Ben Laurich  
**Multiscale analysis of the structural evolution of the southern flank of the Western Jabal Akhdar anticline, Oman**  
(vein examination, structural mapping and inverse remote sensing)

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Ehrenwörtliche Erklärung

Hiermit versichere ich die vorliegende Masterarbeit selbständig und nur unter Verwendung der angegebenen Quellen und Hilfsmittel verfasst zu haben.

Datum, Unterschrift
Abstract

Structural geology models greatly benefit from multi-scale investigations. To understand the complex structural geology of the southern flank of the western Jabal Akhdar anticline (Oman Mountains), this thesis presents a multi-scale analysis on structural elements like faults, fractures and veins of two study areas. Therefore observations from vein analysis, mapping and remote sensing are combined. The outcome is compared to recent models of the regional structural history. The study areas underwent a multiphase evolution. The earliest phase identified is represented by bedding parallel veins, which are interpreted to developed at supra-hydrostatic fluid pressures and a maximum principal stress axis oblique to the bedding. This phase was likely related to the regional obduction of ophiolites. Vertical N-S oriented veins represent the next evolutionary phase with a horizontal minimum principal stress axis in E-W orientation. Subsequent, vertical veins of different strike directions characterise the next phase, where the minimum principal stress axis rotated into horizontal. In the aftermath, normal faults document a phase of N-S oriented extension. This was followed by a doming phase of the Jabal Akhdar anticline, which led to a shallow detachment fault. Several E-W striking conjugated en-echelon vein arrays and E-W oriented strike-slip fault movement represent the next phase. Hairline fractures and hairline veins form the latest evolutionary stage. Recent erosion processes led to the final wadi-dominated morphology of the study areas. In the context of this thesis, detailed geological maps are generated for both study areas.

Title page: Cave in the southern wall of Wadi Dam, eastern Pool area.
Acknowledgements

Investigating the Oman Mountains was an exciting experience. Here I thank all the people who helped me with the completion of this thesis.

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Aachen, 20.12.2010
Ben Laurich

\(^1\) FRACS – Mineral Vein Dynamics Modeling; www.fracs.de.
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1 Introduction

Folded pre-Permian basement in the bowl of the Jabal Akhdar anticline.

The Jabal Akhdar region in particular has experienced a dramatic tectonic history<

van Buchem et al., 2002 (van Buchem et al., 2002)
Cretaceous carbonate rocks of the southern flank of the Jabal Akhdar anticline in the Oman Mountains underwent several tectonic phases with different stress regimes. Thus, several generations of fractures, folds and faults were formed of which some were filled with calcite to become veins. By analysing these structures one can reconstruct the tectonic history that led to today’s geological setting. This thesis aims to evaluate the tectonic history by analysing the relation between vein sets, structural elements which are observed in the field and structural elements that can be derived via satellite images. Two study areas on the southern flank of the western Jabal Akhdar anticline, here called the Gorge area and the Pool area, were investigated. Both areas contain polished limestone outcrops (pavements), which were subjects to three bachelor theses. The geological outcome of the theses is summarized and compared within this study. The following provides an introduction on the location and a literature review on recent theories concerning stratigraphy and structural evolution of the Jabal Akhdar anticline. Chapter 2 explains the methods used within this thesis. The outcome of conducted fieldwork is summarized in chapter 3. This thesis puts an emphasis on the investigation of veins and their evolutionary history, which is described in chapter 4. For the first time en-echelon veins are used to quantify paleo-stress regimes of the southern Jabal Akhdar flank. Larger geological structures are examined using inverse remote sensing, where satellite imagery is tested for the capability to visualise geological features found by fieldwork (chapter 5). All results and interpretations of these chapters are compared and discussed in chapter 6. A conclusion and an outlook on potential further work are given in chapter 7.

1.1 Location of the study areas

The investigated areas were selected based on previous work by Arndt & Virgo (2010), Holland et al. (2009) and Hilgers et al. (2006). Within the two study areas polished limestone outcrops (pavements) provide an excellent opportunity to analyse veins. Thus, the extent of the study areas was defined by the location of the pavements and by the lateral continuity of relevant structural elements within or close to these pavements. Satellite pictures in Figure 1.1 and Figure 1.2 provide a general overview on the Jabal Akhdar anticline. Both study areas are highlighted.
Introduction

Figure 1.1: Satellite picture of the Jabal Akhdar anticline. White box refers to Figure 1.2 (Geoeye imagery 2010, UTM 40Q).

Figure 1.2: Detail of the satellite picture in Figure 1.1. White boxes mark the study areas. Please find high resolution satellite imagery of the areas attached to the back cover of this thesis (Plate 1 and Plate 2) (Geoeye imagery 2010, UTM 40Q).
1.2 General geology (literature review)

To provide a review on the greater geological setting, this chapter summarizes the main elements of the structural evolution of the Oman Mountains. It compiles the outcome of numerous studies.

The Oman Mountains are situated in the southeast of the Arabian Peninsula, between the convergent Arabian and Eurasian plates. They spread from Musandam in the north to the Batain coast in the southeast of Oman (Figure 1.3). The Jabal Akhdar anticline forms the central part of the Oman Mountains, containing its highest peak ‘Jabal Shams’ (3009 m a.s.l.). In general, the Oman Mountains define a collision boundary of dominantly Late Cretaceous age, affected by further compression and uplift during the Tertiary (Ries et al., 1990).

1.2.1 Tectonic evolution

The orogenesis of the Oman Mountains underwent several evolutionary stages. A brief summary of the major events that affected the Oman Mountains is given in Table 1.1.

A rifting during the Permian initialised the breakup of the supercontinent Gondwana northeast of the recent Oman coastline. This rifting formed a tectonic block structure, which was associated to volcanism in the late Permian (Lapierre et al., 2007; Searle et al., 1980). A new passive continental margin was created fronting the newly opened Neo-Tethys Ocean.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Subsequent effect on the Oman Mountains evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Permian</td>
<td>Neo-Tethys Ocean opens and the NE passive margin begins to subside</td>
<td>Transgression and beginning of carbonate sedimentation over the platform</td>
</tr>
<tr>
<td>Cenomanian</td>
<td>Atlantic Ocean opens leading to convergence of the Arabian and Eurasian plates</td>
<td>Intra-oceanic subduction of the Arabian plate started</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>Turonian – Campanian</td>
<td>Subduction of the Arabian continental edge</td>
</tr>
<tr>
<td>Campanian</td>
<td>Collision boundary of Arabia and Eurasia jumps to the Makran subduction zone</td>
<td>Uplift and erosion through stress release of the Oman subduction zone</td>
</tr>
<tr>
<td>Oligocene -Miocene</td>
<td>Closing of the Neo-Tethys Ocean and forming of the Zagros collision zone</td>
<td>Uplift and Erosion. Shaping of the final Jabal Akhdar anticline structure</td>
</tr>
<tr>
<td>Recent</td>
<td>Ongoing convergence of Arabia and Eurasia</td>
<td>Active subduction in the Makran subduction zone, ongoing uplift of the anticline</td>
</tr>
</tbody>
</table>
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\(^2\) Plate motion calculator: http://ofgs.ori.u-tokyo.ac.jp/~okinok/platecalc_new.html
A carbonate platform throughout the entire Oman developed. Alkaline volcanic activity from the middle Triassic to early Jurassic, originating from a rather deep asthenospheric source, implies the definite breakup of Gondwana (Searle et al., 1980). Until the late Cretaceous, thermal subsidence of the continental edge caused further development of a thick proximal carbonate platform and the evolution of a deep sea basin distal to the paleo coastline. This was amplified by the incipient late Cretaceous sea level rise (van Buchem et al., 2002; Robertson, 1988).

Figure 1.4: (a) Opening of the Neo-Tethys and passive margin post-rift thermal subsidence (Middle Permian to Early Jurassic). (b) Mesozoic pre-emplacement geological profile (modified after: Sharland et al., 2001; Bechennec et al., 1990; Blechschmidt et al., 2004 and references therein).
Figure 1.4 shows the End-Mesozoic paleogeography of the Neo-Tethys Ocean. The tectonic setting changed in the end of the Lower Cretaceous (Apt-Alp), when the southern Atlantic Ocean opened, shifting the relative movement of the African plate to Eurasia (Haq, 2005). This movement led to a convergence of the Arabian and Eurasian continental plates and formed an intra-oceanic subduction zone between the oceanic rift and the Arabian passive continental margin (Figure 1.4a). Therein, the Mesozoic oceanic crust and the sediments of the Neo-Tethys Ocean were subducted towards northeast (Breton et al., 2004). This setting led to the attempt to subduct the southern continental edge of the Neo-Tethys Ocean. In addition, the less dense, relatively young oceanic crust (less than 10 Ma), was buoyant upon the asthenosphere (Cloos, 1993). Therefore, the Neo-Tethyan ophiolite sequence was obducted along the northeastern margin of the Arabian plate (Breton et al., 2004). The convergence also exerted compressive stresses over the plate and caused uplift and erosion, resulting in a first stage of metamorphic rock exhumation (Haq, 2005; Breton et al., 2004). The details of this process are controversially discussed and several models provide different explanations for timing and mechanism of the obduction (e.g. Le Metour et al., 1990; Michard et al., 1994; Chemenda et al., 1996; Gregory et al., 1998; Breton et al., 2004). However, the Mesozoic oceanic lithosphere was displaced over hundreds of kilometres, deforming the underlying autochthonous strata of the Arabian plate. Thereby, allochthonous units were stacked upon each other. Usually, emplaced oceanic crust (Semial Ophiolite) is placed on top of volcanic rocks, which are often associated with mountain sized reef limestone blocks, namely the Oman exotics (Haybi Group). These groups are emplaced over distal deep sea sediments (Hawasina Group), which cover proximal sediments of the former continental edge and the former coastal plain (Sumeini Group) (e.g. Bechennec et al., 1990; Searle, 2007). Figure 1.4b shows a simplified sketch of the displacement. The autochthonous units were deeply buried underneath the allochthonous nappes to a depth of approximately 8000 m (e.g. van Buchem et al., 2002). Thereby foliation and cleavages evolved throughout the entire autochthonous series and are therefore post-Coniacian in age (Breton et al., 2004). As a result of the north-eastward subduction, the intensity of metamorphism and deformation decreases from northeast to southwest. In the Early Campanian buoyant continental crust hindered further subduction and the process switched to the Makran subduction zone (see Figure 1.3) due to the ongoing convergence of Arabia and Eurasia (Glennie et al., 1990). Therefore, the old subduction zone got stress released, which led to uplift of the continental edge and the overlying allochthonous units until Early Maastrichtian (Breton et al., 2004; Glennie et al., 1990). From the beginning of Maastrichtian, uppermost units got therefore partly eroded and
unconformably covered by transgressive, shallow marine carbonates, the so-called Neo-Autochthonous units. While probably associated to tectonic events on the plate boundaries, further uplift and erosion during the late **Oligocene - Miocene** brought more autochthonous Mesozoic rocks to the surface and formed the present-day topography of the Oman Mountains (van Buchem et al., 2002; Al-Lazki et al., 2002; Breton et al., 2004; Searle, 2007). By seismic analysis and gravity modelling, Al-Lazki et al. (2002) stated that the continental crust beneath the Jabal Akhdar anticline is about 50 km thick, including 9 km thick pre-Permian basement. This corresponds with structural models that suggest thickening of the crust, either by blind thrust faulting within the basement (Mount et al., 1998) or by a ramp at depth, where the overlying units bulge, forming the Jabal Akhdar anticline (e.g. Searle, 1985; Bernoulli and Weissart, 1987; Hanna, 1990). Recent earthquake activity within the Makran subduction zone indicates that the ongoing convergence of the Arabian and Eurasian plates has not come to an end yet (Kopp et al., 2000). Active faults within the Oman Mountains show that the orogenesis is still ongoing (Kusky et al., 2005).

Therefore we can conclude: the Arabian plate suffered several long-term periods of multiphase tectonic deformation. This is exemplarily reflected in the Oman Mountains, which consequently provide a good field laboratory, containing tectonic windows to several geological formations from recent down to the Proterozoic. Figure 1.5 shows a simplified geological cross section of the Jabal Akhdar anticline. The location of the study areas is highlighted.

*Figure 1.5: NE-SW cross section of the Jabal Akhdar anticline, vertically exaggerated; from Searle (2007).*
1.2.2 Stratigraphy of the examined areas

Figure 1.6 provides an overview of major lithostratigraphic formations of Oman as briefly discussed in the section above. This study focuses mainly on the uppermost Autochthon B units (Natih formation and Muti formation), which are therefore described in the following.

**Natih formation**

The Natih formation represents the youngest sequence of prograding carbonate deposition within the Neo-Tethys Ocean and belongs to the Wasia group (van Buchem et al., 2002). It is very well studied as it holds several world-class hydrocarbon reservoirs and source rocks (e.g. Terken et al., 2001; Pratt and John D. Smewing, 1993; van Buchem et al., 2002). The formation is about 400 m thick and is divided into seven lithostratigraphic members, named from A to G, top to base, respectively (J. Philip et al., 1995). The age of the Natih formation is Cenomanian, based on biostratigraphic studies of foraminifera, echinoids, ammonites and rudists (Smith et al., 1990). Natih rocks consists mainly of wackestone, bioclastic packstone and grainstones. Additionally, van Buchem et al. (2002) described cherty limestones revealing either semicontinuous blankets or isolated nodules (Figure 1.7a), which can also be found in the here examined areas (Figure 1.7b-d). The Natih members A, B and E form steep cliffs, whereas the other members are less resistant (Holland et al., 2009).
Van Buchem et al. (2002) distinguished between two different depositional systems alternating in time: (1) a flat-bedded, mixed carbonate-clay ramp, and (2) a carbonate-dominated ramp bordering a foreland intrashelf basin, where organic matter accumulated and in which later on hydrocarbon development took place. The first depositional system spans the Natih F-G and Natih C-D members. For the later system (Natih members A, B and E), four main depositional environments can be differentiated by facies analysis: intrashelf basin, outer ramp, mid ramp, and inner ramp (van Buchem et al., 2002). In total, van Buchem et al. (2002) identified four third-order sequences (0.5-3 Ma), where location and style of the depositional systems changed. This was due to different depositional factors. Eustacy was the dominant controlling factor in the earliest sequence, clay flux in the second and eustacy and local tectonic uplift, caused by the late Cretaceous flexure of the Arabian plate, were the dominant influences for the depositional systems in the latest two third-order sequences.
Muti formation

The Muti formation is the youngest Autochthon B formation (Figure 1.6) and crops out all around the Jabal Akhdar anticline. It formed in a foredeep basin (Muti basin) at the toe of a peripheral bulge of elder autochthonous units (Robertson, 1987b) and can thus be considered as a typical wildflysch (Breton et al., 2004). The peripheral bulge, formed by the load of the overthrusting allochthonous nappes, migrated over 300 km cratonward synchronous to the obduction. Thus, the Muti formation is of Turonian to Maastrichtian age, depending on the outcrop location (Robertson, 1987b). The Muti formation documents the evolution of the intracontinental subduction and the transition from a passive continental margin to a foreland basin (Robertson, 1987b). In contrast to the Natih formation, sequences of the Muti formation vary strongly by location. Several syntectonic facies are similar in age and lithology, but a continuous sedimentation pattern cannot be observed (Robertson, 1987a). Therefore, Robertson (1987a) distinguished five different members of the Muti formation: the (1) Buday’ah, (2) Riyamah and (3) Qumayrah members, which are oceanward incorporated into the allochthonous nappes, and the (4) Sayja and (5) Hanya members, which unconformably overlie Mesozoic platform carbonate units. The here studied Muti units belong to the Sayja member as they cover the platform carbonates and, being located in a more central part of the Oman Mountains, do not belong to the farther continentward (south-westward) Hanya member. According to Robertson (1987b), the up to 700 m thick Sayja member consists of pelagic sediments (mostly shale) and conglomerates with a calcareous matrix containing limestone clasts, derived from the uppermost levels down to the Permian of the carbonate platform. Non-calcareous shales of the Muti formation might originate from the Arabian continent being accumulated in the Muti basin below the calcite compensation depth (CCD) (Robertson, 1987b). Angular shaped lithoclasts of the conglomerates derived from a more proximal origin. Robertson (1987b) suggests, that they have accumulated submarine as debris-flows (megarudites in some cases), slipping from the advancing peripheral bulge into the Muti basin. Robertson (1987b) stated as well, that the Muti formation, similar to the other autochthonous units, was overridden by the allochthonous nappes and experienced a slight deformation and pressure solution, creating a cleavage in several units. The Muti formation does not contain clasts or other sediment from the allochthonous units, thus suggesting that the advancing allochthonous thrust load remained submerged till the end of the Muti sedimentation (Robertson, 1987b). In contrast, younger facies deposited in the foredeep basin (Juweiza and Simsima formations) often contain ophiolithic detritus (Robertson, 1987a).
1.2.3 Veins

In addition to geological mapping (e.g. M Beurrier et al., 1982), paleontological analysis (e.g. J. Philip et al., 1995), sequence stratigraphy (e.g. van Buchem et al., 2002), mineralogy (e.g. Gray et al., 2004) and palinspastic reconstructions (e.g. Glennie and Boeuf, 1973), one can examine veins to learn about the Oman Mountain orogenesis. Holland et al. (2009) and Hilgers et al. (2006) analysed the ubiquitous veins in many locations within the Jabal Akhdar anticline. They catalogued them into vein sets by a statistical approach considering their orientation, relative age relationship and stable isotopes ($\delta^{18}$O and $\delta^{13}$C analysis, Hilgers et al. (2006)).

![Figure 1.8: The evolution of the fracture network is interpreted to be a result of a 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 perpendicular 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). From Holland et al. (2009).](image)
Figure 1.8 shows a sketch of the evolution of the fracture network derived by Holland et al. (2009). In total, Hilgers et al. (2006) identified seven different vein sets and related them to tectonic events in the Oman Mountains (Table 1.2).

Veins develop by precipitation of minerals from aqueous solutions. They grow into open voids or form by crack-seal mechanisms, creating so-called crack-seal veins. These form under brittle rheological conditions, with material possibly derived by pressure solution in the rock matrix (Ramsay, 1980). As veins heal open fractures, they restore the tensile strength of a rock, which enables the rock to break again in various orientations. By analysing veins, one can determine the pressure and stress conditions necessary for their development. This information can be used to verify or enhance tectonic models. For the Oman Mountains, Hilgers et al. (2006) found that the oldest set of veins (Table 1.2, vein set 1) developed under hydrostatic conditions, whereas vein set 2 formed under supra-hydrostatic pressures at greater burial depth. This might be due to the increasing overburden load of the prograding carbonate platform and due to the advancing allochthonous nappes during Turonian to Santonian times. Vein sets 3 and 4 of Hilgers et al. are related to top-to-NNE bedding parallel shear, with the main principal stress ($\sigma_1$) oblige to bedding (Hilgers et al., 2006). The mechanism and timing of the top-to-NNE shearing is a matter of debate to be associated either to subduction or to exhumation (Le Metour et al., 1990; Breton et al., 2004; Al-Wardi and Butler, 2007). Associated to normal faults, vein sets 5 and 6 formed in an extensional regime presumably during the Eocene. Vein set 7 developed in a compressive regime ($\sigma_1$ parallel to bedding) during updoming of the Jabal Akhdar. All veins usually consist of calcite and quartz precipitated from fluids of the surrounding carbonate host rock. Stable isotope analysis revealed that for younger veins (vein sets 5, 6, 7) an influx of external fluids through the fracture network is likely (Hilgers et al., 2006). This corresponds to the model of uplift and exhumation during the latest evolutionary stages, where the layers were brought closer to shallow groundwater aquifers and where faults increased the bulk permeability of the carbonates (Hilgers et al., 2006).

In several outcrops, tangled, dense vein networks are preserved. Often these show less obvious regularities in spacing and many vein generations offset and cross-cut each other (e.g. Gorge area outcrops, Figure 4.9). However, some outcrops reveal a very regular pattern of veins, such as the here studied Pool pavement (Figure 4.6). Veins of the study areas are described and interpreted in chapters 4.1 and 4.2, respectively.
Table 1.2: Vein sets identified by Hilgers et al. (2006) and their relation to the events on the Oman Mountain evolution. Please note that the here suggested times are not absolute values, as the age is determined by relative age relationships (after Hilgers et al., 2006 and references cited in this thesis).

<table>
<thead>
<tr>
<th>Vein set</th>
<th>Description</th>
<th>Tectonic event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stylolite vein, $\sigma_1$ normal to bedding</td>
<td>Transgression and carbonate sedimentation over the subsiding Mesozoic platform, obduction of ophiolites</td>
<td>Late Permian to Mid Cretaceous, eventually ophiolite opduction during Turonian to Santonian</td>
</tr>
<tr>
<td>2</td>
<td>Extension vein, boudinage vein, $\sigma_1$ normal to bedding</td>
<td>Top-to-NNE shearing, either as a result of buoyant basement in a compressive regime (Breton et al., 2004) or created by ongoing obduction (Le Metour et al., 1990)</td>
<td>Campanian – Paleocene</td>
</tr>
<tr>
<td>3</td>
<td>Pinch &amp; swell vein, $\sigma_1$ oblique to bedding</td>
<td>Development of normal faults, extensional regime</td>
<td>Eocene</td>
</tr>
<tr>
<td>4</td>
<td>Bedding-parallel vein, $\sigma_1$ oblique to bedding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>En-echelon extension vein arrays, $\sigma_1$ normal to bedding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Veins in dilation sites of normal faults, $\sigma_1$ normal to bedding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Veins associated to thrusts, $\sigma_1$ oblique to bedding</td>
<td>Updomeing, compressive regime</td>
<td>Miocene to Pliocene</td>
</tr>
</tbody>
</table>
Methods

2 Methods

In structural geology, numerous methods seek to uncover information about the deformation of rocks, and finally to comprehend the related stress fields. The following chapter provides a review on the methods used for the conducted studies of this thesis, which yield information on the structural evolution of the study areas. The procedures and difficulties of three different sections are described separately: (1) fieldwork methods, (2) methods of pavement analysis and (3) methods of inverse remote sensing. Throughout the thesis, all measurement values of dip and dip direction are given in Clars notation (azimuth / dip) unless noted otherwise.

2.1 Fieldwork methods

The excellent outcrop conditions in Oman (sparse vegetation and little to none pedogenesis) allow a detailed analysis of the pavements’ surrounding geology. The fieldwork on the study areas took 16 days from March, 11th to March, 27th 2010.

2.1.1 Orientation in the field

A global positioning system (GPS) device (GARMIN rino 530HCX) and satellite image printouts (Geoeye 2009) ensured precise orientation and positioning in the field (up to 1 m accuracy). However, the GPS satellite reception in deep and narrow wadis usually is weak and shadows of wadi walls cause ‘black spots’ on satellite images. Unfortunately, there is no topographic map available with a resolution higher than 1 : 100 000.

2.1.2 Mapping of geological units

According to the geological map of Beurrier et al. (1982), the rocks within the Pool area entirely belong to the Natih formation. Several fossils have been photographed and analysed in order to verify the stratigraphic classification. Due to the similarity of the strata, and the homogeneous, undisturbed profile outcropping in the wadi, no distinction of different mapping formations was carried out for this area.

The Gorge area reveals a more complex setting. Here, four geological units have been mapped by lithological classification (see chapter 3.2). Their boundaries were drawn onto a satellite image printout and were further used to compose the geological map. Therefore, the computer program ArcGIS 9.3 by ESRI was used.
2.1.3 Mapping of structural elements

Structural elements like faults, fractures, joints, veins and bedding have been measured using a geological compass. In order to assure accurate values for dip, azimuth and strike direction several measurements (at least four) were taken at each location. For some faults, even if their structure is clearly visible, no fault planes are exposed. This is mostly due to weathered surfaces, precipitated sinter or a probably small vertical offset of the faults. In cases, where a direct measurement was not possible, the orientation has been derived via bearing or by picture interpretation. In this case, a fault has been photographed horizontally and in strike direction in order to analyse its dip using the program Coreldraw X4. Furthermore, faults cropping out exclusively within the conglomeratic Muti unit reveal no determinable offset as the formation is strictly homogeneous. The observed and inferred or concealed lateral extend of faults was drawn on the satellite image printouts, too. Each major fault within the study areas was discussed separately. For the geological profile each fault has been corrected by its apparent dip using the formula:

\[ \tan \beta = \tan \alpha - \sin \theta, \]  

where $\beta$ is the apparent dip, $\alpha$ is the true dip and $\theta$ is the strike direction of the profile. There is only a very slight deviation between apparent and true dip, as the faults strike mostly E-W and the profile is oriented in N-S direction.

The lateral orientation of faults was analysed by a statistical approach. Using ArcGIS 9.3, the determined fault lines were split up into 10 m sections. The strike direction of each single section was computed and used to calculate the mean strike direction and the standard deviation of the entire fault orientation. By this, the standard deviation of the section’s strike direction provides a value for the undulation of a fault. Fault sections which – due to topology effects – differ from the average fault orientation were disregarded.

The shear sense of a fault was determined by the offset of strata and by striations on fault planes. However, several faults do not show any striations. Therefore, the shear sense was derived via indirect methods. In some cases strata are dragged into faults and form small drag folds. In this case, the fold axis was determined by a stereographic analysis. The bent strata were measured at different places on the folds’ surface and plotted as great circles into a stereonet to determine the fold axis. The dip of the fold axis provides general information on the ratio between strike-slip and normal fault movement (i.e. a vertical dipping fold axis implies a pure strike-slip fault, whereas a horizontal dipping fold axis implies a pure normal fault movement). However, we cannot uniquely determine the faults’ movement vector, as the
fold axis also depends on the orientation of the bent strata. To illustrate this problem, Figure 2.1 shows different axes of drag folds with the same movement vector but a different dip of the folded marker horizon. Still, by knowing the dip of unfolded strata, we can use the fold axis as a general indicator for the faults’ shear sense. Moreover, drag folds are usually non-coaxial. Thus, they yield no exact information on the principal stress components.

![Figure 2.1: The axes of drag folds (f) are controlled by the intersection relationships between the folded strata and the fault plane. Thus, the movement vector n cannot be uniquely determined from the axial directions. Modified after Ramsay (1987).](image)

A second method to derive information on shear sense orientation is the examination of conjugate en-echelon vein arrays which are associated to a fault. This is explained in the following chapter ‘methods of vein and pavement analyses’.

### 2.1.4 Geospatial information system (GIS)

The maps of the study areas were created using the program ArcGIS 9.3 (ESRI). Here, the information of a digital elevation model (DEM), the observations of the fieldwork and the structures visible on satellite imagery were combined in order to produce an overview of the geological setting. Structural elements, points of vein examination, relevant outcrops and each mapped unit were digitalized in a separate layer file. These layer files were exported as a kmz file, which can be opened using Google Earth\(^3\). Using the ArcGIS 9.3 implemented layout tool, both geological maps of the study areas as well as several overview images were generated and designed. In order to be consistent with previous work (Holland et al., 2009; Arndt, Virgo & Sobisch, 2010), all data were always treated and displayed in the Universal Transverse Mercator (UTM) coordinate system, zone 40 Q. The geological structures were drawn onto the satellite images, which were processed and digitally enhanced first. This is described in the following section ‘methods in inverse remote sensing’.

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\(^3\) Available at http://www-users.rwth-aachen.de/Ben.Laurich/ and on the attached CD.
2.1.5 Photosynth

A total of 613 pictures of the study areas were meshed together by using the online freeware Photosynth (Microsoft). The uploaded pictures are automatically analysed and combined, thus generating a 3D point cloud of the terrain on which each picture is automatically oriented. Therefore, this tool provides an interactive, dynamic way to explore the study areas. Photosynth was used in order to assist in interpretation and verification of the fieldwork observations. The 3D point cloud was extracted for creating a digital elevation model (DEM) but later was neglected due to compatibility issues and due to a large error in the spatial resolution. However, Photosynth is a useful tool which might get even more powerful by further development within the next years.\(^4\)

2.1.6 Sketches

Despite photographs and measurements, several drawings captured geological structures. These drawings were scanned, vectorized and further used in combination with other information such as photographs, measurements and satellite pictures to create illustrating sketches. Therefore, the program Coreldraw X4 was used. Figure 2.2 illustrates the workflow exemplarily for the geological profile of the Gorge area.

![Figure 2.2: Steps of the workflow from the first in field drawing (a), the vector image (b) to the final illustration (c).](image)

\(^4\) The Photosynth galleries can be found at: [http://photosynth.net/view.aspx?cid=38b9cda0-3ce9-47a5-89a3-bfa8493573e (Gorge area)](http://photosynth.net/view.aspx?cid=38b9cda0-3ce9-47a5-89a3-bfa8493573e) and [http://photosynth.net/edit.aspx?cid=21B2EE2C-3196-424A-BD2B-495B245A04DC&firstview=1 (Pool area)].
2.1.7 Sampling

In total six samples of different mapping units have been taken for lithological description and paleontological examination.

2.1.8 Field equipment

The following equipment was used:

- Geological compass (*Breithaupt COCLA / Krantz I55*),
- Satellite image printouts (*Geoeye 2009*),
- GPS device (*GARMIN rino 530HCX*),
- Digital camera (*Canon EOS 300D, 28-300mm lens*),
- Field notebook,
- Magnifier glass,
- Hammer,
- Sections of a geological map (*Sheet Rustaq NF40-3D, Scale 1 : 100 000, Beurrier et al., published by the Ministry of Petroleum and Minerals Oman, 1986*).

![Figure 2.3: Equipped author.](image)

Figure 2.3 shows the equipped author. Please note the original omani-style Masar as headdress and the water bottle in the side pocket of the backpack – two essential needs to overcome Oman’s hot and dry climate.
2.2 Methods of vein and pavement analysis

An emphasis of this thesis is the investigation of veins as they preserve information of paleo-stress regimes. Structural elements within or close to three pavements, which were separately investigated by Raith (2010), Thronberens (2010) and Wüstefeld (2010), were described in detail. Therefore, several sketches, photographs and measurements were taken. The surrounding geology for each of the three pavements is described individually in chapter 4.

2.2.1 Vein age relationships

In addition to the pavement analyses, veins were examined in several other locations within both study areas (see Plate 1 and Plate 2). Herein, vein intersections have been examined carefully. As a penetrated vein has to be older than the penetrating one, we can reconstruct the relative age relationship of vein sets. Vein orientations, age relationships, and the location of the measurements were noted in the field book. Additionally, photographs were taken to assist in the analysis process. The gathered data were incorporated into a database and interpreted regarding their location and overprinting relation. This way, different vein sets were distinguished. In context of this thesis, a vein set is defined as a group of veins with the same age relationship to other veins. Each vein set was named according to its main strike orientation and habit, e.g. ‘E-W oriented en-echelon veins’. Thereby veins of a set must not pre-date each other. Where dip direction and dip measurements were impossible, the strike direction of a vein was recorded. The gathered information were compared to the outcome of the work of the three separately investigated pavements.

2.2.2 Determination of paleo stress regimes

Each recognized vein set developed under a certain stress regime. We can use the veins’ orientation of each set as a general evidence for the stress directions prevalent during its formation. A sequence of the determined paleo-stress regimes was created by the identified relative age relationships of the vein sets. Thereafter, the sequence was compared to the evolutionary phases of the geological evolution of the Jabal Akhdar anticline. A specific method to derive information on principal stress orientation is the examination of conjugated en-echelon vein arrays. En-echelon vein arrays form in brittle-ductile shear zones, where the vein-hosting rock is deformed in such a way that en-echelon fractures open, which get filled by the vein material (Ramsay, 1987). The strain on the rock shapes the en-echelon veins in a sigmoidal manner. Due to the homogeneity of the examined rocks we can assume that the en-echelon vein arrays are symmetrically related to the principal stress axes at the time of shear
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movement initiation. Thus, the dip direction and dip of conjugated vein arrays provide information on paleo shear sense orientations and give evidence of the former principal stress regime.

Figure 2.4: Sketch of an en-echelon vein array in (a) and corresponding bulk strain ellipse and principal stress axes in (b). The intersection of the shear zones S illustrates the intermediate stress axis. Sketch (a) is modified after Ramsay (1987).

A conjugated en-echelon vein array consists of sinistral and dextral en-echelon shear zones crossing each other. Figure 2.4 provides a schematic diagram of an en-echelon vein array and of the stress and shear orientations associated with it. In the field, the orientation of vein arrays was measured with a geological compass and thereafter plotted into a stereonet. This is shown exemplarily in Figure 2.5. Both shear zones of an array are plotted as great circles, which intersection point represents the intermediate stress axis ($\sigma_2$).

Figure 2.5: Stereonet projection of an en-echelon vein array. Black indicates the maximal stress orientation (compression) and white indicates the minimum stress orientation (extension). Example from spot G9 of the Gorge area.
Both great circles are the envelope to the zone of possible orientations for the maximal stress axis ($\sigma_1$, compression, black) and for the minimal stress axis ($\sigma_3$, extension, white). These beach-ball like projections were drawn onto the satellite images (Plate 1 and Plate 2) to give a comprehensive view on the geometric orientation of en-echelon vein arrays. Considering that the stress regime did not change during the vein array development, both, sinistral and dextral veins should be equally evolved. Thus, the $\sigma_1$ axis has to be exact the dihedral angle between the great circles, which is normal to the intermediate stress axis. Where the shear zones developed unequally, the method can at least be used to construct information on the initial stress regime of the en-echelon vein array. This graphical method is described in detail in Ramsay (1987). Drawn on a map, the generated stereonets provide an overview of paleostress regime distributions.

2.2.3 Sketches and models

For each examined pavement the surrounding structural elements were recorded. Bedding, veins, fractures and faults were examined regarding their orientation and their change in orientation. Sketches and Photographs were made to capture the structural situation. They were further used to build a model of the mechanical principle that lead to the observed setting.

2.3 Methods in inverse remote sensing

Different to most remote sensing work, the here investigated areas were examined by field work first with remote sensing in retrospect to that. Thus we can name this procedure ‘inverse remote sensing’ by which structures found in the field were evaluated on satellite pictures. Moreover satellite image printouts were used to orientate in the field and supported the mapping process.

In order to produce an accurate geological map, several adjustments of the satellite images were made. These are described in the following.

2.3.1 Orthorectification

The in context of this thesis applied DEM derives from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a joint operation between NASA and Japan’s Ministry of Economy, Trade and Industry. The global DEM was published first in 2009 and can be downloaded free of charge\textsuperscript{5}. Its nominal resolution is not better than 30 m

\textsuperscript{5} Amongst others from: http://www.gdem.aster.ersdac.or.jp/search.jsp.
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(Nikolakopoulos et al., 2006). Thus, it is not sufficient to display the steep topography of the wadis within the study areas. In order to georeference, however, the ASTER DEM has been used to ortho-rectify the satellite imagery in ArcGIS 9.3. Orthorectification is the process of stretching a raster dataset to match the spatial accuracy of a map by considering location, elevation and sensor information, such as the nadir angle and satellite position (ESRI, 2008). Thereby, a planimetric image with consistent scale was created. Information on location and sensor adjustment was provided by the vendor Geoeye and attached to the satellite imagery data. The accuracy of the orthorectification was verified by importing recorded GPS routes and waypoints into ArcGIS 9.3. The routes overlay the orthorectified satellite images in the right places. Therefore, the error of the orthorectification lies within the accuracy of the GPS (depending on the signal reception around +/- 15 m).

2.3.2 Colour and contrast adjustments / pan-sharpening

The Geoeye satellite imagery is provided in four multispectral bands (red, green, blue and infrared, resolution 1.65 m) and one panchromatic band (resolution 0.5 m). The range of the multispectral bands is as follows: 450 nm to 510 nm (blue), 510 nm to 580 nm (green), 655 nm to 690 nm (red) and 780 nm to 920 nm (infrared). The colour image resolution was enhanced by pan-sharpening. Therefore, a multiband image was merged with a panchromatic image using the ArcGIS 9.3 ESRI pan-sharpening transformation with weight values of 0.166, 0.167, 0.167 and 0.5 for the red, green, blue and infrared band, respectively.

A series of multispectral images was created by different combinations of the colour bands and by using different weighting factors of the bands. In some cases a contrast enhancement was performed using the program CorelPHOTO. Thereby created full-colour and false-colour images were interpreted for geological structures. The interpretation was conducted systematically in three categories: (1) linear features, (2) planar features and (3) anthropogenic objects.
Results

Sinistral and dextral en-echelon veins overprinting each other
- Pool pavement -

>...every structure in a rock is significant, none is unimportant, even if, at first sight it may seem irrelevant<

Ernst Cloos, 1946
in Ramsay, 1987
Geology of the study areas

This chapter describes the geological settings of the two study areas. It compiles the results of the fieldwork that was carried out as explained in chapter 2. The first section refers to the Pool area, and summarises its main structural and tectonic features. The second section depicts the geological setting of the Gorge area. Furthermore, a detailed geological map and a geological profile illustrate main structural elements and different stratigraphic units. Figure 1.2 highlights the location of the study areas and provides a general overview on the southwestern part of the Jabal Akhdar anticline.

3.1 The Pool area

The fieldwork in the Pool area took 6 days. The attached geological map (Plate A) provides an overview of the structural elements of this 1.15 km² large area. The study area contains the Pool pavement, which is described in detail in chapter 4.1 ‘pavements and veins’. The semi-rectangular study area extends between 508469 m E, 2569635 m N and 506833 m E, 2568918 m N (UTM 40Q) at its most north-eastern and south-western corner, respectively. To the west, the area is bound by the cliffs of a deep wadi.

3.1.1 Local geological setting

The Pool area is dominated by a large wadi, named Wadi Dam. It incises slightly southward titled Natih layers forming up to 200 m steep cliffs. At its outlet from the Jabal Akhdar anticline to the plain in the south the village Barut sources water from the wadi in a concrete falaj system. The falaj starts at an artificial dam visible in the satellite image (Plate 1). At the bottom of the wadi water runs over well polished rock surfaces, which display an outstanding outcrop of numerous calcite veins. In the very east of the study area a karstic spring is located. During the time of investigation, which happened to be one week after a heavy rainfall, the wadi remained dry to the northeast of this spring. Thus, the spring can be considered to be the main source of water for the small creek in the wadi, except for times of periodic heavy runoffs and flash floods. Several parts of the wadi walls are coated with a thick layer of sinter (Figure 3.2), which occasionally seems to cover interesting geological features.

Figure 3.1 shows a general vertical sequence for the Pool area. The base of the Natih formation does not crop out within the study area. The 4 m thick interbedded layer of limestone-shale is less resistant to weathering than the surrounding rocks. It crops out near the bottom of the wadi and forms thereby an impressive, up to 200 m high overhang of the upper
Natif layers. Iron chert nodules within the uppermost strata have a strong weathering resistance and remain on top of the surface, pruned out of the weathered limestone. Two strata contain regular spaced, normal to bedding veins, which are exclusively restricted to a layer and do not occur in neighbouring units. Some parts north of the wadi consist of scree and huge blocks of the Natih formation, which are tilted towards the wadi. This area can be described as collapse structures and slope deposit material. It contains 20 m high tower-like blocks with steep and wide gaps between them, which make the area hard to explore (Figure 3.2).

Figure 3.1: Stratigraphic column of the mapped units within the Pool area. The unit width is in relation to weathering as a measure for relative rock strength. (*) timing of slope deposit according to geological map of Beurier et al. (1982). Column is not to scale, formation thickness is approximate.
Figure 3.2: Picture (a) shows a thick coating layer of sinter at the northern wall of Wadi Dam, field notebook for scale. (b) shows collapsed Natih layers with up to 20 m high blocks, which are southward tilted towards the wadi (centre). (c) is a picture detail of (b) displaying boulders fallen of the cliff (centre).
3.1.2 Lithology

Rocks of the entire study area belong exclusively to the Natih formation as the geological map of Beurrier et al. (1982) illustrates. A few spots where this rule is not applicable are denoted on the geological map of the Pool area. In general, Natih rocks of the Pool area correspond well to Natih rocks within the Gorge area. Figure 3.7 displays a variety of fossils found within the Natih unit. Chert nodules and semi continuous chert blankets can be found everywhere in the upper strata of the Natih unit. However, a distinct area exposes more chert than the surrounding. This area is pointed out on the geological map. As there is no sign for faulting or layer offset next to the chert enriched areas, we can assume a local irregularity in the deposition system. The slope deposit material consists of large angular blocks (up to 2 m in diameter), which originate from the near surroundings and which are strongly related to local collapse structures (Figure 3.2).

3.1.3 Tectonics

The Pool area contains two faults with a significant lateral extent. Smaller features are discussed in relation to the Pool pavement in chapter 4.1. A selection of pictures is meshed together creating a 3D scene. This provides an online, interactive, dynamic way to explore the Pool area. Faults of the Pool area are not numbered serially, but named by letters. This way they can easily be differentiated from numbered faults of the Gorge area.

Fault A

Fault A strikes 105.4° undulating with a standard deviation of 6.95°. In general, it has a sinistral shear sense and shows only a slight vertical offset of less than 1 m, with the northern block down. Here, the shear sense was determined by vein examinations on the Pool pavement, as explained in chapter 4.1. Fault A might be in relation to the partly E-W striking morphology of the wadi that restricts the study area in the west. In between the western limit of the mapped area and the western cliff of Wadi Dam, a small tributary wadi reveals a fault plane of fault A (Plate A). From there, a shear zone with blocky calcite extends into the direction of the wadi cliff and several veins accompany the fault. The veins run into the wadi and are in line of sight with a second fault plane that forms a channel at the bottom of the wadi. This view from the top of the cliff is shown in Figure 3.3. However, fault measurements at the top of the cliff lead to incorrect values, as most exposed planes reveal the orientation of joints and not of the general fault’s strike direction. The joints cross cut the accompanied

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6 Available at: http://photosynth.net/view.aspx?cid=21b2ee2c-3196-424a-bd2b-495b245a04dc
veins, thus being younger than the fault. Therefore, we can consider an increased weathering process in the surrounding of the fault.

Figure 3.3: View from the top of the western wadi wall down to the Pool pavement, which is limited to the south by Fault A (between the white arrows). The black arrow points to a person on the pavement. The arrow is five times as long as the person.

At the bottom of Wadi Dam, fault A forms the southern limit of the Pool pavement and runs through a set of regular oriented veins. Further to the east, fault A is covered by slope deposit material, which does not reveal the presence of a fault. However, a similar oriented fault plane is located in the elongation to the previous described fault (Plate A). The fault plane reveals horizontal striations with 115° in azimuth and <5° in inclination. As this corresponds to the general characteristic of fault A, we can assume a continuation of the fault underneath the slope deposit material. To the east, the fault forms a small linear channel that runs slightly diagonal through the base of the wadi.

Fault B

Fault B runs through the southern part of the study area and strikes to 087° undulating with a standard deviation of 18.7°. Three fault planes crop out along the fault (Plate A).
Measurements of these fault planes reveal an alternating dip direction around 175° and around 360°, as the fault dips around vertical with 85° on average. The most western outcrop of fault B is located in the entrance to Wadi Dam. Here, an up to 60 cm wide fault zone exposes, which is filled with blocky calcite (Figure 3.4). The vertical offset is circa 4 m, with the southern block down.

Next to the fault, four vein sets were found. The youngest set is interpreted to be associated to the fault as it has a parallel orientation. On top of the terrain south of Wadi Dam and in elongation to the above described outcrop of fault B, veins occur frequently with an orientation similar to the fault. They are visible in the satellite image as a semi continuous lineament. A second, smaller fault plane is located on top of the terrain just in line with the veins (Plate A). However, a vertical offset is not identifiable at this location. At the most eastern outcrop of fault B a huge third fault plane (20 m high, 10 m wide) with many striations attests a horizontal movement. The striations are obvious but weathered, so that a shear sense could not be identified. The third fault plane forms a part of the southern wadi wall. On the terrain on top of the wadi wall at this location, the lineament veins run out into the wadi.
A 15 m high, 2 m wide and 10 m deep cave in the southern wadi wall lies in the west of the major fault A and fault B (Plate A). Although the cave’s morphology might be associated to joints, most likely both faults run through this open void and merge in this location. Figure 3.5 shows the cave and illustrates a vertical offset of approximately 3 m (northern block down), which proves the presence of a fault. The fault cave dips 75° - 80° with a strike direction of 100°. However, a lateral continuation to the east is not visible, neither on the satellite imagery nor in the field.

![Figure 3.5: Cave in the southern wadi wall. Interbedded shaly limestone layer (2 m) for scale.](image)

In an undisturbed system, dissipated water would roughly follow the slope dip. However, for a long distance Wadi Dam is oriented W-E, normal to the dip of the slope. As an explanation for this drainage system we can assume W-E oriented structural elements, which became eroded and are thus not visible anymore. Both identified faults A and B influence parts of the wadi’s morphology and can be considered as an evidence for this hypothesis. Moreover, the karstic spring in very east of the Pool area inflows from an eastern direction even if the upper part of the wadi kinks to a N-S orientation.
3.2 The Gorge area

The following chapter provides a review of the fieldwork results for the Gorge area. The Upper and the Lower Gorge pavements (chapter 4.2) are situated within this one square kilometre sized area, which is located between two major doming structures of the Jabal Akhdar anticline, next to the small village Manda‘a. The rectangular study area is situated 513477 m E, 2574115 m N (UTM 40Q) at its most north-western corner and 513914 m E, 2573150 m N (UTM 40Q) at its most south-eastern corner.

3.2.1 Local geological setting

For the Gorge area, a detailed geological mapping on a scale of 1:4000 was carried out. The map is attached to this thesis (Plate B). Please note that the contour lines, derived from the ASTER DEM, have a spatial resolution of only 30 m and can therefore only provide a rough estimation of the altitude. They do not reveal the steep cliffs of the wadi and are displayed only for a general overview on the topology. Please keep this especially in mind for interpreting faults, which do not change significantly in orientation but in their outcrop distribution with respect to the surface’s topology.

Figure 3.6 shows a general vertical sequence of the mapped units. As described by Robertson (1987b), the sequence of the Muti varies depending on the outcrop location. The here shown Muti sequence is in rough correspondence to the closest known recorded stratigraphic columns near Al Hamra and Kahmah (Robertson, 1987b). The base of the Natih formation and the base of the Nahr Umr formation are not cropping out within the study area. Referring to literature, their thickness is up to 300 m and 200 m, respectively (van Buchem et al., 2002; Alsharhan, 1991). The Natih unit is overlain by rocks of the Conglomerate Muti unit, which is partly covered by the Shale Muti unit. In several places, however, detached lenses of the Conglomerate Muti unit, approximately up to 150 m in width, are imbedded within the Shale Muti unit. The conglomerate is more resistant to weathering than the shale, thus leaving topographic highs. Scree and limestone blocks from collapsed or eroded carbonate platform units surround the entire study area and leave a butte in the centre of the area. More recently, alluvial fill accumulated in depressions within the wadis.

In general, the area has a slope dip of approximately 25° inclining to NNE. Small tributary wadis, strike NEE to SWW, incise the surface and join a major N-S striking wadi, which form 80 m steep cliffs and sheer overhangs. At the northern tip of the study area the Nahr Umr formation builds several cuestas, each of about 1 m to 2 m in thickness.
Figure 3.6: Stratigraphic column of the mapped units within the Gorge area. The unit width is in relation to weathering as a measure for relative rock strength. (*) timing of slope deposit according to geological map of Beurier et al. (1982). Column is not to scale, formation thickness is approximate.
3.2.2 Lithology

The mapped units were defined by their lithology. They are described in the following.

Nahr Umr unit

The base of the mapped Nahr Umr unit does not crop out within the Gorge area. Due to the lack of conformably overlying Natih rocks, it remains unclear if the top of the unit belongs to the upper members of the Nahr Umr formation. However, this seems to be likely as the unit has a lateral continuity northward of the study area, where, in the distance, the steep cliffs of the lower Natih formation stack upon this unit. The Nahr Umr unit is relatively prone to weathering as it consists of alternating layers of medium to fine grained calcareous limestone shale and massive limestone beds, which are not thicker than 2 m. Hence the Nahr Umr unit builds several cuestas. The Nahr Umr unit is rich in fossils (Figure 3.7). In general rocks of the Nahr Umr unit are micritic, matrix-based, and reveal a grey yellowish colour. The Nahr Umr unit only reveals a few veins (see chapter 4.2) and is covered by slope deposit material to the east and to the west.

Natih unit

Similar to the previous unit, the base of the Natih unit does not crop out within the study area. The massive limestone beds of the Natih unit are dark grey to blue in colour and reveal only a few fossils (Figure 3.7). According to van Buchem et al. (2002), the member E of the Natih formation contains chert blankets similar to those found in this area (see section 1.2, Figure 1.7). However other studied areas show chert blankets and similar iron concretions in several other members within the Natih formation. Arndt, Virgo & Sobisch (2010) identified them as well in the Shu’aiba formation. Robertson (1987b) noticed that uppermost members of the Natih formation might be eroded and deposited within the Muti basin. Thus the overlying strata must cover the Natih unconformably. The stratigraphic boundary between the Natih and the Muti formations is defined by the so-called Wasia-Aruma break, an unconformity that is named accordingly to the involved formation groups (Figure 3.6) and that can be found in some places of the here studied area as well (next to fault F4, see text below). Different to all other mapped units, the Natih unit contains numerous veins.

Conglomerate Muti unit

The Conglomerate Muti unit is strictly homogeneous, only the lower part contains a bed of calcareous shale. The matrix-based conglomerate consists of angular limestone clasts and a bright grey silty matrix.
Figure 3.7: Variety of fossils within the study areas. Lateral section of (a) a sponge\(^1\) and (b) a gastropod (Natih unit)\(^2\). Picture detail (d) refers to (c), showing a large foraminifera\(^3\). (e) displays a solitary coral\(^4\), (f) relics of a cephalopod\(^5\). Large fossils in (g) are presumably Rudists (Nahr Umr unit)\(^6\). (h) shows a fossil rich biomicrite of the Nahr Umr unit\(^7\).

\(^1\) fossils found in the Natih unit of the Pool area, \(^2\) fossils found in the Gorge area.
The rest of the unit shows no obvious bedding pattern but a 2 m wide spaced layering with a good lateral continuity, which enables to identify faults but no vertical offset. The layering is parallel to the bedding of the interbedded shale and can be best described as a pressure solution cleavage. Fossils can only be found in the clasts, which, according to Robertson (1987b), derive from pre-Muti layers of the carbonate platform formations. Veins within the Conglomerate Muti unit are rare, mostly weathered and always associated to faults.

Shale Muti unit
The Shale Muti unit consists of fine grained non-calcareous claystone-shale alternating in colour between red and yellowish green. The unit layers are obviously bedded and 2 cm to 20 cm thick. Veins in this unit are very few and far between and cannot be associated to other features. In each measurement location the Shale Muti unit reveals two cleavages, of which one is less apparent than the other. Thus, the cleavages are named minor and major cleavage, respectively. The cleavage orientation depends on the layer thickness and on the location within the study area and varies strongly from 126° to 276° in dip direction and from 10° to 80° in dip. Error corrections for bedding dip and layer thickness variations are beyond the scope of this thesis. Pole points in Figure 3.8 show the range of cleavage orientation. According to Robertson (1987b), the sediment material derived mainly from the terrestrial Arabian continent and got deposited calcareous-free within the Muti basin below the CCD.

![Figure 3.8: Stereonet showing pole points of cleavages at the Gorge area, measurement locations (4) as noted in Plate B.](image-url)
Slope deposit unit

Related to the doming of the Jabal Akhdar anticline, this unit consists of limestone blocks and scree from collapsed or eroded carbonate platform formations. The angular blocks make the area hard to walk in and reveal no faults or other structural elements.

3.2.3 Tectonics

Due to the excellent outcrop conditions numerous tectonic elements have been identified. Several of these elements seem to be small and local features, which are only analysed if they reveal important links to the examined pavements (chapter 4) or to larger geological structures. Major structural elements, especially if they are visible in satellite imagery, are examined carefully, analysing their dip, dip direction, shear sense and offset. The following describes these major faults individually. They are numbered serially starting from one in the northern part to eleven at the southern end of the study area. The geological map (Plate B) and the attached profile (Plate C) provide an overview of their location, orientation and shear sense and should be used in addition to this section. Furthermore, a selection of pictures of the Gorge area is meshed together by using Photosynth (see chapter 2).7

Fault one (F1)

This steep fault offsets two different stratigraphic units, the Nahr Umr formation in the north and the younger Natih formation in the south. It is located 65 m north of the Upper Gorge pavement. The average strike direction is 103°, with a standard deviation of 9.4°. Derived by picture interpretation and in field observation (bearing), the average dip is 87°. One outcropping fault plane at 513853 m E, 2573944 m N (UTM 40Q) shows a measured dip direction and dip of 188/79. Figure 3.9 shows fault 1 in the eastern wall of the wadi. Suggesting that the evolution of normal faults within the study area occurred prior to the doming of the Jabal Akhdar, and thus prior to the tilting of the layers, we can back rotate the fault dip by the inclination of the surrounding bedding. This yields the original orientation of the fault. As the average bedding dip is 23°, the original fault dip had to be 64°, thus indicating a normal fault angle. Additionally, a set of conjugated veins next to the fault reveals a vertical orientation of the principal stress axis.

7 Photosynth „Gorge total“, http://photosynth.net/view.aspx?cid=38b9cda0-3ce9-47a5-89a3-bfaf8493573e
The exact offset height of fault 1 is not ascertainable in the field. As the Nahr Umr formation is offset against upper units of the Natih, the vertical offset has to be approximately 300 m according to the average thickness of the Natih formation. However, the offset is possibly smaller, as we do not know the Turonian erosion thickness of the Natih in this location. Paleontological analysis and a detailed sequence stratigraphy would help to solve this issue. In elongation to the west of fault 1, a smaller NW-SE oriented wadi joins into the main wadi (Plate 2). Its strike direction (113°) deviates by only 10° from the fault 1 strike direction, thus indicating a western continuation of this fault for at least 150 m. Slope deposits cover the fault in the east. According to the geological map of Beurrier et al. (1982), however, this fault continues for 5.7 km to the east and has its most western tip within the centre of the study area.

Fault zone two (F2)

Sub parallel to and 125 m south of fault 1, an up to 15 m wide fault zone (F2) juts out from the wadi wall. Its average strike direction is 096° with a standard deviation of 7°. The zone dips close to vertical, exposing two accessible fault planes (A) and (B) (Figure 3.10). Each reveals shear sense indicators.
Strata at the northern fault plane (A) are bent into the fault zone, forming a small drag fold (Figure 3.12). The orientations of the limbs of this fold have been measured in order to interpolate the fault’s movement direction. Figure 3.11a displays a stereonet projection of the limb planes including the thereby devised drag fold axis of 137° in azimuth and 49° in inclination.

Figure 3.11: Stereonets of drag fold axes and limbs. (a) shows the measured values of location A and (b) shows the measured values of location B.
A same analysis at folded layers in (B) shows a drag fold axis of 103° in azimuth and 28° in inclination. Thus, we can interpret a dextral oblique-slip fault with the southern block down. However, this interpretation carries a degree of uncertainty, as the fault zone undulates and the rigid adjacent limestone layers most likely influence the fold forming of the shale layer. Moreover, striations found in (B) indicate two different shear senses (Figure 3.13). Here, vertical striations (320/67) are superimposed by sub horizontal ones (054/07), thus suggesting a vertical motion of a normal fault, followed by a horizontal strike-slip movement. The fault zone sticks up to 45 m into the wadi, indicating a stronger alteration resistance than the surrounding rock. Rocks within the fault zone are highly cemented and yellowish grey in colour. Usually, fault zones developed by brittle deformation may contain a dense mesh of fractures in which circulating fluids deposit cementing minerals like travertine and calcite. Figure 3.14 shows a barred travertine block found on top of the wadi wall at fault F2 in 513781 m E, 2573808 m N (UTM 40Q) where the horizontal orientation of the crystal growth is an evidence for open fractures within the fault zone. A dense network of calcite veins, up to 12 m wide, makes the fault easily visible in the field and on the satellite image. But, what appears from the top view to be one fault line are in fact two different faults cropping out at the same spot.
Figure 3.13: Striations at fault F2 indicating two different shear senses at location (b). Viewing direction to the south, pencil for scale.

Figure 3.14: Barred travertine at fault zone 2. Pencil (approx. 15 cm) pointing to north, top view.
Another fault, hidden to any satellite interpreter, crops out very close to the described fault zone and may have an influence on its vein network. This second fault shows a low angle normal movement (dip 184/33) and is observable in the eastern wadi wall south of the fault zone 2. The attached profile (Plate C) and further descriptions in chapter 4.2 outline the orientations of the setting. In the east of the study area, both faults seem to be developed at separate locations, as the fault line splits up into two branches. The southern branch is inferred by following a web of calcite veins and the northern branch is inferred due to a block of cemented fault rock found further north in a small wadi at 514027 m E, 2573848 m N (UTM 40Q). Slope deposit material covers both faults in the very east and in the very west of the study area.

Fault three (F3)

Fault 3 has no accessible fault plane and is hidden within a narrow, not reachable part of the wadi, where several fallen down blocks of the Upper Natih unit obstruct the passage within the wadi. Fault 3 is located 55 m south of fault 2 and strikes 091° on average with a standard deviation of 6°. It is impossible to estimate its dip and dip direction, as this fault shows no measureable fault plane. Additionally, there is no obvious vertical offset, since strata of the Upper Natih, easily identifiable by its iron concretions (Figure 3.15), occur at both sides of the fault. Generally, the bedding in this area is sub horizontal and flattens out to the east. However, a bundle of en-echelon veins south of fault F3, at 513841 m E 2573770 m N (UTM 40Q), indicate a strike-slip motion. Measurements of these veins devise a maximum principal stress axis of 105° in azimuth and 2.5° in inclination. Moreover, the morphology structure next to the fault forms a small trench, which likely developed due to fluvial erosion along a discrete lineament - such as a fault plane. Alluvial fill, covering most of the underlying fault rock (Plate B), and karst caves of up to 1.5 m in diameter suggest fluvial processes, too. Figure 3.15 shows the immediate environment of fault F3 including caves. Please note the band of iron concretions as a marker for the uppermost Natih units in the Gorge area. To the East, within a small tributary wadi, the bundle of veins, by strike direction related to the fault, appears again. A further continuation of fault F3 to the west is likely due to the morphology of the western wadi wall but might join or intersect with several smaller faults in the area of the Upper Gorge pavement. The alluvial fill as well as the cliff of the trench-like morphology is easily recognisable in the satellite image. A continuation of the fault beyond the slope deposit material is not visible.
Figure 3.15: a) Immediate environment of fault 3. Viewing direction to SE.
b) Picture detail showing (1) a cave and (2) a band of chert nodules (approx. 2 m thickness).
Fault four (F4)

Fault 4 separates the Upper Natih unit in the north from the conglomeratic Lower Muti unit in the south. It strikes towards 082° on average, undulating with a standard deviation of 6°. All major fault planes of this fault occur within the Muti formation. Measurements here lead to an average dip direction and dip of 178/78. Next to the fault, strata of the Natih formation, with most of its included veins, are bent as illustrated in Figure 3.16. This indicates that the veins evolved prior to the bending of the layers. However, certain veins are interpreted to originate from the bending process itself, penetrating and thus being younger than all the other vein sets. The Muti unit next to fault 4 holds out its general layering structure and does not change in dip or dip direction. However, the terrain suggests an antithetic rotation of an entire, cohesive block as illustrated in the attached geological profile (Plate C). It remains uncertain if the bent Natih strata are dragged into the fault or if the structure can be best explained as a ramp similar to those ones described by Holland et al. (2009). This implies that the ramp is only hit, but not formed by fault 4. The evolution of these ramps, however, is not yet understood and a temporal relationship to other structures is not yet established. Shear sense indicators are missing and a dense, chaotic web of several vein generations is associated to the fault, making the reconstruction of any stress regime hardly possible.

Figure 3.16: Sketch of bending layers next to fault 4. Grey lines symbolise veins, grey area stands for alluvial fill and scree. a) and b) refer to following pictures in Figure 3.17.
Figure 3.17: a) View on bent strata next to fault 4. Viewing direction to the west, Max Arndt as scale (~1.70 m).
b) Bent layers south of fault 4. Viewing direction to the east, Enrique Gomez-Rivas as scale (~1.80 m).
A thin fault gauge (~0.2 cm) suggests a continuation of fault 4 within the Natih formation at 513644 m E, 2573674 m N (UTM 40Q). The total vertical ‘offset’, whether induced by the bending or by the fault itself is 50 m. This is inferred by the occurrence of chert nodules found at both sides of the fault area. Fault 4 is covered to the east and to the west by slope deposit material.

Fault five (F5)

Outcropping as an antithetic normal fault within the Muti unit, fault 5 is situated 150 m south of fault 4 along the wadi. Due to the incised topography, fault 5 crops out in a zigzag manner (Plate B). However, corrected by topography, its general strike direction is 097° at a standard deviation of 12°. Different to the faults described previously, fault 5 has a low angle dip of only 19°. Along its fault plane is one of the few possible pathways to enter the bottom of the wadi. A dragged-in shale layer indicates the normal fault shear sense. In an imaginary prolongation, fault 5 intersects with the Upper Natih formation at the bottom of the wadi near to the buckle where Natih layers bend downwards to the south (Plate C). Here, several veins and minor faults suggest a more complex continuation of fault 5 into the Natih. Especially as a small normal fault (vertical offset less than 1 m) reveals a contrary shear sense. Fault 5 forms the morphology of the terrain above the wadi (Plate C). Thus, the eastern prolongation of fault 5 can be inferred by a macroscopic view at the morphology.

Fault six (F6)

Fault 6 is situated 90 m south of fault 5. It is as well a low angle, antithetic normal fault within the Muti unit. Its strike direction, corrected by topography, is 101° at a standard deviation of 3°. Accessible fault planes at the bottom of the wadi wall reveal a dip direction and dip of 351/33. Here, striations (261/25) identify a small sinistral oblique-slip shear component. Figure 3.18 shows a fault plane of fault 6 and bent shale layers of the Lower Muti formation, which cleavage is bent by the fault. Similar to fault 5, an imaginary prolongation of fault 6 intersects the base of the wadi where its morphology is close to horizontal (Plate C). Here, Natih layers are covered by large Muti and Natih boulders with up to 5 m in diameter. A bending of Natih layers, similar to the area next to fault 4, is not observable. Therefore, a continuation of fault 6 displacing the Natih layers is likely. On top of the wadi wall, fault 6 crops out close to a small ridge, which is interpreted as the lifted part of a rotated block. Therefore, the continuation of fault F6 is inferred by following this ridge.
**Figure 3.18:** Cave at the base of the wadi next to fault 6 (F6). The less rigid shale is dragged to the outcropping fault plane.

**Figure 3.19:** Relicts of an old settlement. a) Food can with best-before date of 1983. b) Broken clay vases. c) Foreground: foundation walls of former houses; background: Lower Gorge pavement.
At the base of the wadi, next to fault 6, several relicts of a small village identify a former settlement in this far off and hardly accessible location. Low, broken foundation walls, a lot of goat excrements, clay vases and food cans with a best-before date of 09/1983 can be found here (Figure 3.19).

Fault seven (F7)

Similar to fault 5 and fault 6, this normal fault frames the limit of a rotated Muti block (Plate C). It is located 175 m to the south of fault 6 along the wadi. An accessible fault plane at the bottom of the wadi has a dip direction and dip of 000/46. Again, a 1.5 m thick shale layer within the Conglomerate Muti unit is bent. Along fault 7, erosion formed an open cave in the eastern wadi wall with approximately 20 m in height. Above the wadi wall a small channel runs along the fault. It dissipates rainwater from the north-eastern part of the study area and forms a small tributary valley, which separates the Conglomerate Muti unit against the Shale Muti unit. However, an eastern continuation of fault 7 along this valley remains uncertain as the valley turns to the north and leaves it difficult to determine whether it follows the fault plane or the bedding morphology.

Fault eight (F8)

Fault 8, only 45 m south of fault 7, dips with 190/82 to the opposite direction than the faults previously described. Striations indicate two different movements of which the older ones, being 210° in azimuth and 77° in inclination, are superimposed by more horizontal lineations with 112° in azimuth and 43° in inclination. A vertical offset is not determinable as the fault is only visible intra-stratigraphic within the Lower Muti formation. As the bottom of this part of the wadi is mostly covered by alluvial fill and scree material, the position of fault 8 cannot be precisely identified. From here on to the south, layers of the Upper Natih are covered by the Muti formation and do not crop out again within the study area. A lateral continuation of fault 8 is not observable.

Fault nine (F9)

This fault is not accessible, as it is situated within a narrow and steep part of the wadi. Therefore, no dip measurements have been collected. However, the approximate dip of 70° is identified by in-field observation (bearing). Several conglomeratic boulders of up to 15 m in diameter have been broken out from this fault. Many of them include veins, like the en-echelon array shown in Figure 3.20.
Fault ten (F10)

Situated 65 m to the north of fault 11, this normal fault is visible in the walls of both sides of the wadi. Fault plane measurements have been conducted on the western side, as the steep eastern wall is not accessible. The determined dip direction and dip is 197/68. However, by a macroscopic observation of the eastern wall, a smaller, northward dipping fault joints fault 10 close to the top ground surface. Above the wadi, Fault 10 offsets shale units against conglomeratic units of the Muti formation. Therefore, an offset of 2 m is estimated. Fault 10 only is observable very close to the wadi. To the west, slope deposit material covers the conglomeratic Muti layers, whereas weathering processes of the Muti shale have obliterated the surface to the east.

Fault eleven (F11)

The normal fault 11 clearly offsets conglomeratic units against shale units of the Muti formation (Figure 3.21). It shows an average dip direction and dip of 185/53. This corresponds to the mean strike direction of 083° (standard deviation 9°). Determined by the displacement of the top of the conglomeratic Muti unit, the vertical offset is at least 15 m. Several en-echelon veins enclose fault 11. However, none of them forms a conjugated set and the vertical offset remains the only shear sense indicator. The lateral continuity of fault 11 is
clearly visible in the satellite image, as it offsets different coloured units of the Muti shale. This is the southernmost major geological structure within the study area.

The stereonet in Figure 3.22 shows pole points of the described fault planes. Striations are displayed as arrows (azimuth as pitch). The Figure depicts the overall E-W strike of the faults and the differing azimuth directions of two striation generations. The striations’ inclination is given in brackets. The antithetic faults 5, 6, 7 and 9 are interpreted to belong to a southward dipping detachment fault (see following chapter ‘discussion’).
4 Pavements and veins

In the following, local structural elements of three pavements are described. These pavements are subjects to three B.Sc. theses (Raith, 2010; Thronberens, 2010; Wüstefeld, 2010). For each pavement a rectified high-resolution image was created by stitching up to 213 separate photographs. Raith (2010) accomplished the image for the Lower Gorge pavement, Thronberens (2010) for the Upper Gorge pavement and Wüstefeld (2010) for the Pool pavement. Parts of these studies are presented here in order to compare those to my field work observations. Further, the distributions and orientations of veins within the study areas are shown.

4.1 The Pool area

The following describes the local geological setting of the Pool pavement and the distribution of veins within the Pool area.

4.1.1 Pool pavement

Figure 4.1 shows a high resolution image of the Pool pavement created by Wüstefeld (2010). The 12 m by 90 m large pavement dips uniformly 231/09° and is located at the base of Wadi Dam, 2569404 m N and 507637 m E (UTM 40Q). It contains equally spaced, parallel veins, which are strictly confined to a particular layer and do not occur in the adjacent strata. Apart from the photographed pavement, these layer-confined veins can be found in several other places within the Pool area and occur in two different stratigraphic levels (Figure 3.1, Figure 4.5). The photographed pavement belongs to the lower one being at the base of the wadi, approximately 150 m underneath the top level surface. Analysing these equally spaced, regular oriented veins is a magnificent opportunity to study the relations of veins to other structural elements, as the vein pattern is very regular and largely undisturbed. This indication of low tectonic deformation matches the geological map of the Pool area, which shows only two major faults with relatively small vertical offsets (<4 m). The sinistral strike-slip fault A runs along the pavement in the south and has a visible distinct impact on the vein pattern. Here, the layer-confined veins are block-wise rotated with curved fractures limiting the blocks. The fractures are often filled with calcite forming curved ‘fracture veins’, which converge into the main fault A. Figure 4.2a gives an overview of this area and shows the location of further, but smaller faults.
Figure 4.1: Stitched high-resolution image of the Pool pavement (after Wüstefeld, 2010).
Figure 4.2: Overview of faults and veins in the southeast of the Pool pavement. (a): Top view of the eastern Pool pavement (contoured) showing fault A (solid grey line) and smaller faults (dashed-dotted lines) with shear directions. For scale: white arrow pointing to a standing person on the pavement in the lower left of the image. (b): Picture detail of (a) showing bent veins and fractures (white dotted lines) next to fault A. (c): Close-up view of a rotated block from picture (b). Note the rotated regular spaced veins. (d): Picture detail showing a vein repeatedly offset with a major offset next to a fracture. (e): Section of the eastern Pool pavement north of fault A showing southward bent veins. All pictures in grey scale for contrast enhancement.
Figure 4.2b displays the shear movement along curved veins and fractures next to fault A. Veins north of fault A are curved southward, whereas veins south of fault A are curved northward. The sketch in Figure 4.3 provides a three dimensional impression of the eastern Pool pavement.

Shear planes at the block limiting fractures reveal striations, which clearly indicate a dextral movement. Moreover, the offset of the layer-confined veins shows a dextral movement, too (see Figure 4.2b, Figure 4.2c). Figure 4.4 illustrates the mechanical principle next to fault A. Therein gear wheels show the shear sense of rotating blocks, which counter-clockwise offset the layer-confined veins. The toothed racks indicate the force directions which are necessary to cause the observed rotated vein pattern. Thus we can reconstruct a sinistral shear sense of the main fault A. The gear wheels of the northern and southern side of the fault roll off against each other as the northern and southern wheel axes are not stationary, but move apart sinistral. Dextral strike-slip occurs between wheels at the same side of the fault, which caused striations as mentioned above. It is remarkable that veins north of fault A show a more systematic offset, while the dense vein pattern south of fault A is more chaotic with a larger variety of vein orientations. This might be due to the presence of the smaller faults in the south, affecting the very local strain regime. Close to fault A, these smaller faults bend towards east and merge towards the main fault A. However, the merging itself is observable only at one location. There, fracture veins are s-shaped converging to both, to the smaller and to the main fault. This indicates a contemporaneous development of the faults. We can consider a single tectonic phase displacing the regular arranged veins in this part of the wadi.
4.1.2 Vein sets within the Pool area

Besides the Pool pavement, 18 further locations within the Pool area were examined regarding their veins (Plate 1). By considering dip and dip direction as well as the relative age relation of the veins, 4 major vein sets were identified. Based on field work observations, these vein sets are described in the following, ordered by their relative age relation from old to young.

1. Layer-confined veins

As described above, this set of veins crops out in the Pool pavement. Layer-confined veins occur sub-normal to bedding in two layers within the Pool area. Figure 4.5c shows the view from the upper layer down to the Pool pavement where the veins have the same orientation (~063/75), spacing (~0.6 m) and aperture (~3 cm). A likely reason for the layer confinement of the veins is a difference in the mechanical properties to the adjacent layers. In particular the tensile strength, depending on the plasticity conditions of the rock, has an influence on the fracture rate. Schmidt hammer tests revealed differences in the Young’s modulus (E) of the layers. The layer of the Pool pavement (E = 35.57 MPa) is less rigid than its overlying layer (E = 33.19 MPa) and more rigid than its underling layer (E = 49.12 MPa), with overlapping value ranges, as the standard deviations are 8.84 MPa, 9.3 MPa and 6.24 MPa, respectively (Stark and Zeeb, personal communication). However, tensile strength
depends on several further factors, such as temperature and speed of the deformation. In some locations the vein containing layer is much richer in fossils than the adjacent layers. Moreover the vein tips at the top and at the base of the layer are often bounded by stylolites, which might have a limiting influence on the vein propagation. Layer-confined veins are offset by fault related veins (Figure 4.2e). No crosscutting relation was observed to bedding parallel veins. Thus, their relative age relation remains unclear.

2. Bedding parallel veins

Within the Pool area, a few bedding parallel veins occur mostly in the upper layers. Like strata, bedding parallel veins are offset by faults and are thus cross-cut by fault related veins. However, the vertical offset of the faults within the Pool area is generally very small. Figure 4.5a displays a fault related vein offsetting two bedding parallel veins.

3. Veins related to faults

In several locations veins are found to be related to faults. This is exemplarily shown in Figure 4.5b, which displays a calcite cemented fault gauge breccia next to fault A, and in Figure 4.5d, where a 20 cm thick vein with blocky calcite crystals is shown. Figure 4.2e shows curved veins next to fault A. These veins clearly offset layer-confined veins. Further, striations on these veins allowed to determine the shear sense of fault A. Especially at the base of the wadi, faults often are accompanied by conjugated arrays of en-echelon veins. These are used to determine principal stress orientations. The orientation of the en-echelon veins is mostly E-W, as shown in stereonet projections in Plate 1.

4. Hairline veins

A group of veins with a thin aperture (~ 1 mm) cross-cut all other described vein sets. This group is called ‘hairline veins’. These veins often are accompanied by joints and can be found in numerous locations within the entire Pool area. The average dip direction of the hairline veins is 351° at a standard deviation of 3.9° only. The dip ranges from 63° to 88°. Hairline veins influence the weathering pattern of the outcropping rocks, as fissures often develop along these veins. This is likely due to thermal weathering. In some cases fissures evolve into large joints with several metres depth. Some of these joints are visible in the wadi walls, being always of same orientation. Figure 4.5f shows a weathering pattern along joints. In contrast to that, Figure 4.5e displays a mud-crack like weathering pattern of the limestone in a location where no joints and hairline veins exist.
Figure 4.5: Veins and weathering patterns in the Pool area. (a) Two bedding parallel veins offset by a fault related vein. (b) Calcite cemented fault gouge breccia next to fault FA. (c) View from the upper layer with layer-confined veins down to the Pool pavement. Note that the veins are in similar orientation. (d) Blocky calcite crystals next to fault A. (e) Mud-crack like weathering pattern of limestone (grey) with iron chert blankets (brownish). (f) Weathering pattern along joints, pencil pointing to north.
4.2 The Gorge area

In order to provide complete images of the geological setting that frames both Gorge pavements, structural elements of their closer surroundings are described below.

4.2.1 Lower Gorge pavement

The Lower Gorge pavement is located at 2573459 m N and 513630 m E (UTM 40Q). It is 70 m by 120 m large with an average dip of 163/21.

As part of his studies, Raith (2010) used the stitched image to create a map view sketch (Figure 4.6). This sketch highlights veins and faults of the pavement. Several E-W striking normal faults are visible in the pavement, but only two cross it entirely. However, these faults are only small features with less than 0.3 m vertical offset. A small strike-slip movement of less than 0.2 m is indentified by a horizontal offset of several veins in the pavement. Figure 4.7 displays a detail of the Gorge profile (Plate C), showing two faults limiting the pavement to the north and to the south.

North of the pavement, the base of the wadi dips close to horizontal and consists of large conglomerate blocks, which most likely cover the outcrop of fault 6. Being clearly visible in the eastern wadi wall, the faults’ elongation can be inferred to continue to the base of the wadi, where it just hits the sub-horizontal part. Thus we can strongly assume that the morphology in this location was shaped by movements along this fault and that it thereby limits the northern extend of the Lower Gorge pavement.

To the south, the pavement is ‘cut off’ by an outcropping E-W striking fault. Only 20 m south of this fault a series of similar oriented faults continue into the eastern wadi wall, where they develop a flower structure like system (Figure 4.8). This structure forms an overhang sticking out from the wadi wall. In fact, this overhang was used to take the pavement photographs from. Striations and a visible offset at the base of the wadi are signs for a positive flower structure. They indicate an upward movement of the inner block. The fault very next to the pavement reveals a normal offset of up to 1.8 m, with a strong three-dimensional variation. However, the fault creates a step in the wadis’ morphology and thus restricts the southern extend of the Lower Gorge pavement.
Figure 4.6: Stitched high resolution image of the Lower Gorge pavement (a) with highlighted veins and faults (b) (Raith, 2010).

Figure 4.7: Profile detail of the Gorge area. Underlying pictures show the eastern wadi wall. Red rectangle #1 refers to Figure 3.18, #2 and #3 refer to Figure 4.8.
Figure 4.8: Structural features south of the Lower Gorge pavement: (a) sketch of faults (black lines) in a flower structure like system from the eastern wadi wall shown in (b). Striations have been measured in locations 1 and 2. Point 3 indicates the overhang from which pavement photographs in Raith (2010) were taken from. Sketch (c) and picture (d) show the most eastern outcrop of the fault limiting the southern extent of the Lower Gorge pavement.
4.2.2 Upper Gorge pavement

The *Upper Gorge pavement* is located at 2573806 m N and 513732 m E (UTM 40Q). Being smaller than the *Lower Gorge pavement*, its area is 14 m by 60 m large and dips southward with an inclination of 09° in the west to 26° in the east. For this pavement Thronberens (2010) created a high resolution image, which is shown in Figure 4.9. Fault zone 2 limits the pavement in the north, where a dense and chaotic vein pattern occurs. By a macroscopic view the vein portion is even higher than the portion of the host rock in this location. On the high resolution image this vein pattern is visible in the northeast showing several E-W striking en-echelon veins.

A second important feature is an extensional duplex structure. The roof fault of this duplex crops out on top of the wadi close to the fault zone 2, dips to the south and is visible in the eastern wadi wall next to the pavement. Figure 4.10a shows a detailed profile of the eastern wadi wall, of which the structural elements are in general correspondence to the opposite western wall (Figure 4.10b). The pavement is sketched in the foreground of Figure 4.10b in order to illustrate the relation between structural elements in the pavement and in the wadi walls. Several imbricate faults run through the pavement creating an offset of veins. However, most imbricate faults do not show a continuously strait behaviour in three dimensions. Thus, the vein pattern is slightly irregular offset but shows a general trend along the undulating E-W striking faults. To the south the pavement ends at a 2 m high step, created by an abrupt imbricate fault. A part in the northeast of the pavement shows a curved surface with a dip up to 26°. Here strata are bent as shown in the profile sketch in Figure 4.10a. This bending might be associated to a floor fault of the duplex structure which unfortunately does not crop out. It can therefore only be assumed in the profile.
Figure 4.9: Stiched high-resolution image of the Upper Gorge pavement (Thronberens, 2010).
Pavements and veins

Figure 4.10: a) Profile sketch of an extensional duplex structure in the eastern wadi wall next to the Upper Gorge pavement. Foreground: simplified 3-D model of the Upper Gorge pavement.

b) Background: Photo and sketch of structural elements in the opposite (western) wadi wall. Foreground: simplified 3-D model of the Upper Gorge pavement. Black lines: faults; dotted black lines: inferred faults; grey lines: strata; white lines on the 3-D model: veins; grey planes in the profiles: limestone-shale strata.
4.2.3 Vein sets within the Gorge area

Besides the photographed pavements discussed above, 13 separate locations of the Gorge area were examined for their veins (Plate 2). Figure 4.11 displays the poles of all involved vein measurement values excluding pavement data. It provides an overview of the general distribution of the veins’ orientations.

![Figure 4.11: Stereonet of all vein measurement values of the Gorge area excluding data of the pavements (pole-points). (a) shows unclassified data, (b) shows data classified by age relationships. Vein sets are named according to their strike direction.](image)

At a first glance all veins seem to be in chaotic distribution and without any obvious clustering (Figure 4.11a). During field work several age relationships were recorded. Based on these relationships and in conjunction with the orientation data, six major vein sets were identified, which are distributed in clusters as Figure 4.11b illustrates. The sets were named according to their main strike direction.

Next to faults the vein density is generally higher than in the surrounding strata. However, continuous straight and long veins as well as veins with a regular spacing are best preserved in tectonically rather undisturbed locations. Within the Gorge area regular spaced veins are restricted to certain layers of the Nahr Umr unit, whereas veins of all other sets occur in the Natih unit. Rocks of the Natih unit contain more veins than all other mapped units. Figure 4.13c indicates the different vein densities between the Conglomerate Muti unit and the Natih unit. Within the Conglomerate Muti unit veins primarily occur next to faults. Veins in the Shale Muti unit occur sporadically. The alluvial fill as well as the slope deposit material contain no veins at all, except for those within the redeposited limestone blocks. All veins in the Gorge area consist of calcite with a rare exception at location G3. There, a few N-S oriented quartz veins occur.
Age relationships

All age relationships were determined by crosscutting relations of the vein sets. Crosscutting veins were examined in five locations (G3, G4, G9, G10, G12). Veins in other examined locations reveal no exposed intersection or show no clear overprinting relations (i.e. no ‘vein offset’ or a chaotic, dense and tangled vein network). The histogram in Figure 4.12 shows the number of measurement values versus strike direction of each recorded vein set. It has a class width of 10°. Relative age relationships of crosscutting veins are indicated by colour. This graphic rendition is adapted after Holland et al. (2009) and modified in order to display the distribution and the number of measurement values. The hereby identified relative age relationships are from old to young: (1) bedding parallel veins, (2) N-S en-echelon veins, (3) N-S striking veins, (4) NW-SE striking veins and (5) E-W en-echelon veins. This sequence is consistent for all measurement values with a sole exception at location G9, where N-S striking veins are found to be younger than the E-W en-echelon set. This might be due to a reactivation of the N-S striking set at this location, which is a zone of complex tectonics relating to fault 4.

*Figure 4.12: Histogram of strike values of veins. The basic population is 62. Colours indicate the relative age of a vein set for each location. All sets are labelled according to field observations: (bp) = bedding parallel veins, no strike direction, close to horizontal, (N-S) = N-S striking veins, (N-S En) = N-S striking en-echelon set, (NW-SE) = NW-SE striking veins, (E-W En) = E-W striking en-echelon set, (Qz) = quartz vein. See text for details.*
Figure 4.12 does not show dip information, but the displayed vein classification is in correspondence to the vein clusters in Figure 4.11b, which takes the dip information into account. Thus, we can generally distinguish the vein sets of the gorge area by their strike direction. However, older veins are occasionally bent or displaced by younger veins (i.e. 070 striking N-S vein in location G4). This was taken into account during field work. In consequence, all sets in Figure 4.12 are labelled according to field observations, which generally match the classification by strike direction.

Bedding parallel veins

Bedding parallel veins can be found throughout the mapped Natih unit. At some locations they are boudinaged with N-S oriented neck veins as an indicator for horizontal E-W extension (Figure 4.13a). Like the strata, bedding parallel veins are displaced by faults, but do not provide any offset value for the mapped major faults. Bedding parallel veins form under supra-hydrostatic fluid pressure close to or even higher than the lithostatic pressure with a maximum principal stress oblique to the bedding and a minimum principal stress close to vertical.

North to south veins

This major set of sub-vertical veins is oriented N-S with an average dip direction and dip of 280/40. It is restricted to the mapped Natih unit. N-S veins vertically offset bedding parallel veins as shown in Figure 4.13b. Usually N-S veins are straight and long features, easily recognisable in the field. Next to faults, however, these veins are bent, sheared and crosscut by other vein sets as displayed in Figure 4.13f. According to the vein orientation, the minimum principal stress prevalent during the vein formation was in E-W orientation, with maximum principal stress N-S or vertical oriented.

N-S en-echelon veins

N-S oriented en-echelon veins are found at location G9 only. Figure 4.11 and Figure 4.12 clearly show the different orientations of the sinistral and dextral vein arrays. According to this information, the maximum principal stress orientation was to NNW (341/55), determined following the method described in chapter 2.
Figure 4.13: Compilation of veins within the Gorge area. (a) shows boudinaged parallel to bedding veins. (b) illustrates a parallel to bedding vein offset by a N-S striking vein. Please note the bedding parallel stylolites. (c) shows different vein densities within the Muti (foreground) and the Natih (background) unit next to fault 4. (d) displays a dextral E-W striking enechelon vein within the Muti unit next to fault 11. Top view from the eastern cliff of the wadi. (e) shows E-W striking enechelon veins sub-parallel to fault 3 (not in picture). Simon Virgo for scale (sitting). (f) shows a N-S striking vein bent and sheared by E-W striking veins, pencil pointing to north.
Northwest to southeast veins

These sub-vertical veins are only observed at location G3 and G10, where they are on average oriented with 220/73 and 043/70, respectively. This indicates a minimum principal stress in NE-SW orientation.

E-W en-echelon veins

Different to all other sets, E-W oriented en-echelon veins are visible in the Natih unit and in the Conglomerate Muti unit. Usually, the veins occur next to faults. Figure 4.13d shows an en-echelon vein array in the Muti Conglomerate unit next to fault 11, whereas Figure 4.13e displays several en-echelon veins arranged linear and sub-parallel to fault 3. Except some rare cases, E-W en-echelon veins are not cut by any other vein and are thus the youngest vein set of the Gorge area. Stereonets in Plate 2 show the geometry of E-W en-echelon veins for the locations G9 (upper stereonet), G12, G4 and G10. The extension is constantly N-S oriented. The determined maximum principal stress axis varies strongly in inclination from 03° to 71°, but has always a general E-W striking direction. This vein set seems to be related to faults. Thus we can interpret local differences in the stress regime as a cause for the variation in inclination.

Regular spaced veins

This vein set is restricted to certain layers within the Nahr Umr unit. It consists of many parallel veins with a distinct linear strike of 075°. Each vein reveals an aperture of 2 cm to 5 cm. The spacing between the veins is very regular between 1 m to 1.5 m. Unfortunately, the regular spaced veins do not crosscut with any other vein set. Thus a relative age relationship is not determined.

Quartz veins

The quartz veins occur at location G3 only (Plate 2). Being different in composition to all calcite veins described above, the quartz veins imply a changed fluid composition during their formation. Based on crosscutting relationships, the quartz veins are younger than the N-S veins, but older than the NW-SE veins. A likely source for silica-rich fluid might be the overlying Shale Muti unit and the originally overlying Hawasina formation. This would imply a more open fluid flow system as described by Hilgers et al. (2006). However, silica-rich fluid could originate from the nearby chert nodules as well.
Relation to veins in the *Gorge pavements*

Thronberens (2010) and Raith (2010) measured several veins within the pavement outcrops and classified certain age relationships. Their outcome is in general correspondence to the vein analysis in the surrounding *Gorge area*, except the following observations:

- Regular spaced veins occur only within the Nahr Umr unit and therefore are not present in the pavements.
- Veins of the N-S en-echelon set are found in location G9 only and do not occur within the pavements, so do quartz veins of location G3.
- Both pavements reveal NE-SW oriented en-echelon veins, which are not found in the surroundings and which are younger than the E-W en-echelon set.
- NW-SE veins of the *Lower Gorge pavement* are found to be younger than the fault related E-W en-echelon veins. This is inconsistent with observations in the surrounding. Here, further investigation is needed.

Figure 4.14 compares three stereonets of the vein measurements in the different investigated areas.

![Stereonets of vein measurement values in the Gorge pavements and the surrounding (pole-points).](image-url)
5 Remote sensing

As there were no detailed topographic maps available, satellite image printouts were used to orientate in the field. Identified geological features on these printouts were surveyed on site. This chapter describes the results of this ‘inverse ground truthing’. Additionally, the printouts were used to discover the lateral extend of geological features identified in the field. This was an additional tool for the geological mapping.

5.1 Structures visible on the satellite images (inverse ground truthing)

The 0.5 m resolution of the Geoeye satellite imagery (Geoeye fact sheet; N.N., 2010b) allowed detailed remote sensing observations of the following (1) linear elements, (2) planar elements and (3) anthropogenic elements.

1. Linear elements

On satellite imagery, several geological, linear features are visible for both study areas. They represent faults, fractures and associated vein bundles as well as joints filled with bright alluvium.

For instance, the spatial distribution of fault B in the Pool area was only identifiable due to satellite imagery. The fault crops out at the entrance of Wadi Dam, where it exposes an easily identifiable fault plane (Figure 3.4). Yet by fieldwork the fault was not detectable on the terrain to the east. However, navigating along the lineament visible in the satellite picture (Figure 5.1a), several smaller outcrops of the fault plane were found. The lineament represents a bundle of veins, which link the found outcrops.

Figure 5.2a displays four lineaments of the northern Gorge area:

(1) fault 1, visible by offsetting Nahr Umr unit against Natih unit,
(2) fault zone 2, noticeable by dense, bright vein bundles,
(3) bright alluvium in the trench next to fault 3 and
(4) fault 4, offsetting the Muti unit against the Natih unit.

By fieldwork, these lineaments were either found to be faults or linear features associated to faults. Unfortunately they are covered by slope deposit material in the east and in the west of the Gorge area, making it impossible to trace them for a longer distance.
Remote sensing
Fractures reveal no offset of strata and are therefore harder to detect in satellite images. Arrows in Figure 5.1b point out strongly weathered fractures of several metres depth within the *Pool area*.

2. Planar elements

Based on colour differences several planar elements appear in the satellite images. This is due to different lithological compositions of strata. Figure 5.2b shows this exemplarily for the southern *Gorge area*, where the red and green Muti Shale unit is brought against the darker Conglomerate Muti unit and the slope deposit material. Thereby, we can identify fault 11, as the colour differences visualize the offset of this fault.

Less obvious is the example in Figure 5.1a, which shows a slight brownish area in the west. By changing the red versus the blue band and by replacing the green band with the near infrared band of the satellite image, the area becomes blue and stands out against the yellowish surrounding more obviously. This difference in colour is caused by the occurrence density of chert nodules. Chert nodules are more weathering resistant than the surrounding limestone. Thus, they accumulate on top of the surface and are responsible for the brownish colour in the satellite image. By fieldwork, there was no offset of strata found, which indicates that the occurrence density of chert nodules could be caused by local facies variations during the sedimentation. Figure 5.1d and Figure 5.1e illustrate the different occurrence densities.

Additionally, the false colour image in Figure 5.1b distinguishes the slope deposit material north of the wadi, as the colour distortion in this area is different to the more consistent colours of the planar dipping Natih unit. Apparently this is caused by the rough topography, as toppled limestone blocks and blocky slope deposit material scatter the sunlight more inhomogeneous and create shadows.

Please note that the Shale Muti unit south of the *Pool area* can be distinguished from the Natih unit as well.
Figure 5.2: Satellite imagery of the Gorge area (UTM 40Q). Picture (a) shows the northern part of the Gorge area, white arrows indicate lineaments originated by the faults 1 to 4, orange arrows point out a goat path. Picture (b) shows the southern Gorge area, orange circles indicate houses of the village Manda’a. The white arrow marks fault 11, visible due to the offset of differently coloured strata.
Figure 5.3: Imagery of the Pool area. Satellite picture (a) shows the dam (1) and the falaj (2) as well as the shadow casting over the wadi (3). Satellite picture (b) shows pile graves visible as dots (arrows). The graves are seen in photograph (c) as well (fieldbook for scale). (d) is a photograph taken from the wadi base. It shows the approximately 0.5 m wide falaj in the right (arrow). The round black mark in (a) and (b) indicate the location and viewing direction of (c) and (d). Coordinate system in (a) and (b) is UTM 40Q.
3. Anthropogenic elements

Figure 5.2 displays a goat trail and houses of the Gorge area. Figure 5.3a shows the embankment dam and the falaj system of the Pool area. To the west of Wadi Dam, several points (8 m to 10 m in diameter) are visible on the satellite image (Figure 5.3b). They are found to be pile graves, which are mostly broken and empty. The graves are made out of stacked limestones and have a grave-chamber cavity inside. Besides small water pumps, graves within caves (Figure 3.15) and the abandoned village mentioned in chapter 3, there are no other than the here shown anthropogenic objects in the study areas.

5.2 Structures not visible on the satellite images

Even if the satellite imagery is of good quality, there are still several objects, which are undetectable by remote sensing. In general this is due to the following four reasons:

1. Resolution

The spatial resolution of the pan-chromatic band of the Geoeye satellite imagery is 0.5 m. Objects smaller than 0.5 m, however, are detectable if their intensity of emitted radiation is in large contrast to the emitted radiation of the surrounding. Each pixel of each band of the satellite imagery has a digital number (DN) representing the average signal intensity of the area recorded within this pixel. Hence, any object influences the DN of a pixel by its size and by its emitted radiation. For instance the narrow falaj system, being darker to the surrounding, is visible in Figure 5.3a while the narrow goat paths in Figure 5.4 are not entirely in sufficient contrast to the surrounding and thus partly undetectable. Veins are usually brighter than the surrounding host rock and yield a high DN (Figure 5.2). Thus, they are partly detectable in the satellite imagery. However, it is difficult to distinguish whether a fracture filled with alluvium, one vein with a large aperture or - more likely - a bundle of smaller veins create the high DN of a pixel. Moreover, it is not possible to determine the high-resolution morphology of a shown object or the age relationship of intersecting structures, as Figure 5.2a illustrates by the vaguely visible veins.

2. Colour

Despite the resolution problem, objects larger than 0.5 m are sometimes invisible as well. A reason for this is the similarity of the objects emitted radiation to the emitted radiation of the surrounding. Two areas of similar colour create no significant change in the DN for
any band of the satellite image. Thus, we cannot observe any contrast in the satellite image, which would reveal the object. This holds true for the linear structures of fault 5 to 10 in the Gorge area. These faults crop out intra-stratigraphically and do not offset strata of different colour. Thus, the faults are not visible in the satellite imagery (Plate 2).

3. Shadows
Figure 5.3 shows a part of Wadi Dam. The wadi wall, approximately 200 m in height, cast a shadow over a large part of the wadi’s base, hiding all structures within this area. To overcome this issue, older satellite images were used. These were taken at another time of the day and show a different shadowing (Digital Globe; N.N., 2010a). Unfortunately the older satellite images are of poorer resolution (pan-chromatic = 0.6 m, multispectral 2.44 m) and are georeferenced differently (offset approximately 19 m).

4. Topography
The lack of any topography map with a sufficient resolution makes it impossible for remote sending to discover the vertical geometry of any object described in this thesis. The here used DEM has a resolution of only 30 m. The orthorectification of the satellite images is thereby not adequate to interpret the vertical sequence of strata within the scale of the study areas. Due to the off-nadir angle of the satellite, steep topography sections averted from the image sensor could not be recorded. In fact, not a single structural information within the steep wadi walls is visible in the satellite imagery.

Figure 5.4: (a) satellite picture showing some goat paths in the Gorge area (UTM 40Q). For a better recognition, goat paths are highlighted in (b).
6 Discussion

In the following the examinations of the preceding chapters are discussed. Observations in mapping, vein analysis and remote sensing are interpreted in order to provide an answer to the question:

What was the structural evolution that led to today’s geological setting of the study areas?

6.1 Insights from stratigraphy & lithology

To start our interpretations, we can assume a carbonate platform, tectonically undisturbed, which formed within the Neo-Tethyan ocean and which uppermost formation is the Natih formation. According to the lithological description in van Buchem et al. (2002) and regarding the geological map of Beurrier et al. (1982), parts of both investigated study areas belong to this formation. Within the study areas, the occurrence of chert nodules and semi-continuous chert blankets varies between locations. Van Buchem et al. (2002) stated that the chert formed dominantly in regressive systems with a low organic influx. We can interpret local variations in paleo seafloor topography as cause for the different occurrence densities.

Coarse, angular limestone clasts and the calcareous matrix of the mapped Conglomerate Muti unit suggest a rapid submarine deposition as debris flows. This is consistent with Robertson’s (1987b) theory of a foreland basin. Non-calcareous shale of the mapped Shale Muti unit was certainly deposited in greater depth below the CCD.

Both study areas underwent the phase of regional obduction with a large load of allochthonous units. Strong evidence therefore is the occurrence of ophiolite sequences south of the study areas and the occurrence of mountain sized Oman Exotics blocks (Jabal Misht), which overlie autochthonous units southward and northeastward of the Gorge area.

Two cleavages of the Shale Muti unit show a different dip direction with a large variation in dip (Figure 3.8). The major cleavage dips roughly west and the minor cleavage dips roughly south. Further studies concerning bedding correction of the cleavage measurements might reveal the tectonic phase associated to the cleavages. For instance, Al-Wardi and Butler (2007) as well as Breton et al. (2004) stated a relation of cleavage formation to a phase of top-to-NNE shear within the Jabal Akhdar region following the southwestward obduction.

Erosion of the allochthonous units and uplift of the Jabal Akhdar anticline brought the carbonate platform units back to the surface. Being exposed to weathering and erosion, the topography of the study areas got deeply incised by wadis. Sporadic, but heavy drainage run-offs flooding these wadis formed the here studied polished limestone pavements. Moreover,
differential erosion of the units formed cuestas, overhangs and topographic highs. In relation to the updoming, limestone scree from autochthonous formations cover the younger Shale Muti unit on a topographic high in the centre of the Gorge area (Map B). This butte is an evidence for a larger slope deposit material coverage in the past. Thus, in accordance with the geological map of Beurrier et al. (1982), the age of the slope deposit unit can be accounted as sub-recent to recent.

6.2 Insights from structural elements

The Jabal Akhdar anticline underwent a multiphase tectonic evolution. Several structural elements within the study areas represent certain phases of this evolution.

Veins

Hilgers et al. (2006) and Holland et al. (2009) related bedding parallel veins to the top-to-NNE shearing event in the Jabal Akhdar region. For evidence, Hilgers et al. (2006) mentioned shear indicators on the surface of the veins and noted that these bedding parallel veins offset other vein sets, which are most likely in relation to or even predating the prior event of obduction. In this study, however, bedding parallel veins represent the oldest set and are offset by all other found veins. Bedding parallel veins within the study areas are only truncated and reveal no exposed vein surface and no shear indicators. Although Hilgers et al. (2006) and Holland et al. (2009) examined veins of same orientation, it is still possible that bedding parallel veins of my study areas originate from a different evolutionary phase, which took place prior to the top-to-NNE shearing. However, the supra-hydrostatic fluid pressure, which is necessary for horizontal, bedding parallel vein formation, has most likely similar causes for both types of bedding parallel veins. Supra-hydrostatic fluid pressures might have formed from in a high-pressure cell (Holland et al., 2010), where allochthonous Hawasina sediments could have sealed the limestone units. Thereby, fluid pressures, close to or even higher than the lithostatic pressure, would have been tectonically driven by the horizontal compressive stress of the obduction process, potentially accompanied with disequilibrium compaction (Hilgers et al., 2006). This is similar to observations in accretionary prisms (e.g. Screaton and Saffer, 2005; Praeg et al., 2009). Based on stable isotope analysis ($\delta^{18}$O, $\delta^{13}$C), Hilgers et al. (2006) excluded gas generation and long range fluid movement from high-to low-pressure cells to be a significant processes for supra-hydrostatic pressure generation.

By overprinting, sub-vertical to vertical N-S oriented veins are the next structural evidence for an evolutionary stage. The vein orientation indicates a change of the minimum principal stress into a horizontal E-W direction. This might have been due to a decrease in
N-S oriented stress, when the obduction process switched to the Makran subduction zone during the Campanian (Glennie et al., 1990). Rarely occurring boudinaged neck-veins inside bedding parallel vein structures (Figure 4.13) indicate an E-W extension as well. N-S en-echelon veins at location G9 (Plate 2) suggest also an E-W extension. The N-S oriented veins are not associated to fault-like structures but are long and straight linear features offset by all other found structural elements except the bedding parallel veins mentioned above. This is inconsistent with observations by Hilgers et al. (2006) and Holland et al. (2009), who described veins associated to E-W striking normal faults as the next evolutionary stage subsequent to the bedding parallel vein formation. However, Arndt, Virgo & Sobisch (2010) and Holland et al. (2009) described several vertical veins, which they related to the process of obduction. During the formation of these veins, the minimum stress rotated horizontally, leading to vertical vein formations with different strike orientation. This may be reflected by vertical veins of the NW-SE striking set and by NE-SW striking veins found in the Upper and Lower Gorge pavement. Though an anti-clockwise rotation of the minimum principal stress axis, as stated by Arndt, Virgo & Sobisch. (2010) and Holland et al. (2009), cannot be identified for the here studied areas. Admittedly, a certain relative age relationship between the last two mentioned sets and the E-W striking en-echelon veins remains unclear, as different vein age relationships were determined. The geometries of en-echelon veins are visualized in stereonets, similar to the simplified ‘beach ball’ projection of earthquakes (Plate 1 and Plate 2). Frequently, en-echelon veins accompany faults and provide information on shear sense and principal stress orientation. The displayed vein arrays of both study areas reveal a rough NNE-SSW extension and an ESE-WNW compression. The determined maximum principal stress axis (white dot within each stereonet) varies strongly in dip. This can be explained by very local differences in stress regimes in relation to the nearby faults. Different to other vein sets, en-echelon veins occur within the Natih unit and within the Conglomerate Muti unit. The tensile strength of both units certainly differs. As an evidence for this, the high vein density in the Natih unit is a sign for a more brittle rock property, whereas the pressure solution cleavage of the Conglomerate Muti unit is a sign for a more ductile material, which strains rather than fracture (in relation to the speed of a deformation). That en-echelon veins can be found within the Muti unit implies a certain change in the mechanic rock properties of the Muti rocks to become more brittle whilst the en-echelon vein formation. We can interpret the erosion-driven unloading of covering allochthonous units and thus a vertical pressure and temperature release as a reason for this change. Thus, E-W striking en-echelon veins formed presumably closer to the surface than the other vein sets.
Discussion

Moreover, E-W striking en-echelon veins are not deformed or offset and consequently younger than major shearing events such as obduction or top-to-NNE shear.

Faults

None of the described faults intersect in a way that allows a direct chronological sequence analysis of the faults’ activity. In an indirect analysis, however, we can separate three fault generations.

Faults, which are interpreted to belong to the earliest generation, are faults 1 and 2 of the *Gorge area*. Shear sense indicators like striations, drag folds and the offset of strata show a vertical movement. Conjugated en-echelon veins next to fault 1 and striations next to fault 2 also indicate vertical orientation of the maximum principal stress axis (Plate 2, location G11). Assuming, the evolution of the normal faults 1 and 2 was prior to the doming of the Jabal Akhdar, we can rotate back the faults’ dips (F1: 193/87; F2: 186/90) by the average dip of the surrounding bedding (190/23). In consequence, the original faults were dipping in a more typical normal fault angle (F1: 193/64; F2: 186/67). The fault plane dips to the south, offsetting the southern block down. Thus, in offset direction both faults 1 and 2 are inconsistent with a top-to-NNE shearing event, but developed probably in the following stress regime with N-S oriented extension. This is in accordance with observations by Hilgers et al. (2006), who described veins which accompany faults of an extensional regime postdating the top-to-NNE shear event (Hilgers’ vein sets 5 and 6, see Table 1.2).

The faults 4 to 11 of the *Gorge area* belong to the second fault generation. They probably form a local detachment fault with the northern blocks tilted antithetic to the bedding, similar to the domino model or bookshelf model described in Ramsay (1987). Figure 6.1 shows an overview panorama of the southern part of the eastern wadi wall in the *Gorge area* and the sketched profile as an illustration. The sketched fault blocks collapsed sideways and moved against each other by shearing along normal faults. By the rotation triangular areas above and below each block occurred. The upper triangular areas form small valleys, partly filled with alluvium and boulders, which eroded from the uplifted edges of the rotated blocks. The top edge of a rotated block forms a ridge, which is easy to trace in the topology of the *Gorge area*. The lower triangular areas are filled by ductile flow of shaly layers in the underlying units (Figure 3.18).
Figure 6.1: (a) Photo stitch of the eastern wadi wall in the Gorge area. (b) Profile section showing observed faults (black lines) and inferred faults (dashed lines). Conglomerate Muti unit is in green, limestone Natih unit is in blue. (c) Simplified sketch showing rotated blocks of the domino model. Grey arrow illustrates the updoming movement in the north of the Gorge area.
However, this does only provide an incomplete picture, as the faults of the rotated blocks likely continue within the Natih unit. The extension of the outcropping fault F4 is interpreted as sole fault oriented roughly parallel to the bedding. This is supported by altitude differences of the rotated blocks, which decreases towards the south. Thus, we can interpret a normal fault motion relative to the units underlying a potential sole fault. Each rotated block underwent a rigid body rotation, which is indicative for a brittle deformation. This is supported by the en-echelon veins within the Muti unit mentioned above.

The extensional duplex structure next to the Upper Gorge pavement potentially belongs to the second fault generation, too. Small normal faults, potentially associated to the first fault generation, predate the duplex movement, as shown in Figure 6.2. Here dragged en-echelon veins indicate the age relationship. We can assume a relatively shallow fault activity for fault group two with the updoming movement of the Jabal Akhdar anticline in the north as the key-driving mechanism. Therein the local $\sigma_1$ is vertical. On regional scale, however, $\sigma_1$ might be horizontal to enable the doming process. This is similar to a model by Hanna (1990), who stated that normal faults throughout the Jabal Akhdar are driven by the local gravity potential of the massif. This theory of a 'culmination collapse', however, is controversially discussed (e.g. Al-Wardi and Butler, 2007; Breton et al., 2004). Contrary to Hanna’s (1990) implications, several faults do not dip away from the massif and remain constant in dip with depth (e.g. faults with a top-to-NNE shear, faults within the pre-Permian basement and within Wadi Nakhr (e.g. Breton et al., 2004; Holland et al., 2009)). Both attributes, the dip direction away from the massif and the dip reduction with depth, apply for the here interpreted
detachment fault, and we can suggest that this structure is at least partly driven by local gravity-sliding processes. However, Searle (2007) also stated major listric normal faults downthrowing to the south, which bound the flanks of the Jabal Akhdar anticline (see cross section in Figure 1.5, Wadi Ghul). Searle (2007) also found these faults to be active during the uplift of the autochthonous units but, contrary to Hanna (1990), not in relation to a ‘culmination collapse’. Searle (2007) stated a compressive regime during the Late Cretaceous, associated with ophiolite emplacement, as the operating force for these major listric normal faults. It remains unclear if the observations by Searle can be appropriately related to any of the here described fault generations.

Sub-horizontal striations superimpose vertical striations on several fault planes of the Gorge area (i.e. F2, F8). This indicates a reactivation of normal faults by strike-slip movement. Further structural elements like drag folds and the positive flower structure system mentioned in chapter 4.2.1 also originate from this strike-slip movement and are interpreted as the third fault group.

![Figure 6.3: Tectonic map of the Pool area. Stereonets show the geometric orientations of en-echelon vein arrays (white dot is the maximum principal stress axis). The mapped faults A and B are shown by black lines (dashed = inferred). (+) and (-) symbolise the relative vertical movement, the numbers show the determined vertical offset. The arrows schematically represent the inferred local stress regime (maximum (grey, compression) and minimum (white, extension) principal stress axes). For orientation compare to photograph in Figure 3.3 and to PlateA.](image)

Besides the age relationship of the striations, vertical faults associated to the flower structure suggest a formation after a tilt of the bedding and are thus subsequent to fault group two. Fault group three is most apparent in the Pool area. There, by sub-horizontal striations, both faults, A and B are identified as strike-slip faults. However, vertical offsets are identified as
Both faults merge in the southern wall of Wadi Dam, in the east of the Pool area and can be interpreted as a conjugated set, similar to the found conjugated en-echelon vein arrays at smaller scale. Figure 6.3 illustrates the setting and shows values of the faults’ vertical offset. Please note, that the faults’ vertical offset directions imply an upward movement for the area between the faults A and B. This stress regime generally matches with the determined strain of the conjugated en-echelon veins. By vein analysis in chapter 4.1.1, the shear sense of fault A is well examined to be sinistral, but there is unfortunately no shear sense indicator for the southern fault B. The strike-slip fault group three shows $\sigma_1$ being horizontally oriented, striking E-W. This is in accordance with Hilgers et al. (2006), who found sub-horizontal grooves on veins to be consistent with reactivation of normal faults as strike-slip faults.

Joints and hairline fractures, often filled with calcite (see ‘hairline veins’ in chapter 4.1.2), are the youngest structural set in the Pool area. Their orientation is on average 351/80, which indicates a differing stress regime to the third fault generation. Even if the main orientation of fractures strikes E-W, there are some NNW to SSE striking fractures of similar aperture. Both fracture orientations likely form a conjugated set. However, the number of measurement values for the second fracture orientation (4) is too small for profound interpretations of a stress regime. Here, further investigations are necessary.

In conclusion, it is interpreted that both areas underwent the regional process of obduction, which caused phases of supra-hydrostatic fluid pressure (bedding parallel veins) and phases of a stress regime with a horizontal rotating $\sigma_3$ axis. The obduction was presumambly followed by a phase of N-S extension (first fault development) and by a phase of updoming (detachment fault). Overprinting striations and faults in the Pool area indicate a subsequent E-W strike-slip motion. Weathering and erosion formed the final shape of today’s geological setting. Figure 6.4 shows a simplified block model of a multiphase evolution of the fracture network within the study areas. The evolution phases are compared to the model by Holland et al. (2010).
Figure 6.4: Simplified block model illustrating the multiphase evolution of a fracture network of the study areas. The model is not to scale. Smaller blocks (a)-(i) from Holland et al. (2010) are shown for comparison (Figure 1.8).

The Nahar Umr and Natih formations (carbonate platform sediments) are unconformably overlain by the Muti formation (wildflysch) in (1). The Muti formation is neglected in the following, as most veins occur in the Natih formation. (2) illustrates bedding parallel veins as the oldest structural element in the study areas. Representing a following phase, (3) shows N-S oriented veins. (4) comprises veins formed perpendicular to the bedding, where the minimal principal stress axis was horizontally oriented. Here block models by Holland et al. (2010) show a more differentiated sequence of these veins with an anticlockwise rotation of the minimal principal stress axis. Normal faults, probably related to N-S extension prior to the Jabal Akhdar doming phase, are represented in (5). The following doming and likely associated detachment faults are illustrated in (6). Model (7) displays strike-slip reactivation of normal faults, the shear sense is not yet clear. Exhumation and weathering led to the formation of joints and associated hairline veins as shown in (8). Veins are not shown in (6)-(8) for reasons of clarity. (9) shows a map view sketch of the final vein, fault and fracture orientation. E-W trending, mostly fault related veins of the phases (5)-(7) are displayed. The phases (f) and (g) from Holland et al. (2010) are not shown, as (f) displays an isolated ramp structure, which was not found in the study areas and (g) shows top-to-NE shear and related bedding parallel veins, which could not be described for the study areas. See text for details.
6.3 Vein analysis, mapping, remote sensing – a comparison

In the context of this thesis, three different working methods were accomplished. Vein analysis, mapping and remote sensing techniques were used to create a multi-scale examination of the two investigated areas. Several outcomes would not have been established without a combination of these methods.

Vein analysis is most important for reconstructing the structural history of the study areas, as veins preserve information on paleo-stress regimes. In particular, the examinations of conjugated en-echelon veins allow to specify the strain of vein-hosting rocks, which gives an evidence of the according paleo-stress regime. The simplified stereonet projection provides a comparison of en-echelon arrays in different localities and crosscutting veins reveal relative age relationships of paleo-stress regimes. In conjunction with fault analysis, conjugated vein arrays are useful to roughly distinguish the orientation of the main principal stress axis next to a fault. This helps to determine fault type and slip direction.

Mapping, as a basic geological discipline, is the most revealing investigation method. The general scope of mapping is wide. It spans from examinations of calcite mineral striations to outcrop analysis and to tracing of faults and mapping units. The whole range of mapping observations provides information of the geological setting. Interpreting these information allows to draw conclusions about the evolutionary history of the study areas.

Within this study, inverse remote sensing is accomplished using satellite imagery of 0.5 m pan-chromatic resolution. The most mentionable advantage is the possibility to continuously change the working scale and to get an instructive overview of the areas. In the field, satellite image printouts help to identify the lateral extend of geological structures. For instance, fault B in the Pool area would not have been found without the satellite imagery observations and the extent of dense chert occurrences is well visualized by false colour imagery. As a drawback, this method does not provide information on evolutionary history. Moreover, remote sensing, especially without verification by mapping, easily leads to misinterpretations as linear features in the imagery are often not structural elements like faults, but cueastas or steps in topography.
7 Conclusion and Outlook

Two study areas on the southern flank of the western Jabal Akhdar anticline were investigated for their structural evolution. Therefore, methods of vein analysis, remote sensing and mapping were combined. The field work on the study areas took 16 days from March 11th to March 27th 2010.

Several veins sets in the study areas reflect a multiphase structural evolution. The study areas underwent a phase of supra-hydrostatic fluid pressures (bedding parallel veins). This phase was followed by a stress regime with a horizontal, E-W oriented \( \sigma_3 \) axis, which enabled the formation of vertical N-S striking veins. In the aftermath of this regime, a period of horizontal rotation of the \( \sigma_3 \) axis followed. This is demonstrated by multiple vertical veins with different strike directions. The relative timing between these vertical veins is unknown. A set of E-W striking en-echelon vein arrays, frequently associated to normal faults, demonstrates a subsequent phase of N-S extension in the study areas. The orientation of conjugated en-echelon vein arrays is illustrated using a stereonet projection technique (Plate 1 and Plate 2) and shows an E-W strike-slip motion.

In an indirect analysis, three fault generations were identified. Each generation reveals a N-S extension. Two tilted faults in the north of the Gorge area form the first fault generation, which offsets the southern block down. This generation is followed by further normal faults and rotated blocks, interpreted to form a local detachment fault. The third fault generation represents a strike-slip movement, which partly reactivated older faults and which is best apparent by strike-slip faults in the Pool area. The youngest structural elements are hairline fractures and veins in the Pool area.

The sequence of described structural elements is in correspondence to existing theories of the regional structural evolution. However, except a cleavage, there is little to support the theory of a top-to-NNE shear within the study areas. For the investigated locations bedding parallel veins are not related to the top-to-NNE shear, but to an earlier evolutionary phase of the Jabal Akhdar anticline. This is controversial to vein observations by Hilgers et al. (2006).

The detailed geological maps (Plate A and Plate B), developed in this thesis, improve the investigated section of the existing geological map of Beurrier et al. (1982), which is of a poorer resolution (scale 1:100000).
Inverse ground truthing showed the limited capability of satellite imagery to visualize geological structures. Remote sensing techniques, as well as mapping would be greatly improved by the use of a more accurate DEM, which could be derived either by digitalizing high-resolution topography maps or by using Terra-Sar-X data. However, the method to visualize the extend of chert nodule occurrences is useful for further remote sensing projects (e.g. in determining horizontal offsets in satellite imagery).

The outcome of this thesis may be used in several further projects of the FRACS consortium, as it provides an elemental connection between structural elements in different scales. This is an opportunity to distinguish the multi-scale relevance of single-scale results, such as the interpretation of thin-sections, scan lines or mapping projects. Moreover, this thesis provides an image on the geological setting that frames the three pavements investigated in Raith (2010), Thronberens (2010) and Wüstefeld (2010).

Stable isotope analysis of veins and vein-hosting rocks within in the Jabal Akhdar anticline was accomplished by Hilgers et al. (2006), Holland et al. (2009) and recently by Arndt & Virgo (2010). These studies suggest an influx of meteoric fluid in the vein system during later stages of vein formation, presumably since the evolution of first E-W striking normal faults. Stable isotope measurements of the here described vein sets could verify this assumption. Moreover, the stereonet visualization method of en-echelon vein arrays can be accomplished in further studies of different locations in the Jabal Akhdar anticline. This could be used to create a statistically firm map of en-echelon vein array orientations, which can provide information in stress regime distributions.

In summary, this thesis provides comprehensive information on the local structural evolution of two study areas on the southern flank of the western Jabal Akhdar anticline. The outcome of this thesis can be used in further studies to verify and enhance structural models of the complex regional evolution.

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8 Terra-Sar-X is a commercial satellite and a mission of the European Aeronautic Defence and Space Company (EADS) to acquire radar images with up to 1 m resolution.
8 References


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9 Appendices

Plate A  geological map of the *Pool area* (1:4000)  
*annexed*

Plate B  geological map of the *Gorge area* (1:4000)  
*annexed*

Plate C  geological profile section of the *Gorge area*, course as shown in Plate B  
*annexed*

Plate 1  satellite imagery of the *Pool area* showing localities of vein measurements and photographs used within this thesis as well as geometric orientations of en-echelon vein arrays  
*back fold-out plate*

Plate 2  satellite imagery of the *Gorge area* showing localities of vein measurements and photographs used within this thesis as well as geometric orientations of en-echelon vein arrays  
*back fold-out plate*

CD  digital version of this thesis, data collection, Photosynth movies, satellite imagery, digital geological maps as *.shp, ArcGIS, and *.kmz, Google Earth  
*annexed*

Web links  Field photographs (312) of the *Pool area*:  
*http://photosynth.net/view.aspx?cid=21b2ee2c-3196-424a-bd2b-495b245a04dc*  
Field photographs (301) of the *Gorge area*:  
*http://photosynth.net/view.aspx?cid=38b9cda0-3ce9-47a5-89a3-bfafa8493573e*

Measured vein orientations  
*following pages*

Measured fault orientations  
*following pages*
**Measured vein orientations – Pool area**

All values in Clars notation (dip direction / dip) unless noted otherwise. Relative age relationship: 1 = oldest vein set of location. Locations refer to Plate 1

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**Measured vein orientations – Gorge area**

All values in Clars notation (dip direction / dip) unless noted otherwise. Relative age relationship: 1 = oldest vein set of location.

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**Measured fault orientations – Pool area**

All values in Clars notation (dip direction / dip) unless noted otherwise. Fault names and locations refer to Plate A

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### Measured fault orientations – Gorge area

All values in Clars notation (dip direction / dip) unless noted otherwise. Fault names and locations refer to Plate B

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east wadi wall  335  30  327  38  

Fault 7  east wadi wall  175  46  
east wadi wall  178  47  
east wadi wall  180  38  
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east wadi wall  190  53  
east wadi wall  178  50  
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east wadi wall  180  43  

Fault 8  east wadi wall  193  75  196  79  
east wadi wall  194  84  225  76  
east wadi wall  183  86  108  30  
east wadi wall  113  55  
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Fault 10  west wadi wall  193  75  
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west wadi wall  196  60  

Fault 11  west wadi wall  175  54  
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east wadi wall  170  66  
east wadi wall  182  58  
east wadi wall  185  58  
east wadi wall  180  50  

Appendices
Geological map

Map B - Geology of the Gorge area

Legend

Quaternary
- Alluvial fill
- Slope deposit (scree)

Cretaceous
- Muti
- Shale
- Muti
- Conglomerate
- Natih
- Limestone
- Nahr Umr
- Limestone, shale

Symbols

- Fault
- Fault (inferred)
- Contour line*
- Fault dip
- Bedding dip
- Cleavage 1 dip
- Cleavage 2 dip

Scale 1:4,000
UTM 40Q, WGS 84
Geoeye imagery 2010

*Contour lines derived from ASTER DEM data (30 m resolution).
Mapped by: Ben Laurich, Geologie - Endogene Dynamik, RWTH Aachen, Germany. November 2010.
Geoeye 2009 satellite imagery showing vein measurement localities (index 'P'), stereonets illustrating the geometric orientation of conjugated en-echelon vein arrays, and localities of photographs used in this thesis (index 'Fig.') (UTM 40Q).
Geoeye 2009 satellite imagery showing vein measurement localities (index 'G'), stereonets illustrating the geometric orientation of conjugated en-echelon vein arrays, and localities of photographs used in this thesis (index 'Fig.') (UTM 40Q).

Plate 2 - Gorge area