
horizontal principal stresses of at least 290° that caused a subsequent overprinting of existing veins
is the simplest explanation, and this is in agreement with all collected data. This result is also in
agreement with the study of Holland et al. (2009b) who identified an early generation of veins with
a strike about 150°, overprinted by veins rotating progressively anticlockwise. They also found the
amount of rotation to exceed 180°. However the oldest generation of veins described by them is
oriented N-S but these were not observed in the study area. This interpretation is also consistent
with data from outcrops where three mutually overprinting vein sets show direct indications of
anticlockwise rotation of successive generations of veins. However, there are some exceptions and
more work is needed to fully test this model.

Figure 26: Conceptional sketch showing a representative part of a dilatant normal fault in block
view. The low strain tip zone of the faults is characterized by calcite filled mode I en-echelon
vein arrays. In map view these appear as vein bundles. Towards the center of the fault the throw
and the dilatational component increases, appearing as a calcite-cemented fault core. Fault-parallel
vein bundles can also be found around the central part, where the cemented fault core overprints them. It is hypothesized the vein bundles formed early during fault formation. Note: The figure represents a fault in the subsurface; the top plane of the sketch does not represent the surface of the dip slope.
In summary, the structural interpretations of this study are largely consistent with previous work by Breton et al. (2004), Hilgers et al. (2006), Al-Wardi and Butler (2007), Holland et al. (2009b) and Gomez-Rivas (2011). Improvements we can make on previous structural models are in the timing of the veins at high-angle-to-bedding versus the faults. The evidence in previous studies on this subject was less strong than presented here, but more work is needed to resolve this further.

**Relation to Tectonic Evolution**

The bedding-parallel veins belong to two bedding-parallel shearing events that are widely identified in Al Jabal al-Akhdar: top to SSW-directed emplacement of the Hawasina and Semail Nappes (Searle, 2007), followed by top-to-NNE shearing related to exhumation and orogenic collapse (Breton et al., 2005; Hilgers et al., 2006; Al-Wardi and Butler, 2007). This phase was regional in extent and took place from Turonian until Early Maastrichtian (Breton et al., 2005).

Normal faulting started after this phase, since bedding-parallel veins are offset by the normal faults. As shown by the maps of Beurrier et al. (1986) and Holland et al. (2009b), this fault system is present in most of the Al Jabal al-Akhdar, cutting the sequence from basement to the overriding nappes, including the Muti Formation. The same fault system was described in the paper by Filbrandt et al. (2006) who proposed that it is the “same age and density” as the Campanian faults in the subsurface of Block 6 in the Interior of Oman. This corresponds to extensional faulting during the Maastrichtian in northeast Oman as analyzed by Fournier et al. (2006) and in Abu Dhabi (Johnson et al., 2006). A possible explanation is the subsequent shift of the Mutih-Fiqa trench southward onto the Arabian Plate as proposed by Robertson (1987). While the deposition of Fiqa in Block 6 was still active (cf. Filbrandt et al., 2006), the autochthonous limestones of Al Jabal al-Akhdar had already been overridden by the nappes. We favor this interpretation but note that the evidence to support this correspondence is not very strong, and these faults could also correspond to those of Phase 2a of Fournier et al. (2006) and be much younger (post-Eocene).

Alternatively, the reactivations of the normal faults and the post-fault veins could correspond to Phase 2a and Phase 3 of Fournier et al. (2006), or to the strike-slip phases #5 and #7 that were postulated by Gomez-Rivas et al. (in preparation).

Finally, the folding of the fault system during the creation of the Al Jabal al-Akhdar anticline is interpreted to correspond to the Miocene–Pliocene compressional event seen in many studies (Poupeau et al., 1998; Fournier et al., 2006).

**Relationship to Faults and Fractures in Reservoirs of North Oman**

The porosity in the limestone reservoirs in North Oman ranges between 10% and 30% and high fluid overpressures were absent during structural evolution (Wagner et al., 1990). In contrast, the rocks studied here were deformed at much greater depths, at significantly higher temperatures, lower porosities and under high fluid overpressures. These conditions were probably related to pore collapse and under-compaction during the obduction of Hawasina and Semail Nappes. These conditions are more favorable for crack-seal processes, although interestingly the Brittleness Index in both systems may have been comparable (van Gent et al., 2010b). Thus the application of this study’s results to the reservoirs in the foreland needs to be investigated and depends on the target reservoir. On the other hand, as already noted by Filbrandt et al. (2006), the rocks studied in this project can provide a world-class analog of structures in the subsurface and the detailed study provided here can be extended to a much larger area.

**CONCLUSIONS**

The full exposure of clean rock incised by deep wadis provides the basis for an exceptionally accurate map, based on direct field observations without interpolated areas. Ground-truthing of the satellite-based interpretations of structural elements shows that faults can be mapped with high confidence using remote-sensing data. The mapping extends far into the subseismic range,
to throws down to a few dm with this quality of data and under such exceptional outcropping conditions.

The interpretation of Holland et al. (2009b) lineaments in satellite images being cemented fractures needs to be corrected: the majority of the lineaments are open fractures (which may be reactivated veins).

The prominent set of conjugate EW-striking faults with throws from several centimeters to hundreds of meters are commonly dilatant and contain bundles of coarse-grained calcite veins, which may be brecciated during reactivation. Another important feature is formed by several sets of calcite veins with minor offset and at high-angle-to-bedding, sometimes in en-echelon sets, and, less prominently, bedding-parallel calcite filled shear veins with a NNE-trending striation.

A recent joint system is present in most units; joints can often be shown to be reactivated microveins. We hypothesize that the present-day joint system is strongly controlled by the presence of a pervasive anisotropy formed by microveins and it may not reflect the present-day stress field in a simple manner.

Analysis of clear overprinting relationships between veins at high-angle-to-bedding is consistent with the interpretations of Holland et al. (2009b); we interpret the anticlockwise rotation of strike orientation to include the fault-related veins.

The normal faults post-date the bedding-parallel shear veins in the study area, but data are not sufficient to allow differentiation of the two generations (top-to-the-SW followed by top-to-the-NNE) recognized by previous authors. This clearly places the age of these faults after the overthrust of the Semail and Hawasina Nappes. Based on the orientation statistics and throw data we interpret these faults to have formed as a conjugate normal- to oblique fault set, which was rotated together with bedding during the folding of the Al Jabal al-Akhdar anticline. This, together with the similar orientations, is consistent with (but no proof for) the interpretation that these faults are of the same age as the regionally developed, normal to oblique-slip faults mapped in the subsurface of North Oman and the UAE, which evolved during the early deposition of the Fija Formation in the Campanian. The correlation of normal faults with the Oligocene age extension as proposed by Fournier et al. (2006) is discussed, placing the folding of the Al Jabal al-Akhdar anticline in the Early Miocene–Pliocene.

The faults in the study area formed at much greater depth and fluid pressures, so that direct use of these structures as analogues for fault and fracture systems in subsurface reservoirs in Oman should be done with care.

ACKNOWLEDGEMENTS

The authors want to thank the German University of Technology in Muscat, Sultanate of Oman, for logistic support. Enrique Gomez-Rivas, Paul Bons and Daniel Koehn are acknowledged for pointing out the importance of strike-slip structures. We thank Steven Cox and Paul Stenhouse for discussions, as well as Christian Meeßen for providing structural data of microveins in the study area. We furthermore thank Pascal Richard and an anonymous reviewer for their constructive comments that helped to improve the manuscript.

This study was carried out within the framework of DGMK (German Society for Petroleum and Coal Science and Technology) research project 718 “Mineral Vein Dynamics Modelling”, which is funded by the companies ExxonMobil Production Deutschland GmbH, GDF SUEZ E&P Deutschland GmbH, RWE Dea AG and Wintershall Holding GmbH, within the basic research program of the WEG Wirtschaftsverband Erdöl- und Erdgasgewinnung e.V. We thank the companies for their financial support and their permission to publish these results. The authors thank GeoArabia’s Assistant Editor, Kathy Breining, for proofreading the manuscript, and Designer Arnold Egdane for preparing the graphics for press.
REFERENCES


Fault and vein networks, Oman Mountains


Simon Virgo studied Geology at the RWTH Aachen University where he received his Diploma with honours in 2010. He is currently undertaking a PhD within the framework of the interdisciplinary FRACS research consortium (DGMK funded project 718 “Mineral Vein Dynamics Modeling”) at the department of Structural Geology, Tectonics and Geomechanics at RWTH Aachen University. Simon is investigating the properties of evolving vein networks and the mechanical influence of veins on subsequent fracture nucleation and propagation. His research involves numerical modeling (Discrete Element Method) and microstructural and image analysis, as well as fieldwork in the Oman Mountains. He is furthermore involved in the development of new techniques in the field of digital microscopy in cooperation with the Fraunhofer Institute for Applied Information Technology (FIT).

s.virgo@ged.rwth-aachen.de

Max Arndt is a Research Associate at RWTH Aachen University (Germany) since 2010. He holds a German Diplom (summa cum laude) in Geology from RWTH Aachen University (2010) focusing on structural geology and applied geophysics. Max is currently pursuing a PhD degree within the interdisciplinary FRACS research consortium (DGMK funded project 718 “Mineral Vein Dynamics Modeling”). His current research involves geochemical and structural study of fluid flow regimes in vein and fault networks (from stable isotopes) as well as microstructures of veins in the autochthon of the Oman Mountains.

m.arndt@ged.rwth-aachen.de

Zoé Sobisch is currently working with Statoil ASA. She received a German Diploma in Geology from the RWTH Aachen University in 2010 focusing on petroleum system modelling and structural geology. Zoé joined Statoil ASA in 2010 as an Exploration Geologist in the Norwegian Sea and North Sea and is currently working in Exploration Excellence: Petroleum System Analysis providing special geoscience services within exploration.

zsob@statoil.com

Janos L. Urai is Dean of the Faculty of Science and Head of the Department of Applied Geoscience at the German University of Technology GUtech in Muscat, Oman, and Professor of Structural Geology, Tectonics and Geomechanics at RWTH Aachen University in Germany. He was C&C Huygens Fellow of the Netherlands Organisation for Scientific Research and Senior Research Geologist at Shell Research. Janos’ current projects aim at understanding salt deformation and salt tectonics, evolution and resealing of fault and fracture systems in carbonates, the morphology of pore networks in unconventional reservoirs, and the development of state-of-the-art geoscience teaching in the Middle East.

j.urai@ged.rwth-aachen.de

Manuscript submitted August 6, 2012;
Revised November 7, 2012;
Accepted November 13, 2012