Diagenesis and fluid system evolution in the northern Oman Mountains, United Arab Emirates: Implications for petroleum exploration

Liesbeth Breesch, Rudy Swennen, Ben Dewever, François Roure and Benoit Vincent

ABSTRACT

The diagenesis and fluid system evolution of outcrop analogues of potential sub-thrust Cretaceous carbonate reservoirs in the Musandam Peninsula, northern United Arab Emirates, is reconstructed during the successive stages of the Oman Mountains development. Detailed petrographic and geochemical analyses were carried out on fracture cements in limestones and dolomites mostly situated close to the main faults, which were the locations of major fluid fluxes. The main result of this study is a generalised paragenesis subdivided into four diagenetic time periods. Based on analyses of syn-tectonic veins and dolomites a large-scale fluid system is inferred with migration of hot brines with H₂O-NaCl-CaCl₂ composition along Cenozoic reverse faults. These brines were sourced from deeper formations or even from the basal decollement and infiltrated in the footwall. These results are compared with similar studies, which were carried out in other regions worldwide.

Furthermore some implications for reservoir characteristics and hydrocarbon scenarios could be postulated. It must be noted that the majority of the analysed rocks do not have sufficiently high porosities to be regarded as reservoir rocks. However, some diagenetic processes that can improve the reservoir quality were observed. For example dolomite crystallisation occurred in patches at the carbonate platform border, which created poorly connected reservoirs. Other possible exploration targets could be the footwall blocks of the Cenozoic reverse fault zones. When the migration of hot brines along these faults and into the footwall would be combined with petroleum migration, the footwall block could act as a potential hydrocarbon trap sealed by the fault. The fluid system evolution is incorporated in a schematic model of the geodynamic framework of the region in order to summarise the different diagenetic and fluid events, which took place during the northern Oman Mountains evolution up to now.

INTRODUCTION

Within the framework of ongoing oil and gas exploration in structurally more complex areas, the fluid systems and hydrocarbon and reservoir potential of foreland fold-and-thrust belts (FFTB’s) were investigated in numerous studies all over the world, e.g. in Pakistan (Grélaud et al., 2002; Benchilla et al., 2003), Albania (Van Geet et al., 2002; Vilasi et al., 2006; Dewever et al., 2007; Breesch et al., 2007), Venezuela (Schneider, 2003), Mexico (Ferket et al., 2003; 2004; 2006), Spain (Travé et al., 1998; 2000; 2005), Canada (Vandeginste et al., 2005; 2006; 2007; 2009) and Sicily (Dewever et al., 2006, 2010). An integrated approach, including the combination of structural geology, petrography and geochemistry as well as basin modelling, was used to determine the main controls on the reservoir characteristics in FFTB’s (Roure et al., 2005).

Despite the rich offshore oil accumulations in the Arabian Gulf, the Oman Mountains still are a frontier exploration region. Two gas/condensate fields (Margham and Sajaa) are productive in the northern United Arab Emirates (UAE) in the vicinity of the thrust front (Glennie, 2005; Figure 1). A deep seismic data acquisition carried out across the foothills of the northern UAE (Ministry of Energy, UAE, 2007), however, revealed the existence of a wide underthrusting of autochthonous or para-autochthonous units. These units are derived from the former Arabian margin in the footwall of the far-travelled allochthon made up of the Hawasina Nappes and Semail Ophiolite. The main objective of this paper is the reconstruction of the diagenesis of the Jurassic – Cretaceous rocks and
We studied site Town Ruus Al Jibal Group

Alluvial fan and Wadi deposit

Alluvial fan gravel

Low eolian dune

Eolian dune ridge

Figure 1: (a) Geologic map of the Oman Mountains (from Robertson and Searle, 1990). (b) Geologic map of the northern Oman Mountains outlining the location of the studied outcrop sites, the wells, the D4 regional traverse.
the fluid system evolution during the successive stages of fold-and-thrust belt development. The study area is located in the Musandam Peninsula in the northern UAE, which constitutes an outcrop analogue of the subthrust carbonate platform duplexes imaged by recent seismic surveys (Ministry of Energy, 2007). A detailed petrographic and geochemical study was carried out on fracture cements in limestones and dolomites, mostly situated close to the main faults, which were the locations of major fluid fluxes. Apart from the importance of the fluid system reconstruction in petroleum systems, diagenetic processes can have an important influence on reservoir properties. Therefore the risk of reservoir damage remains a challenge in exploration in areas affected by diagenesis.

The results of this study with respect to diagenesis, fluid flow and stable-isotope trends in the carbonate rocks of the Musandam Peninsula are compared with similar studies carried out in other regions of the world. As a summary, the fluid system evolution is incorporated in a schematic model of the geodynamic framework of the region. Based on these results and in combination with subsurface data, some implications for reservoir characteristics and hydrocarbon scenarios in the northern UAE are formulated.

GEOLOGICAL SETTING
Geology of the Oman Mountains

The Oman Mountains in the United Arab Emirates (UAE) and Oman extend over 700 km from the Strait of Hormuz in the north to the Arabian Sea in the south. The formation of this mountain range took place during two orogenic events separated by a period of tectonic relaxation (Searle et al., 1983). After an episode of extension during the Neoproterozoic to early Cambrian, leading to the deposition of the Hormuz Salt, the study area formed part of the stable Gondwana Supercontinent during most Palaeozoic times. During the mid Permian, rifting commenced and the Neo-Tethys Ocean opened as the Iranian microcontinent migrated northwards (Baud et al., 2001, and references therein), forming a continental slope and basin at the northeastern margin of the Arabian Platform. In the Late Triassic to Early Jurassic time, the axis of ocean-floor spreading moved eastwards leading to compression of the Neo-Tethys deposits during an eastward-directed subduction in the mid Cretaceous (Glennie, 2005). The present-day Semail Ophiolite formed in the back-arc of this subduction zone. During the Campanian, the ocean started to close and the Semail Ophiolite, the Hawasina basin deposits, the Haybi volcanic complex and Sumeini slope deposits were obducted in a stacking pattern onto the autochthonous Arabian Platform. A foreland basin formed in front of the advancing thin-skinned thrust sheets of the Oman Mountains (Searle, 1988b). Slab detachment may have occurred during the Palaeogene, accounting for a slight unflexing of the foreland lithosphere. Because no continent-continent collision took place between the plates in the study area, the relief was not very pronounced with the current topography developing during a later Cenozoic orogenic event.

The exact timing of the Cenozoic post-obduction tectonic phase is still debated (Warrak, 1996), but it is most likely to have taken place from Oligocene or Miocene onward. The deformation caused large-scale folding and thrusting in the northern Oman Mountains, transporting the carbonate platform deposits of the Musandam Peninsula over 15 km westwards along the Hagab Thrust (Searle, 1985; Robertson et al., 1990). Internally, the allochthonous or para-autochthonous platform succession was affected by steep reverse faulting. The present-day northern Oman Mountains consist of the carbonates of the Arabian Platform, the Dibba Zone and the Semail Ophiolite (Figure 1). The Dibba Zone is dominantly made up of the Hawasina Nappes and the underlying Sumeini slope complex exposed in a few tectonic windows.

Location and Stratigraphy of the Studied Outcrops

The studied outcrops have a roughly north-south distribution (Figure 1). Four of the studied outcrops are located along wadis cutting across the Musandam Platform (Wadi Sha’am, Wadi Ghalliah, Wadi Bih and Al Khatt). Wadi Batha Mahani is situated in the transition between the Musandam Peninsula and the Dibba Zone. The outcrop in Jabal Gharaf is situated in a tectonic window where the Sumeini Nappes crops out in the Dibba Zone (Figure 1).
Dominantly shallow-marine carbonates are exposed in Wadi Sha’am, Wadi Ghalilah and Wadi Bih whereas deeper-marine carbonates crop out in Jabal Gharaf, Wadi Batha Mahani and Al Khatt. In the northern group, the studied sequences belong to the Upper Triassic Elphinstone Group and the Lower Jurassic Musandam Group (Ellison et al., 2006; Figure 2) with the exception of the footwall rocks of the Cretaceous Thamama Group in Wadi Ghalilah. The strata, which crop out in the southern area belong to the Jurassic Musandam 3 Formation, the lower Cretaceous Thamama Group and the upper Cretaceous Aruma Group (Ellison et al., 2006; Phillips et al., 2006; Figure 2).

The Musandam Peninsula is structurally dominated by the Hagab Thrust, which is a subhorizontal fault with a large frontal fold in its hanging wall exposed in the Hagil Window (Figure 3, section

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**Figure 2: Stratigraphy of the Musandam Platform and Dibba Zone (modified from Robertson et al., 1990) and lithostratigraphical column of the Ghalilah Formation, Musandam formations and Thamama Group in the Musandam Peninsula (modified from Ellison et al., 2006; Phillips et al., 2006).**

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D-D'). North of this window, its trace is less clear and it is probably represented by a system of reverse faults (Ellison et al., 2006). In Wadi Sha'am these faults subdivide the cliff-face in several fault blocks (Figure 3, section A-A'). The studied outcrop is situated in the first fault block in the western side of the wadi in the Musandam 1 Formation. The reverse fault in Wadi Ghalilah can be traced north to south for more than 30 km (Figure 3). In the footwall, the lower Cretaceous Thamama Group crops out and is overthrust by the Upper Triassic Ghalilah Formation in the hanging wall (Figure 3, section B-B'). The outcrop near the entrance of Wadi Bih is located in the footwall of one of the reverse faults, which are associated with the frontal fold of the Hagab Thrust (Figure 3, section D-D'). Rocks of the Triassic Milaha and Ghalilah formations are overthrust by the Permian Ghail Formation.

The only outcrop within the Dibba Zone is located in a side-wadi of Wadi Khabb, which is the main wadi intersecting Jabal Gharaf (Figure 4a). Jabal Gharaf is a tectonic window where the Sumeini carbonates can be seen in outcrop (Figures 4a and 4b). The Ausaq Conglomerate and the Mayhah Formation, which belong to the Aruma Group, are exposed on the northern side of the study area. The Shamal Chert Formation, on the southern side was originally thrusted over the Mayhah Formation during late Cretaceous nappe obduction. This fault has been reactivated as a normal fault.

The outcrop area in Wadi Batha Mahani is bounded by two thrust faults: (1) Wadi Batha Mahani which lies above a major Cretaceous fault zone that separates the Musandam Platform from the Dibba Zone (Figure 4c) and was reactivated as a normal fault; and (2) the Hagab Thrust. The outcrops in the study area consist of Middle to Upper Jurassic Musandam 2 and 3 formations, unconformably overlain by Cretaceous Thamama Group rocks (Figures 4c and 4e).

The study area near Al Khatt (Figure 4c) consists of NS-oriented ridges, which are parallel to the thrust front of the mountains (Figure 4d). The Upper Jurassic Musandam 3 Formation is overlain by lower Cretaceous Thamama Group limestones (Figures 4c and 4d).

**Northern Oman Mountains: A Special Case of Foreland Fold-and-Thrust Belt (FTTB)**

The northern Oman Mountains do not possess the structural architecture of a classical FTTB. The common development of a FTTB starts with the deposition of carbonates in a passive margin setting. Deformation by thrust emplacement of nappes of ophiolites and basinal domains propagates from the hinterland toward the foreland, thereby burying the carbonate reservoirs in a foredeep. Eventually the carbonates are tectonically accreted in the allochthonous units of the thrust belt and are uplifted and unroofed by erosional processes (Roure et al., 2005).

The beginning of the development of the northern Oman Mountains is in line with this general picture. The Musandam carbonate platform originated on the passive margin of the Arabian Plate and during late Cretaceous thrust emplacement, far-travelled palaeo-oceanic nappes were stacked on the Arabian passive margin. The flexural Aruma foreland basin developed due to tectonic loading and migrated to the west. The tectonic compression had ceased before the carbonate platform was taken into the orogen. However, it cannot be excluded that some of the shortening propagated forelandward with the development of basin inversion and deep structural closures. The major shortening of the Musandam Platform, however, took place in a second Cenozoic deformation phase coeval with the Neogene Zagros Orogeny. This time the carbonate platform series was accreted to the tectonic wedge with out-of-sequence propagation of Neogene thrusts toward the surface, which cut across the former basal contact of the Hawasina Nappes and Semail Ophiolite accretionary wedge.

**Subsurface and Hydrocarbon Scenarios in the Northern United Arab Emirates (UAE)**

In addition to industry profiles, deep seismic profiles across the foothills of the northern UAE were recently acquired by the Ministry of Energy (UAE, 2007). One of these profiles crosses the Dibba Zone just south of the Musandam carbonate outcrops (Figure 1). It shows evidence for a tectonic duplication of the Palaeozoic and Mesozoic series below the topographic culmination of the
Musandam Peninsula. The duplication resulted from a post-Cretaceous stacking of tectonic duplexes made up of the Arabian Platform (Figure 1). The basal contact of the upper carbonate unit is out-of-sequence. This relationship can be observed in the tectonic Hagil Window (Figures 1 and 3, section D-D’) located along the western side of the Musandam outcrops, where the Musandam carbonates are thrust directly on top of the Hawasina units along the Hagab Thrust.

In contrast, the precise location of the lateral facies change during the Jurassic and Cretaceous between the Musandam and Sumeini-type series, which have been underthrust beneath the Hawasina Nappes
and Semail Ophiolite allochthonous wedge in the Dibba Zone, cannot be determined unequivocally on seismic profiles. In an allochthonous hypothesis, with substantial shortening, the platform would extend to the east until the place where the ophiolites are involved in a wide nappes anticline, in a similar way as in Al Jabal al-Akhdar in Oman (Figure 1). A hypothesis with more limited shortening, places this facies change just east of the last Musandam outcrops (Figure 1).

The total amount of Neogene shortening in Arabian para-autochthonous units could amount up to a maximum of 30 km. Not all the deformation was transferred toward the foreland. The displacement at the front of the Hagab Thrust is only 15 km and the rest of the shortening is accounted for by backthrusting in the foredeep and out-of-sequence thrusting within the Sumeini-Hawasina allochthon.
Type II marine source rocks are well known in the Mesozoic platform series (Jurassic and Cretaceous), whereas more terrestrial type II-III source rocks occur in the upper Cretaceous – Palaeogene (Pabdeh) Foreland sequence (Beydoun and Dunnington, 1975; Blinton and Wahid, 1983; Hassan and Azer, 1985; Alsharhan and Nairn, 1991, 1997; Alsharhan and Kendall, 1991; Loufti and El Bishlawy, 1986; Beydoun, 1988, 1991, 1993; Alsharhan, 1991, 1997; Alsharhan and Nasir, 1996; Al-Husseini, 1997; Taher, 1997; Terken, 1999; Terken et al., 2000, 2001; Akrawi and Ayoub, 2000). These Mesozoic source rocks have been deeply buried beneath the flexural sequences of the northern UAE foredeep, and account for long range, lateral migration of oil toward the western offshore, i.e. the Arabian Gulf. However, questions remain as to the source rocks of the gas-condensate fields in the foothills (Sajaa and Margham fields; Figure 1). Were their hydrocarbons derived from eastward migration from the same sources in the foredeep, or from another source area farther to the east, in the distal portion of the Arabian margin, which is now underthrust beneath the allochthon?

The flexural deformation of the Arabian foreland due to tectonic loading by the Oman and the Zagros Mountains resulted in an asymmetric foredeep basin, which becomes deepest along the sea shore of Ras Al-Khaimah in the northern UAE. Therefore most of the hydrocarbons generated along the passive margin of Arabia have migrated towards the foreland in the southwest thus explaining why the major oil discoveries are located in offshore Abu Dhabi and Dubai (Alsharhan, 1989).

Figure 4: Geologic map and cross-sections of the southern outcrop locations. (a and b) Geologic map and cross-section of Jabal Gharaf (modified from Robertson et al., 1990); (c) Geologic map of Wadi Batha Mahani and Al Khatt (from Ellison et al., 2006); (d) Cross-section at Al Khatt (from Eilrich and Grötsch, 2003); and (e) Cross-section outcrop at Wadi Batha Mahani.
METHODS

In order to reconstruct the fluid system, sampling was concentrated on calcite- or dolomite-filled fractures and dolomites mostly in the vicinity of important faults and thrust zones. In the field, the fracture orientations were measured and the occurrence and density in relation to the distance from the main faults were studied (Breesch et al., 2009). Differences between the damage zone, hanging wall and the footwall of the faults were noted. Different generations of fractures were distinguished and their relative timing was determined by crosscutting relationships between each other and with stylolites. Finally, the orogenic phase to which these faults belong was determined based on the geological setting and the literature.

After polishing of rock samples, thin sections were prepared from selected samples. Polished rock samples and thin sections were stained with Alizarine Red S and potassium ferricyanide (Dickson, 1966). A total of 261 thin sections was studied under microscope with plane polarised transmitted light to establish their sedimentary facies and to identify diagenetic phases and crosscutting relations. Incident light was used for the study of opaque phases. Cathodoluminescence petrography was carried out on a Technosyn Cold Cathodoluminescence device model 8200, Mark II, operating at 10–16 kV gun potential, 200–400 µA beam current, 0.05 Torr vacuum and 5 mm beam width. Thin sections and wafers were excited by long-wavelength ultraviolet light (366 nm spectral line of Hg) in order to observe their fluorescence. Doubly polished sections (100–150 µm thick) were prepared for fluid inclusion (FI) microthermometry measurements on a Linkam THMSG 600 heating–cooling stage. The
stage was calibrated by measuring phase changes in synthetic fluid inclusions of known composition. Reproducibility of the final melting temperature ($T_{m}$) was within 0.2°C, and of the homogenisation temperature ($T_h$) within 2°C.

Carbonate powders for stable-isotope analysis were sampled using a drill with a bit of 0.3 mm in diameter. The powders were reacted with 100% phosphoric acid at 75°C using a Kiel III online carbonate preparation line connected to a ThermoFinnigan 252 mass spectrometer. Values are reported in per mil relative to VPDB. Reproducibility was checked by replicate analysis of laboratory standards and is better than 0.05 (1). The oxygen values for dolomite were corrected using the fractionation factors proposed by Rosenbaum and Sheppard (1986).

The following isotope values were reported in the literature for respectively early Cretaceous marine and Late Triassic to Early Jurassic marine carbonates. Early Cretaceous marine values fall within the range between -3 and -1‰ for $\delta^{18}O$ and between +1 and +3‰ for $\delta^{13}C$ (Grötsch et al., 1998). Marine values for the Cenomanian to Campanian range for $\delta^{18}O$ between -4 and -1‰ and for $\delta^{13}C$ between +1 and +3‰ (Veizer et al., 1999). More regional values from the literature can also be used for reference. Budd (1989) performed stable-isotope analyses on core samples of several wells in a Thamama reservoir in the Arabian Gulf. For the Barremian to Aptian Kharaih and Shu’aiba formations, average values vary between -4.5 and -6.0‰ for $\delta^{18}O$ and between +3.1 and +4.6‰ for $\delta^{13}C$. A well in Sharjah, UAE, was studied by Wagner (1990) resulting in $\delta^{18}O$ values of -5.0 to -3.0‰ and $\delta^{13}C$ values of +1.3 to +3.5‰ for limestones of the early Cretaceous. Carbonate rocks of the Muti Formation of Turonian to Santonian age from Al Jabal al-Akhdar in the Oman Mountains have $\delta^{18}O$ values between -7.2 and -2.4‰ and $\delta^{13}C$ values between +0.5 and +3.6‰ (Hilgers et al., 2006).

Norian calcarenites and calciturbidites of a slope setting in the Batin Plain of northeast Oman located at the southern Neo-Tethys margin, display $\delta^{18}O$ values between -9.2 and -4.1‰ and $\delta^{13}C$ values between -0.4 and +1.7‰ (Hauser et al., 2001). Tethyan values from the Alps and the Carpathians for the Norian to Rhaetian brachiopod and whole-rock carbonates vary for $\delta^{18}O$ between -3.0 and 0.0‰ and for $\delta^{13}C$ between +1.0 and +4.0‰ (Korte et al., 2005). Jurassic limestones from the literature show a range from $\delta^{18}O$ between -3.0 and 0.0‰ and for $\delta^{13}C$ between 0.0 and +4.0‰ (Jenkyns et al., 2002).

**DIAGENESIS AND FLUID FLOW**

**Timing of Diagenetic Stages based on Stylolite Development**

In carbonate-dominated foreland fold-and-thrust belts (FFT) worldwide, the paragenetic sequence can usually be subdivided into three relative time periods based on the existence of two sets of stylolites: a first set consisting of burial or bed parallel stylolitic planes (BPS) and a second set consisting of tectonic stylolites (TS; Ferket, 2004; Roure et al., 2005). The pre-BPS period corresponds to burial of the foreland to a depth of up to ca. 800 m when burial stylolites start developing. BPS can continue to develop during increasing burial up to even several kilometres in depth. The development of tectonic stylolites (TS) characterises the onset of tectonic deformation. The post-TS period can be subdivided into the syn- and post-deformation history of the orogen (Van Geet et al., 2002; Ferket et al., 2003; Swennen et al., 2003). After deformation, the strata may be subjected to a second burial cycle with development of a second generation of burial stylolites (Breesch et al., 2007). A renewed period of tectonic deformation with possible development of a second generation of tectonic stylolites may also occur.

**Observations and Data:** In the Musandam Peninsula two generations of burial stylolites developed (BPS1 and BPS2). Differentiation between them is very difficult since their development was more-or-less a continuous event. Other constraints such as distinct orientations or crosscutting relations with other time-constrained diagenetic products or structural features can however be used to differentiate between BPS1 and BPS2. The BPS2 formation thus represents a renewed stylolite development event and not a distinct event. Based on these criteria BPS1 and BPS2 were observed in the outcrops located in Wadi Bih and Wadi Sha’am, whereas in Wadi Ghalahileh only BPS1 and in Al Khatt only BPS2 are present. Tectonic stylolites with N-S strikes were observed in the Wadi Ghalahileh outcrop (Breesch et al., 2009). In the Dibba Zone, both burial stylolites (BPS) and tectonic stylolites (TS) were observed. The latter are characterised by a NE-SW orientation.
Interpretation: The occurrence of these different burial and tectonic stylolite generations is interpreted to be the consequence of the two tectonic deformation phases, which took place in the northern Oman Mountains. As for the burial stylolites in the Musandam Peninsula, the distinction between BPS1 and BPS2 is based on the burial evolution in the study area compared with the minimum depth of stylolite development. BPS1 was formed when the platform deposits were buried deep enough (800 m or more). The second generation of burial stylolites (BPS2) originated from the burial due to the nappe emplacement on the Arabian Platform in the late Cretaceous. The NS-oriented tectonic stylolites are perpendicular to the maximum principal stress and occurred during Cenozoic compression (Searle, 1988b). They are interpreted to have originated from this compressional phase during movement of the platform along the Hagab Thrust.

In the Dibba Zone, burial stylolites could have developed since burial in the Sumeini slope deposits (Jabal Gharaf) exceeded 800 m. The Mayhah Formation is approximately 700 m thick and was covered by 100 to 300 m of the Muti Formation (Phillips et al., 2006). The NE-SW orientation of the tectonic stylolites, which are present in the Dibba Zone can be related to the late Cretaceous compressive deformation with a principal stress direction oriented NW-SE.

In the Musandam Peninsula, no tectonic stylolites related to the late Cretaceous deformation were observed. This is probably because no thrust faults propagated into the Musandam Platform since the area was not taken into the orogen at that time. This implies that the deformation was limited to the far-travelled tectonic nappes (including the Sumeini and Hawasina nappes and Semail Ophiolite) and that decoupling may have separated these nappes and the underthrusted Musandam foreland. The diagenetic influence of the late Cretaceous deformation on the Musandam Peninsula was restricted to deep burial due to the nappe emplacement.

Based on the occurrence of burial and tectonic stylolites and the prevailing diagenetic environment, the paragenesis of respectively the Musandam platform carbonates (Figure 5) and the Sumeini slope carbonates (Figure 6) can be generalised and subdivided into four diagenetic periods:

1. pre-BPS1 eogenetic,
2. post-BPS to pre-TS mesogenetic,
3. post-TS syn-tectonic, and
4. post-deformation.

Although these four diagenetic periods are the same for both areas, their age relative to the tectonic events is fundamentally different (compare timeline in Figures 5 and 6). The paragenesis of the Permian – Jurassic platform carbonates and deep-water lower Cretaceous carbonates in the Musandam Peninsula does not differ fundamentally and is discussed together. The paragenesis of the Sumeini slope carbonates from the Dibba Zone, however, is slightly different and the timing and relation with the tectonic deformation differs completely.

PARAGENESIS OF THE MUSANDAM PLATFORM AND SUMEINI SLOPE CARBONATES

Pre-BPS1 Eogenetic Period

Observations and Data: Finely crystalline host-rock dolomites (Figure 8a) with microbial crinkle laminations and fenestrae were observed in an alternating succession of dolomite and limestone in the Musandam 2 and 3 formations in the outcrop locations of Wadi Batha Mahani and Wadi Sha’am (Table 1). These non-ferroan dolomites are characterised by orange to red cathodoluminescence (Figure 8b) and display similar $\delta^{18}O$ values as the adjacent host rock limestones, with values between -2 and -7‰ and slightly more negative $\delta^{13}C$ values between 0 and -3‰ (Figure 7.1).

Few real fracture-shaped veins originate from this period in the northern UAE (Table 1; Figures 5 and 6). Examples of these veins can be found in different formations in different outcrops, i.e. in the Mayhah Formation in Jabal Gharaf (Table 1; Figure 8c), in the Thamama Group carbonates in
Al Khatt and in the hanging and footwall rocks of the Ghalilah Formation and the Thamama Group in Wadi Ghalilah (Breesch et al., 2009; Figure 8d). The pre-BPS diagenetic veins are usually thin and sometimes composed of several veinlets or stockwork veins with elongated blocky to fibrous cement morphology and crystals spanning the whole width of the vein (Figure 8d). In some cases the crystals are stretched and have serrated crystal boundaries (Figure 8c) Most of these veins display dull cathodoluminescence similar to their host rocks. The stable-isotope values of these pre-BPS veins plot in two clusters (δ13C between +1 and +3.5‰ and δ18O between -2.5 and -6.5‰; δ13C between -1.5 and 0‰ and δ18O between -8.5 and -7‰), which coincide with their respective δ13C host rock signatures but have slightly more depleted δ18O values (Figures 7.1, 7a, 7c and 7d).

Figure 5: Generalised paragenetic sequence and burial curve of the Musandam Platform carbonates, related to the tectonic deformation in the area.

Al Khatt and in the hanging and footwall rocks of the Ghalilah Formation and the Thamama Group in Wadi Ghalilah (Breesch et al., 2009; Figure 8d). The pre-BPS diagenetic veins are usually thin and sometimes composed of several veinlets or stockwork veins with elongated blocky to fibrous cement morphology and crystals spanning the whole width of the vein (Figure 8d). In some cases the crystals are stretched and have serrated crystal boundaries (Figure 8c) Most of these veins display dull cathodoluminescence similar to their host rocks. The stable-isotope values of these pre-BPS veins plot in two clusters (δ13C between +1 and +3.5‰ and δ18O between -2.5 and -6.5‰; δ13C between -1.5 and 0‰ and δ18O between -8.5 and -7‰), which coincide with their respective δ13C host rock signatures but have slightly more depleted δ18O values (Figures 7.1, 7a, 7c and 7d).
The fluid analysed in fluid inclusions in vein calcites in the Ghalilah Formation in the hanging wall of Wadi Ghalilah is characterised by low marine salinities (2.9 to 5.9 wt% NaCl; Table 1) and elevated homogenisation temperatures due to stretching (H$_3$ white-yellow veins in Wadi Ghalilah; Breesch et al., 2009; Table 1).

Dissolution with subsequent geopetal infill and microsparitisation of the shallow-marine deposits of the northern situated Ghalilah, Milaha and Musandam 1 formations is observed. The lower part of the Ghalilah Formation in Wadi Bih contains nodular limestones and hardground surfaces with soil-related nodules (Figure 8e). These nodules have approximate $\delta^{18}$O and $\delta^{13}$C values of -5.5 and -6‰ (Figures 7.1 and 7e). Apart from nodules, vugs filled with sediments also occur. The limestones were also partially to completely microsparitised. In Wadi Sha’am the pellets and intraclasts of the intraclastic grainstone and the micrite of the mudstones of the Musandam 1 Formation have been microsparitised. In these rocks numerous molds with brown-coloured geopetal infill are present (Figure 8f).

Limestone dissolution and precipitation of radiaxial fibrous calcite cement within geodes and nodules has been observed in the Musandam 2 and 3 formations in Wadi Batha Mahani (calcite precipitates in Table 1). These non-ferroan calcite precipitates display complex cathodoluminescence zonations and are characterised by negative values for $\delta^{18}$O and $\delta^{13}$C (respectively between -8.2 and -3.8‰ and between -11.0 and -3.8‰; Figures 7.1 and 7b).
**Table 1:**
Summary of the characteristics of the diagenetic products from the different time periods and outcrop locations in the Musandam Peninsula and Dibba Zone including structural texture, microscopic texture, composition, cathodoluminescence characteristics,

<table>
<thead>
<tr>
<th>Location</th>
<th>Structural Texture</th>
<th>Host rock Formation</th>
<th>Microscopic Texture</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-BPS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synsedimentary dolomite</td>
<td>WBM</td>
<td>Breccia fragments and matrix</td>
<td>Musandam 2 and 3 fms</td>
<td>Planar-s</td>
</tr>
<tr>
<td>Host-rock dolomite</td>
<td>WS</td>
<td>Host rock dolomitisation</td>
<td>Musandam 1 Fm</td>
<td>Xenotopic dolomudstone- cloudy idiotopic-s</td>
</tr>
<tr>
<td>Irregular grey calcite veins</td>
<td>JG</td>
<td>Stockwork veins, matrix of synsedimentary breccias</td>
<td>Mayhah Fm</td>
<td>Elongated blocky to fibrous</td>
</tr>
<tr>
<td>Grey calcite cement</td>
<td>Al Khatt</td>
<td>Thin fractures and molds of gastropods and corals</td>
<td>Thamama Group</td>
<td>Blocky to elongated blocky</td>
</tr>
<tr>
<td>Hanging wall veins:</td>
<td>WG</td>
<td></td>
<td>Ghailah Fm</td>
<td></td>
</tr>
<tr>
<td>H1 orange to brown calcite veins</td>
<td></td>
<td>Fracture-shaped veins</td>
<td>Brown twinned elongated blocky</td>
<td>Ferroan cc</td>
</tr>
<tr>
<td>H2 grey calcite veins</td>
<td></td>
<td>Fracture-shaped veins</td>
<td>Blocky crystals with dense mechanical twinning</td>
<td>Non-ferroan cc</td>
</tr>
<tr>
<td>H3 white-yellow calcite veins</td>
<td></td>
<td>Horstail-shaped veins with several veinlets</td>
<td>Elongated crystals spanning veinlets broken smaller crystals with twins in the centre</td>
<td>Ferroan cc</td>
</tr>
<tr>
<td>F1 white calcite footwall veins</td>
<td></td>
<td>Ein-echelon arrays of veinlets</td>
<td>Thamama Group</td>
<td>Blocky to fibrous crystals</td>
</tr>
<tr>
<td>Calcite precipitates</td>
<td>WBM</td>
<td>Geodes and nodules</td>
<td>Musandam 2 and 3 fms</td>
<td>Radial fibrous</td>
</tr>
<tr>
<td><strong>Post BPS to Pre TS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown calcite veins</td>
<td>Al Khatt</td>
<td>Breccia veins with floating host rock fragments</td>
<td>Thamama Group</td>
<td>Rhambohedral to baroque crystals + dark brown rim with sweeping extinction</td>
</tr>
<tr>
<td>Yellow brown dolomite- calcite veins</td>
<td>WB</td>
<td>Fracture-shaped veins</td>
<td>Ghailah Fm</td>
<td>Xenotopic-A</td>
</tr>
<tr>
<td>White-brown calcite-dolomite veins</td>
<td>WS</td>
<td>Fracture-shaped veins and molds and vugs</td>
<td>Musandam 1 Fm</td>
<td>Cloudy coarse saddle dolomite, sweeping extinction</td>
</tr>
<tr>
<td>White calcite veins with quartz</td>
<td>JG</td>
<td>Congulate system of en echelon vein arrays</td>
<td>Ausaq Fm</td>
<td>Elongated blocky to blocky</td>
</tr>
<tr>
<td>White calcite cement</td>
<td>Al Khatt</td>
<td>Centre of brown veins or large fractures in centre fault zone</td>
<td>Thamama Group</td>
<td>Blocky to sparry mm-sized crystals with abundant mechanical twins and clear cleavage planes</td>
</tr>
<tr>
<td>White calcite veins</td>
<td>WB</td>
<td>Fracture-shaped veins</td>
<td>Ghailah Fm</td>
<td>Elongated blocky+ fine crystalline blocky crystals</td>
</tr>
<tr>
<td>F2 white calcite footwall veins</td>
<td>WG</td>
<td>Fracture-shaped veins</td>
<td>Thamama Group</td>
<td>Extensive mechanical twinning</td>
</tr>
<tr>
<td><strong>Post TS syntectonic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibrous brown calcite veins</td>
<td>JG</td>
<td>Breccia matrix cement, slickensides, stockwork veins, fracture-shaped veins</td>
<td>Fault zone Mayhah/ Shamal Chert Fm</td>
<td>Elongated to fibrous + dark brown blocky</td>
</tr>
<tr>
<td>F3 white calcite footwall veins</td>
<td>WG</td>
<td>Within tectonic stylolites</td>
<td>Thamama Group</td>
<td>Large blocky crystals</td>
</tr>
<tr>
<td>F5 white calcite footwall veins</td>
<td>WG</td>
<td>En echelon and fracture-shaped veins</td>
<td>Thamama Group</td>
<td>Border: veinlets with elongated blocky crystals</td>
</tr>
<tr>
<td>Stockwork veins</td>
<td>WG</td>
<td>Stockwork microfractures</td>
<td>Thamama Group</td>
<td>Centre: fine crystalline brecciated calcite</td>
</tr>
<tr>
<td>Dolomite recrystallisation and cement</td>
<td>WBM</td>
<td>Thin border around breccia clasts, in pores, as clusters</td>
<td>Musandam 2 and 3 fms</td>
<td>Calcite with abundant mechanical twins</td>
</tr>
<tr>
<td>Quartz cement and silification</td>
<td>WBM</td>
<td>Interbreccia fragment pores</td>
<td>Musandam 2 and 3 fms</td>
<td>Fine-crystalline</td>
</tr>
<tr>
<td>Host rock dolomite</td>
<td>WB</td>
<td>Host rock dolomitisation</td>
<td>Milaha Fm</td>
<td>Fine-crystalline idiotopic-S</td>
</tr>
<tr>
<td>Pink dolomite cement</td>
<td>WB</td>
<td>Cavities and parallel fractures</td>
<td>Milaha Fm</td>
<td>Xenotopic-C saddle dolo with undulose extinction</td>
</tr>
<tr>
<td>Dolomite recrystallisation and cement</td>
<td>WS</td>
<td>In dolomite host rocks, vug fillings</td>
<td>Musandam 1 Fm</td>
<td>Euhedral to slightly baroque</td>
</tr>
<tr>
<td><strong>Post deformation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow calcite veins</td>
<td>JG</td>
<td>Long continuous fracture-shaped veins</td>
<td>Mayhah and Ausaq Fm</td>
<td>Blocky to elongated blocky</td>
</tr>
<tr>
<td>Fibrous calcite veins</td>
<td>WBM</td>
<td>Fracture-shaped veins</td>
<td>Musandam 2 and 3 fms</td>
<td>Fibrous to elongated blocky</td>
</tr>
<tr>
<td>Calcite speleothems</td>
<td>WBM</td>
<td>Fractures</td>
<td>Musandam 2 and 3 fms</td>
<td>Alternating radial fibrous and blocky crystals</td>
</tr>
<tr>
<td>Black calcite cement</td>
<td>Al Khatt</td>
<td>Dispersed in host rocks and in remaining pores in fractures</td>
<td>Thamama Group</td>
<td>Fine-crystalline, slightly rounded, few twins</td>
</tr>
<tr>
<td>White calcite cement</td>
<td>WB</td>
<td>Cavities and parallel fractures</td>
<td>Milaha Fm</td>
<td>Large sparry crystals</td>
</tr>
<tr>
<td>White calcite cement</td>
<td>WS</td>
<td>Vugs and molds</td>
<td>Musandam 1 Fm</td>
<td>Blocky</td>
</tr>
</tbody>
</table>
Table 1: (continued) microthermomentry measurements and stable-isotope results. Abbreviations: $T_h$ = homogenisation temperature; $T_{fr}$ = freezing temperature; $T_{fm}$ = temperature of first melt; $T_{m\ ice}$ = temperature of last melt of ice; $T_{hh}$ = temperature of melt of hydrohalite.

<table>
<thead>
<tr>
<th>CL Characteristics</th>
<th>Fluid Inclusions (°C)</th>
<th>Stable Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_h$</td>
<td>$T_{fr}$</td>
</tr>
<tr>
<td>Orange to pink zoned red-yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orange to red with bright red overgrowths</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dull yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dull orange with sector zonation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dull brown and yellow luminescent zones</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow to dull</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark brown to non luminescent</td>
<td>(131 to 175)</td>
<td>-50 to -33</td>
</tr>
<tr>
<td>Dark dull</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex zonations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very fine bright- non zonations non luminescent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark brown with yellow patches</td>
<td>(75 to 146)</td>
<td>-72 to -55</td>
</tr>
<tr>
<td>Non luminescent</td>
<td>-43 to -42</td>
<td>-19</td>
</tr>
<tr>
<td>Dull orange with luminescent twin planes</td>
<td>124 to 174</td>
<td>-70 to -55</td>
</tr>
<tr>
<td>Dull</td>
<td>115 to 226</td>
<td>-40.2 to -34.1</td>
</tr>
<tr>
<td>Quartz: non</td>
<td>122 to 209</td>
<td>-41.2 to -35.7</td>
</tr>
<tr>
<td>Dull brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dull orange finely zoned to sector zoned</td>
<td>(75 to 165)</td>
<td>-59 to -56</td>
</tr>
<tr>
<td>Dull to non luminescent</td>
<td>-43 to -41</td>
<td>-1.4 to -0.9</td>
</tr>
<tr>
<td>Bright orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dull to non luminescent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dull with zonations and yellow spots</td>
<td>81 to 166</td>
<td>-95 to -68</td>
</tr>
<tr>
<td>Non luminescent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) purple to non and 2) pink to yellow phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non luminescent</td>
<td>100 to 250</td>
<td>-35 to 32</td>
</tr>
<tr>
<td>Dark red</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark red cores- bright non zoned rims</td>
<td>139 to 193</td>
<td>-75 to -63</td>
</tr>
<tr>
<td>Red core and red zoned rim- red overgrowths</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bright orange with yellow spots</td>
<td>(155 to 286)</td>
<td>-41.3 to -34.1</td>
</tr>
<tr>
<td>Dull orange growth zoning</td>
<td>120 to 200</td>
<td>-45 to -37</td>
</tr>
<tr>
<td>Non luminescent-bloody dull orange</td>
<td>60</td>
<td>-43 to -39.5</td>
</tr>
<tr>
<td>Large-scale bright-non luminescent zoning</td>
<td>-46 to -39</td>
<td>-0.6 to 0</td>
</tr>
<tr>
<td>Non lum border and large orange zonations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrily zoned bright phase-non lum phase</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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See facing page for Figure 7 caption.
Interpretation: The fine-crystalline host rock dolomites are interpreted as pene-contemporaneous or syn-sedimentary dolomites resulting from dolomitisation of the carbonate platform in shallow-marine to sabkha conditions. This interpretation is mainly based on their microbial textures and their alternation with limestone layers (Breesch et al., 2010).

The observation that the pre-BPS calcite veins in the study area consists of different veinlets and the microscopic textures of the veins are characteristic for the crack-seal vein forming mechanism (Bons, 2000, 2001). Crack-seal veins as defined by Ramsay (1980) are veins that originate from successive cracking and sealing of a fracture. The calcite cement is interpreted to have been precipitated by a locally derived, slightly heated probably marine fluid based on the following: (1) timing early in diageneconomy before BPS development took place, (2) host-rock buffered dull cathodoluminescence, (3) host-rock buffered stable-isotope values, and (4) the marine salinities of the fluid inclusions.

The horizons with soil nodules in the Ghalilah Formation represent emersion periods. During these intervals meteoric water could have infiltrated the rocks resulting in karstification, which caused dissolution, vug formation and microsparitisation. The radiaxial calcite nodule precipitation in Wadi Batha Mahani is also a result of karstification and subsequent cementation (Breesch et al., 2006). This interpretation is supported by the negative isotope values of the precipitates. There are two possible scenarios for this mid Cretaceous emersion phase. In the first scenario, the emersion is related to the migration of a flexural forebulge over the platform due to tectonic loading during the Turonian – Campanian. The other scenario implies a Cenomanian foreland inversion (Callot et al., 2010). In this study no evidence supporting either of those scenarios was found.
Comparison with Literature: These results are consistent with data from the literature. The presence of crack-seal veins during the pre-BPS period is consistent with the predicted development of hydraulic fractures due to overpressures during dewatering and compaction prior to thrust loading (Roure [10]).

Figure 8: Typical diagenetic products from the pre-BPS period in the Musandam Peninsula and Dibba Zone.

(a and b) Fine-crystalline synsedimentary dolomite with orange dull luminescent cathodoluminescence in the Musandam Formation, Wadi Batha Mahani.

(c) Early crack-seal vein displaying elongated calcite crystals with serrated borders in the Mayah Formation in Jabal Gharaf.

(d) Crack-seal vein characterised by several veinlets and chaotic calcite crystals from the Ghalilah Formation in the hanging wall of the Wadi Ghalilah outcrop.

(e) Soil nodules near an emersion surface in the Ghalilah Formation in Wadi Bih.

(f) Molds within the Musandam 1 Formation in Wadi Sha‘am.
Post-BPS to pre-TS Mesogenetic Period

In the Musandam Peninsula this diagenetic period is confined between the BPS1 and TS developments. It also comprises the period between the formation of the two burial stylolite generations BPS1 and BPS2 (Figure 5). In the Dibba Zone there is only one generation of BPS (Figure 6). Since burial stylolites are considered to start forming at a burial depth of 800 m (Finkel and Wilkinson, 1990; Railsback, 1993), the BPS generations in outcrops of different formations could be of different ages.

Observations and Data: Common diagenetic products of the post-BPS to pre-TS period in the northern UAE are the brown veins with ferroan saddle dolomite fill. Major parts of this fill have been partially to completely calcified (Figures 9a and 9b) in a later stage. These ferroan dolomites or calcites are present as mainly brown calcite veins in the Thamama Group in Al Khatt (Figure 9a), yellow-brown dolomite-calcite veins in the Ghalilah Formation in Wadi Bih and the saddle dolomite fill in the white-brown calcite-dolomite veins in the Musandam 1 Formation in Wadi Sha’am (Figure 9b) in the Musandam Peninsula (Table 1). The veins themselves are fracture-shaped or breccia veins. The dolomite crystals are often characterised by a saddle or baroque morphology (Figures 9a and 9b) and are sometimes rather cloudy or with brown, rimmed crystals and with sweeping extinction (Table 1). These ferroan dolomites are dull to non-luminescent due to their high iron content. When replaced by calcite, these crystals show fine bright non-cathodoluminescence zonations (in Al Khatt; Table 1).

Most of the samples for isotope analyses were composed of calcite. Seven samples of ferroan dolomite from Wadi Sha’am were analysed for oxygen and carbon resulting in a range for δ¹⁸O between -8.9 and -5.2‰ and for δ¹³C between -1.8 and +0.3‰ (Figures 7.2; 7f; Table 1). The calcified saddle dolomite samples show some quite varied, depleted stable-isotope signatures in the different locations where they occur (with δ¹⁸O values between -13 and -5‰ and δ¹³C between -7 and 0‰; Figure 7.3). Some of the samples have similar signatures as the ferroan dolomite samples but others more specifically in Al Khatt display an alteration trend towards depleted δ¹³C values. The original isotope signatures were altered by the calcification of the dolomites and therefore the values are plotted with the telogenetic phase in Figure 7c (interpretation see further in this paper). The fluid composition could be determined by measuring melting temperatures of primary fluid inclusions in the partly calcified ferroan dolomites in Wadi Bih. The large range in last melting temperatures of both hydrohalite and ice however did not allow calculating a narrow salinity range. The fluid has a H₂O-NaCl-CaCl₂ composition with high but variable salinities (Table 1). The homogenisation temperatures varied much between 75 and 146°C (Table 1). A second system with secondary fluid inclusions was measured as a low saline (0.88 to 1.74 wt%) H₂O-NaCl fluid (Table 1).

The veins with ferroan saddle dolomite fill are crosscut by a second type of veins, which originates from the pre-TS period in the northern UAE. Examples of these white calcite veins can be found in Al Khatt, Wadi Bih (Figures 9c and 9d), Wadi Ghalilah and in Wadi Sha’am as the second fill of the white-brown calcite-dolomite veins in the Musandam 1 Formation (Table 1). In Jabal Gharaf these veins are white en-echelon calcite veins in vein arrays at angles of up to 55°, where calcite is accompanied by quartz cement (Figures 9e and 9f). The common features of the white calcite veins in the different locations are their fracture-shape and coarsely crystalline blocky to elongated blocky calcite morphology with abundant mechanical calcite twins (Figures 9c, 9d and 9f; Table 1). Their cathodoluminescence is mostly dull with some zonations (Table 1). The isotope trends of the pre-TS veins seem to be location or formation dependent. The δ¹³C values of the white calcite veins are similar to the host rocks in Jabal Gharaf-Al Khatt, Wadi Bih and Wadi Sha’am (Figures 7.1 versus 7.2; Figures 7a, 7c, 7e and 7f; Table 1). In Jabal Gharaf-Al Khatt, the δ¹⁸O values show a trend from between -2 to -4‰ towards depleted oxygen values up to -9‰. The oxygen values of the white calcite veins in the Ghalilah Formation in Wadi Bih are depleted and vary between -10 and -14‰ (Figure 7.2; Table 1) whereas the δ¹⁸O values of the calcite fill in Wadi Sha’am varies between -6.2 and -3.3‰ (Table 1; Figures 7.2 and 7f).
Figure 9: Typical diagenetic products from the post-BPS to pre-TS period in the Musandam Peninsula and Dibba Zone.
(a) Fracture cemented by calcified dolomite crystals with relics of ferroan saddle dolomites from the Al Khatt outcrop.
(b) Dark brown calcified dolomite crystal from Wadi Sha’am.
(c and d) Burial calcite vein with coarse-crystalline elongated blocky texture and abundant mechanical calcite twins when viewed under crossed polars from the Wadi Bih location.
(e) Outcrop picture of a conjugated set of en-echelon calcite-filled shear veins in the Ausaq Formation, Jabal Gharaf.
(f) Elongated blocky texture of the en-echelon shear veins in the Ausaq Formation under crossed polars. Quartz crystals are associated with this generation.
Fluid inclusions were measured in the white calcite cement in Wadi Sha’am and Wadi Bih. The measured fluid is a H$_2$O-NaCl system, with rather high temperatures (from 124°C up to 174°C) and moderate salinities in Wadi Bih (around 6 wt%; Table 1) to high salinities in Wadi Sha’am (up to 23 wt%; Table 1). Measurements on secondary inclusions in the white calcite cement in Wadi Bih resulted in low salinities from 1.57–2.41 wt% (Table 1). The authigenic quartz cement (Figure 9f) is restricted to the white *en-echelon* veins of the Sumeini slope carbonates in the Dibba Zone. Microthermometry of fluid inclusions in both the calcite and the quartz crystals resulted in a low salinity (1.74–2.74 wt%) H$_2$O-NaCl fluid with high homogenisation temperatures (range of $T_h$ = 115–226°C; Table 1).

**Interpretation:** For the ferroan saddle dolomites, rather high temperatures (minimum 60–80°C) can be invoked based on their depleted oxygen isotopes and their baroque dolomite crystal form (Radke and Mathis, 1980; Spötl and Pitman, 1998; Davies and Smith, 2006). Homogenisation temperatures showed a large range (75–146°C; Table 1) and were not considered reliable and especially the higher values. Only the results from the primary fluid inclusions in the ferroan dolomites will be considered here since the results from the secondary fluid inclusions belong to the discussion about the calcification of the dolomites in the next sections. The dolomitising fluid has a H$_2$O-NaCl-CaCl$_2$ composition with high but variable salinities and is most likely a formation fluid. The source and transport mode of this warm formation fluid are not clear. The dolomite precipitation and hence the volume of fluid was rather limited since it is only present as one type vein infill. A possibility is that the Mg/Ca ratio and the iron content of the precipitating fluids increased due to precipitation of iron-poor calcite cements. Another hypothesis for the source and transport mode of the fluid is that saline, magnesium and iron-rich fluids infiltrated along extensional fractures from the Sumeini and Hawasina nappes thrust on top of the platform where they interacted with magnesium-rich mafic rocks. Iron-rich fluids could also derive from Palaeozoic or Neoproterozoic to lower Cambrian siliciclastic series, whereas Mg could derive from Neoproterozoic to lower Cambrian, Permian or even Jurassic evaporites and salt.

The isotope data of the calcified ferroan saddle dolomites in Al Khatt, Wadi Bih and Wadi Sha’am resulted in a complex spread of values (Figure 7.3), which is probably caused by the calcification of the original dolomites. Therefore these results will be discussed with the telogenetic phase.

The second generation of veins from the pre-TS period (i.e. the fracture-shaped white calcite veins) are interpreted as burial veins based on their petrographic and stable-isotope characteristics. In the Dibba Zone these burial veins are shear-related due to their occurrence as a conjugate set of *en-echelon* fractures.

The temperature of the fluids responsible for calcite precipitation in burial veins depends on the burial depth. The differences in oxygen-isotope values in the different locations can therefore be explained as burial and thus temperature dependent. Veins in the Upper Triassic Ghalilah Formation might have been buried deeper and therefore have had higher precipitation temperatures than veins in the Upper Jurassic or Cretaceous formations in the other outcrops. The trend towards depleted values in Jabal Gharaf-Al Khatt (Figure 7.2) can be interpreted to relate to temperature fractionation due to increasing temperatures during burial. The carbon-isotope signatures of the veins are probably host-rock buffered since they are similar to the host-rock values. Moreover carbon tends to be easily host-rock buffered since the incorporated carbon originates mainly from the carbonate rocks (Moore, 2001) and temperature fractionation is not an important factor (Anderson and Arthur, 1983).

The moderate to high salinities of the fluid either originated from evaporated seawater or are derived from interaction with evaporites. Here again only the primary inclusions were considered. The low-salinity fluid measured in the Jabal Gharaf calcite and quartz crystals could represent infiltration of a meteoric fluid. Alternatively it could result from dilution of more saline fluids. Dilution typically occurs when water is released during metamorphic reactions, clay reactions (smectite-illite transformation) or clay dewatering (Boles and Franks, 1979). One of these processes could have taken place in the shaley Hawasina units.
Comparison with Literature: The results from the northern UAE appear to be in conflict with diagenetic features described in the literature. According to Swennen et al. (2003) the post-BPS to pre-TS veins are often characterised by hydraulic and crack-seal fracturing due to the pressure buildup and fluid release at the onset and during the first episodes of tectonic compression. With increasing tectonic stress, the host rocks are compacted and layer-parallel shortening structures such as tectonic stylolites develop (Andrews and Railsback, 1997; Roure et al., 2005). In several FFTB settings, these hydraulic and crack-seal fractures are observed prior to TS development (e.g. Van Geet et al., 2002; Swennen et al., 2003; Ferket et al., 2004; Guilhaumou et al., 2004). These veins are often host-rock buffered with respect to oxygen and carbon isotopes but in some cases the $\delta^{18}O$ is depleted compared with the host rocks due to a temperature fractionation effect.

In the northern UAE no hydraulic and crack-seal fractures, which are formed between BPS and TS development, have been observed during mesogenesis. These types of veins have been observed in most studied outcrops but they date from the later post-TS syn-tectonic time period (see next section). The lack of hydraulic fractures in the mesogenetic post-BPS to pre-TS period is likely due to the dominantly carbonate lithology of the Musandam Platform. The carbonates could have prevented overpressures to develop before an efficient seal (the Sumeini-Hawasina allochthon) was tectonically emplaced on top of the platform (Callot et al., 2010).

The occurrence of ferroan saddle dolomites is favoured in deep burial environments with elevated temperatures in most case studies reviewed by Radke and Mathis (1980), Spötl and Pitman (1998) and Davies and Smith (2006). They are however not characteristic for FFTB's or certain diagenetic time periods. Dewever et al. (2010) report similar syn-tectonic ankerite and iron-rich dolomite precipitated during compressive deformation in a cavity system in the Sicilian FFTB. This system acted as a high-permeability conduit along which warm aqueous fluids and hydrocarbons migrated, contemporaneous with migration of identical fluids along thrusts.

Post-TS Syn-tectonic Period
The development of tectonic stylolites is normally concurrent with the onset of deformation and the post-TS period can be subdivided in a syn-tectonic or syn-deformation period and a post-deformation period. The tectonic stylolites from the outcrops in the Musandam Peninsula date from the Cenozoic deformation phase (Figure 5), whereas the development of tectonic stylolites in the Dibba Zone is coeval with the onset of the late Cretaceous deformation (Figure 6).

Observations and Data: The veins from the post-TS syn-tectonic period in the Musandam Peninsula are represented by a variety of morphologies such as breccia veins, breccia cements, hydrofractures, stockwork veins and slickenfibres (Table 1; Figures 10a and 10b). Typical examples of this vein type are the stockwork veins in the fault core (Figure 10a) and the veins in the Thamama Group rocks in the footwall in Wadi Ghalilah (Breesch et al., 2009) as well as fibrous brown veins, which are restricted to the fault zone in Jabal Gharaf (Figure 10b). The calcite fill is often characterised by mechanical twins and by veinlets with elongated blocky cements separated by inclusion bands (Figures 10c and 10d). The $\delta^{18}O$ isotope values of the calcite cements in Wadi Ghalilah vary between -6.7 to -3.8‰ whereas the $\delta^{18}O$ of the calcite in the fibrous brown veins of the Jabal Gharaf fault zone are more depleted ranging from -12.3 to -5.9‰ (Figures 7a and 7d and syn-tectonic veins in 7.3). The $\delta^{13}C$ values are similar to the host rock values but with a trend to more negative values for the brown fibrous calcite veins (Figure 7a). Microthermometry on the fluid inclusions present in the F5 calcite footwall veins in Wadi Ghalilah revealed a fluid with a H$_2$O-NaCl-CaCl$_2$ composition, high homogenisation temperatures (81–166°C; Table 1; Breesch et al., 2009).

Another diagenetic phase from this time period are non-ferroan dolomites (Figure 5). Most of these dolomites replace host-rock limestones, such as the host-rock dolomitisation of the Milaha Formation in the fault zone (footwall side) of a reverse fault in Wadi Bih (Figure 10e; Table 1). They also replace earlier dolomites as in the dolomite recrystallisation of syn-sedimentary dolomites and dolomite breccias in the Musandam Formation in Wadi Batha Mahani (Breesch et al., 2006; 2010) and in Wadi Sha’am (Figure 10f). In Wadi Bih and Wadi Sha’am, some minor dolomite cements are also present (Figure 10e). The non-ferroan dolomites in Wadi Bih and Wadi Sha’am display $\delta^{13}C$ values similar to the host rock but with a range of negative $\delta^{18}O$ values between -11.5 and -6.3‰ (Figures 7.3, 7e
The data from the dolomites in Wadi Batha Mahani show a covariant trend for δ¹³C and δ¹⁸O with depleted values up to -8.5 and -9.9‰, respectively, for the recrystallised dolomites (Figures 7.3 and 7b). The dolomitising fluid could be characterised by measuring fluid inclusions in non-ferroan pink dolomite cement the Milaha Formation, Wadi Ghalilah with a phase of veinlets separated by parallel inclusion bands and a second phase with broken crystals.

Figure 10: Typical diagenetic products from the post-TS syntectonic period in the Musandam Peninsula and Dibba Zone.

(a) Stockwork veins in the fault damage zone of the reverse fault in Wadi Ghalilah.

(b) Brown syntectonic calcite generation present in fault breccias or as stockwork veins in the Mayhah Formation, Jabal Gharaf.

(c and d) Syn-tectonic crack-seal vein in Thamama Group rocks in the footwall in Wadi Ghalilah with a phase of veinlets separated by parallel inclusion bands and a second phase with broken crystals.

(e) Replacive dolomites and saddle dolomite cement in the Milaha Formation, Wadi Bih.

(f) Dolomite mud infill in a BPS zone, recrystallised to a coarse-crystalline dolomite phase in Wadi Sha’am.
ice) at high temperatures of at least 139 up to 193°C (Table 1). In Wadi Batha Mahani dolomitisation is associated with silicification and quartz cementation. The oxygen-isotope measurements on the quartz cement resulted in $\delta^{18}O$ values between 18.46 and 20.60‰ SMOW (Table 1) with a mean of 19.06‰ SMOW. Fluid inclusion evidence from the quartz indicates dolomitisation by a $H_2O-NaCl-(KCl)$ fluid with high homogenisation temperatures ($T_h = 100–250°C$; Table 1). The $\delta^{18}O$ composition of the dolomitising fluid was calculated using the mean $\delta^{18}O$ value of the quartz cement and an average temperature of 174°C using the fractionation equation of Clayton et al. (1972) and resulted in +5.6‰ V-SMOW.

**Interpretation:** The above described macroscopic vein textures of the post-TS veins range from breccia veins, breccia cements, hydrofractures, stockwork veins and slickenfibres. They are mostly found in or associated with fault zones. The microscopic texture of the calcite fill in the veins is characterised by mechanical twins and by veinlets with elongated blocky cements separated by inclusion bands (Figures 10c and 10d). All these characteristics are typical for syn-tectonic hydrofractures and crack-seal veins, which can be interpreted to originate in high fluid-pressure systems (Ramsay, 1980; Bons, 2000).

The quite depleted oxygen-isotope signatures combined with host-rock buffered carbon-isotope signatures are characteristic for temperature fractionation and thus point towards increased precipitation temperatures. The measurements on the fluid inclusions in some of the calcite veins also resulted in high formation temperatures with $T_h$ between 81 and 166°C (Table 1) and high salinities exceeding 20 wt% (Table 1; Breesch et al., 2009). The isotope and microthermometry results can therefore be explained by sourcing of warm, saline fluids.

The host-rock dolomitisation and non-ferroan dolomite cement precipitation is also closely associated with faulting, i.e. with Cenozoic thrusting along the Hagab Thrust in Wadi Batha Mahani (Breesch et al., 2006; 2010) and more locally in the vicinity of the Cenozoic reverse faults in Wadi Bih and possibly also in Wadi Sha’am. Based on this association and its timing after the TS development the dolomitisation phase is also interpreted to be syn-tectonic.

The depleted oxygen-isotope values in Wadi Bih and Wadi Sha’am are most likely caused by temperature fractionation due to high-temperature dolomitisation. The covariance of $\delta^{13}C$ and $\delta^{18}O$ was interpreted by mixing during sampling of recrystallised syn-sedimentary dolomites and dolomite breccias with different degrees of recrystallisation (Breesch et al., 2006; 2010). The end member of this trend is very negative and such low values can best be explained by dolomite formation at high temperatures. The clear shift of $\delta^{13}C$ away from the host-rock buffered values may be related to the maturation of hydrocarbons (Breesch et al., 2010).

The Mg and Fe in the brines required for dolomitisation are generally derived from an exotic source, such as from compaction of shaly strata (Roure et al., 2005). In the Wadi Batha Mahani location, shales from the nearby Dibba Zone are a possible source. Another potential source is serpentinnised peridotites and ophiolites (Davies and Smith, 2006) from the Semail Ophiolite. Palaeozoic or Neoproterozoic to lower Cambrian siliciclastic series are also a potential source for iron, whereas Jurassic, Permian or Neoproterozoic to lower Cambrian salt and evaporites could have supplied Mg.

The high temperatures are confirmed by fluid inclusion microthermometry in Wadi Bih resulting in a fluid with $H_2O-NaCl-CaCl_2$ composition and variable high salinities and high temperatures of at least 139 up to 193°C (Table 1). In Wadi Batha Mahani measurements on quartz cement associated with the dolomitisation resulted in a $H_2O-NaCl-(KCl)$ fluid with high homogenisation temperatures ($T_h = 100–250°C$; Table 1).

Based on these isotope and fluid inclusion results, the fluids responsible for the precipitation of both the syn-tectonic calcite and dolomite are dominantly hydrothermal or at least high-temperature brines, which were channeled along thrust and reverse faults. Another remarkable characteristic is the $H_2O-NaCl-CaCl_2$ composition of these fluids, except for the dolomites in Wadi Batha Mahani. The fluid characteristics can be summarised as: $T_h$ between 80 and 250°C with several fluxes possible, salinities of more than 20 eq. wt% NaCl + CaCl$_2$ (Table 1) and an average $\delta^{18}O$ value of +5.6‰ V-SMOW. From the different study locations it became clear that there existed a fluid-flow system with migration of...
hydrothermal brines along Cenozoic reverse faults (Breesch et al., 2009, 2010). These reverse faults are all connected to the Hagab Thrust. Therefore, it suggests that the brines were sourced from deeper formations or even from the basal decollement via the Hagab Thrust.

The penetration of these ascending brines into the carbonate rocks seems to be restricted to the footwall of the reverse faults. In this context, the concept of compartmentalisation with respect to diagenesis and fluid infiltration was introduced by Breesch et al. (2009) in the case study of Wadi Ghalilah, where both the hanging wall and footwall of a Cenozoic reverse fault were studied with respect to their calcite-filled fractures. The influence of the syn-tectonic fluid migration along this fault was limited to the footwall unit and no signs of precipitation by a syn-tectonic fluid were found in the hanging wall. The hanging and the footwall blocks were compartmentalised by the fault, which forms a fluid barrier (Breesch et al., 2009). The observations in Wadi Bih also support this conclusion. The fault-related saddle dolomites in Wadi Bih are restricted to the Milaha and Ghalilah formations in the footwall. The Ghail Formation in the hanging wall is devoid of any fluid-related features. In other similar settings close to Cenozoic reverse faults that divide the Musandam Platform into fault blocks (e.g. Wadi Sha'am and Wadi Rahabah) there may not be any unequivocal proof of fluid migration along these faults; but here also the mineral-filled fractures are restricted to the footwall block. A conclusive explanation for the footwall preference of the fluid infiltration is lacking. A possible explanation is that the porosity and permeability of the rocks in the footwall are slightly higher than in the hanging wall, due to their shallower burial before thrusting. However this pattern is not evident in the outcrop today.

**Comparison with Literature:** The post-TS period in FFTB’s from the literature is often characterised by the presence of shear-related veins (Ferket et al., 2006). In the Musandam Peninsula such shear veins were not observed. The development of hydraulic fractures and crack-seal veins in the northern Oman Mountains in this period (instead of prior to TS-formation as in FFTB’s from literature) could partly be the result of their formation by fault activity and not only by overpressures in the reservoir rocks as described by Roure et al. (2005). Normally, the hydraulic fracturing is due to a so-called squeegee episode when fluids are expelled from the subthrust units laterally toward the foreland (Lünsenschloss et al., 1997; Machel and Cavell, 1999). During this episode the direction of the maximum principal stress is horizontal. Due to layer-parallel shortening, an increasing sedimentation rate in the foreland and tectonic loading in the hinterland, an increase in overpressure is created with hydraulic fracturing.

The presence of the hydraulic fractures in the post-TS period in the study area can also be a consequence of the different tectonic history of the orogen. In the Musandam Peninsula, the tectonic stylolites formed during the Cenozoic compressional phase. The tectonic stress was directly applied to the Musandam Platform and compression took place before overpressure could build up. Therefore tectonic stylolites could have originated before the hydraulic fractures formed. In a typical fold-and-thrust belt evolution, however, the tectonic stress and pressure increases gradually when the thrusts are migrating toward the foreland (Roure et al., 2005).

According to a review by Davies and Smith (2006), hydrothermal fluid flow occurs mostly in tectonic settings with elevated heat flow (i.e. in settings with crustal thinning, rifting and volcanism). Consequently hydrothermal dolomitisation is more likely to occur in extensional settings instead of strongly contractional tectonic settings such as FFTB’s. Thrust faults seem to be unfavourable sites for extensive hydrothermal mineralisation and dolomitisation (Davies and Smith, 2006). These general observations could account for the limited distribution (restricted to vein fillings or breccia patches) of the hydrothermal products in the study area. Hydrothermal dolomitisation or more commonly recrystallisation, which is limited in space and necessary fluid volume, has also been observed in FFTB settings during compressional tectonics (e.g. Al-Aasm and Clarke, 2004; Murgia et al., 2004; Vandeginste et al., 2005).

Compartmentalisation of fluid flow, as manifested in a number of study locations in the UAE, is a common process in FFTB’s (Moretti et al., 2000; Lefticariu et al., 2005). The preference for infiltration of fluids into only one of the fault blocks (i.e. either in the footwall or the hanging wall) seems to change locally. A case study in Sicily has shown that fluids migrating along main thrusts
preferentially infiltrate their hanging wall. The preference for the hanging wall is probably linked to the over-pressured nature of the fluids (Larroque et al., 1996). The fluids attempt to escape upwards by fracturing the overlying hanging wall of the thrust. The preference for hanging wall or footwall in several cases in Venezuela seems to be governed by the porosity and permeability of the rocks (Moretti et al., 2000). Fluids migrating in faults in an extensional or transtensional tectonic setting however seem to prefer infiltration in the downthrown side of related faults (Davies and Smith, 2006). Several mechanisms such as buoyancy-driven or overpressure-driven fluid flow and increased fracturing in the preferred fault wall were put forward (Davies and Smith, 2006). Based on this literature review there is no consistency in fault wall preference of fluid flow but different, probably local factors, seem to dominate.

Post-deformation Time Period

Observations and Data: This period in the northern UAE corresponds to a telogenetic period (Figures 5 and 6). Some fracture-shaped veins developed in the Musandam Peninsula, i.e. the fibrous calcite veins in Wadi Batha Mahani (Figure 11a) and some thin parallel fractures in the Milaha Formation in Wadi Bih (Table 1). Post-tectonic calcite cement is present in dissolution-related features such as moulds and vugs in the Musandam 1 Formation in Wadi Sha’am and in irregular seams in the host rocks like, for example, the black calcite cement in Al Khatt (Figure 11b). Caves and karst cavities formed with calcite precipitation inside, such as stalagmites and botryoidal crusts in Wadi Batha Mahani (Figures 11c and 11d; Table 1). Dedolomitisation was also associated with this diagenetic stage. In Jabal Gharaf in the Dibba Zone, fracture-shaped yellow calcite veins, which crosscut all the other vein generations, originate from this period.

The calcite cements in both the Musandam Peninsula and the Dibba Zone are characterised by generally large non-ferroan (except the yellow calcite veins in Jabal Gharaf) transparent blocky crystals and the absence of mechanical calcite twins (Figure 11e). The cathodoluminescence is usually orange to bright coloured, sometimes non-luminescent with zonations (Figures 11e and f; g and h; Table 1).

In the stable-isotope plot in Figure 7.3, two clusters of stable-isotope values of these calcite cements (post-tectonic calcite) can be observed. The first cluster is represented by calcite cements from Jabal Gharaf and Wadi Bih (Figures 7a and 7e) and shows δ¹³C and δ¹⁸O values similar to and slightly more depleted than their host rocks (Figure 7.1). The second cluster is characterised by very negative δ¹³C (down to -9‰) and δ¹⁸O (down to -13‰) values, dominantly from samples in Al Khatt and Wadi Batha Mahani (Figures 7.3, 7b and 7c). A few samples from Wadi Bih and Wadi Sha’am make the connection between these clusters (Figures 7.3; 7e and 7f). The calcite speleothems from Wadi Batha Mahani are characterised by δ¹⁸O values between -9.9 to -5.6‰ and δ¹³C values between -6.6 to -3.9‰ (Table 1; Figure 7.3).

Mainly low-temperature one-phase fluid inclusion associations are present except in the fluid inclusions in the fibrous veins in Wadi Batha Mahani which are characterised by high homogenisation temperatures between 120 and 200°C (Table 1). The measured salinities are low, mostly lower than seawater (except some inclusions from Jabal Gharaf and in the fibrous veins in WBM; Table 1).

The dedolomitisation or calcification of the ferroan dolomites of the post-BPS to pre-TS period will also be discussed in this section. The isotope and fluid inclusion data were already presented in the post-BPS to pre-TS section (Table 1; Figure 7.3).

Interpretation: The occurrence of calcite cement in thin fractures, irregular seams and dissolution features (such as molds, vugs and cavities, together with their clear, blocky calcite crystals with apparent lack of twinning) all point towards a post-tectonic origin. The presence of stalagmites and karst precipitates, the zoned cathodoluminescence characteristics of the calcite cement and the dominantly low temperatures and salinities of the fluid in the fluid inclusions support precipitation by a meteoric fluid. This phase could represent a present-day karstification due to meteoric water infiltration. The slightly depleted oxygen isotopes in Jabal Gharaf and Wadi Bih can be due to meteoric water precipitation. The strongly depleted isotope signatures in Wadi Batha Mahani and Al Khatt, however, are too negative to be caused by meteoric water alone and can best be explained...
Figure 11: Typical diagenetic products from the Post deformation period in the Musandam Peninsula and Dibba Zone.
(a) Fibrous calcite veins from the Musandam Formation in Wadi Batha Mahani.
(b) Irregular seam of black calcite cement which cuts through other cement generations in Al Khatt.
(c and d) Vertical-directed calcite stalagmites and botryoidal crust-forming calcite speleothem in dissolution cavities in Wadi Batha Mahani.
(e and f) Late calcite filling on top of dolomite cement in a mold in the Musandam 1 Formation, Wadi Sha’am. Blocky transparent calcite without twins with a thinly zoned bright and non-luminescent cathodoluminescence phase.
(g and h) Microscopic characteristics of the fibrous calcite veins in Wadi Batha Mahani. Elongated blocky crystals with growth zoning and dull orange to red luminescent zoning.
by the infiltration of heated meteoric fluids. Higher temperatures are in correspondence with the higher homogenisation temperatures, measured in the fibrous veins in Wadi Batha Mahani (Table 1). At Al Khatt, a fluid circulation system with heating of freshwater could be inferred. The fluid circulation starts with the infiltration of meteoric water during telogenetic uplift. These fluids are channelled downwards through rocks and fractures while heating up on its way before rising again. In an analogy to the current thermal springs in Al Khatt, these waters have moderate temperatures (40–50°C) when they resurface (Rizk and Eletr, 1997; Table 1). The calcite speleothems in Wadi Batha Mahani, however, are typical karst precipitates from freshwater at low temperatures as shown by their quite depleted isotope signatures (Figure 7.3) and low salinities (Table 1).

The isotope values of the calcified ferroan dolomites show quite depleted δ¹⁸O and δ¹³C values. Dedolomitisation typically takes place in the meteoric realm (e.g. Kenny, 1992; Nader et al., 2008). Calcification of the ferroan dolomite cement in a freshwater environment is supported by the isotope trend towards lower δ¹³C values in the calcified dolomites in Al Khatt, which can be interpreted as a meteoric water line (Figure 7.3). Furthermore the fluid in secondary fluid inclusions in the ferroan dolomite cement in Wadi Bih was measured as having low salinity (0.88 to 1.74 wt%) H₂O-NaCl fluid (Table 1). This fluid system implies low salinity meteoric fluid was responsible for dedolomitisation.

Comparison with Literature: The occurrence of telogenetic, karst-related features is in general agreement with the observation of karst-related veins and precipitates in FFTB’s from the literature (Ferket et al., 2000, 2003). Dedolomitisation has not often been reported in the literature in relation with FFTB development except for a Quaternary dedolomitisation by meteoric water along fractures in the FFTB of the Southern Alps (Ronchi et al., 2004) although this process seems to be quite common in dolomitised sequences. Dedolomitisation often results from the migration of karst-related meteoric waters (e.g. Kenny, 1992; Nader et al., 2008).

The meteoric fluid circulation system in Al Khatt is comparable to the system proposed for normal faults in the Aegean region in Turkey by Verhaert et al. (2004). A similar model of shallow convection cells also applies for the hot springs in Banff (Canadian Rockies), where meteoric water enters the system at places where Palaeozoic carbonates crop out, becomes heated in the deep underthrust synclines, and emerges again at the surface near steeply dipping thrust fronts (Schneider, 2003).

GEODYNAMIC AND FLUID SYSTEM EVOLUTION

The evolution of the fluid system and regional diagenetic processes is summarised and placed in the geodynamic framework of the northern Oman Mountains development. The different stages are illustrated in a schematic sketch section in Figure 12.

Stable Shelf: Permian to Early Cretaceous

During the Permian to early Cretaceous pre-deformation period the study area was situated on a stable shelf, consisting of a carbonate platform with a slope and basin (Figure 12a). Further east in the back-arc of the subduction zone in the Neo-Tethys Ocean, the later Semail Ophiolites were formed. In the carbonate platform this period corresponds to the pre-BPS1 eogenetic period (Figure 5) when syn-sedimentary dolomites and early hydraulic fractures originated by cracking and sealing. Deeper in the older strata the first set of burial stylolites (BPS1) were generated. The fluids responsible for the hydraulic fracturing were overpressured due to burial (Roure et al., 2005). They are characterised by local circulation, low salinities and host-rock buffered isotope signatures.

Development of the Aruma Foredeep: Cenomanian

During this stage in Cenomanian times, a flexural forebulge migrated westwards and the Aruma foredeep developed along the margin of the platform carbonates due to the initiation of the tectonic loading (Figure 12b; Searle, 1988b). The emergent parts of the Musandam Platform were exposed to meteoric water infiltration that resulted in an early karstification phase (Wadi Batha Mahani; Breesch et al., 2006) and dissolution and microsparitisation of the shallow-marine deposits of the northerly situated
Ghalilah, Milaha and Musandam 1 formations. The Aruma deposits overlie shelf, slope and basin sediments. In the Sumeini slope deposits, currently situated in the Dibba Zone, hydraulic fractures from the pre-BPS period and burial stylolites were formed (Figures 6 and 12b), followed by shear-related veins with calcite and quartz cement in the post-BPS to pre-TS period (Figures 6 and 12b). Meanwhile, BPS1 development continued at depth in the Musandam Platform and also affected the younger deposits. The Neo-Tethys Ocean was closed and shortening began with the obduction of the Semail Ophiolite (Figure 12b).
Thrust Emplacement and Tectonic Relaxation: Late Cretaceous – Eocene

In the Santonian, the deformation front associated with the obduction of the ophiolites accounted for the development of a tectonic wedge involving the Hawasina basinal units. This accretionary wedge, together with the ophiolites, was thrust over the former Arabian margin in the Campanian (Figure 12c; Ministry of Energy, UAE, 2007). The Aruma deposits locally acted as a decollement horizon (Searle, 1988b). The thrust emplacement consisted of a dominantly SW-directed stacked sequence of thin-skinned thrust sheets (Searle, 1988b). It is remarkable that not one thrust fault was activated in the platform itself (Ministry of Energy, UAE, 2007). The surface topography of the orogen remained close to sea level from this stage onwards.

The post-BPS to pre-TS mesogenetic burial period in the Musandam Platform occurred during the Santonian – Campanian time. The thrusting caused deep burial of the inner-slope and outer-platform units, locally reaching 4,500 m in depth. As a consequence a second generation of burial stylolites (BPS2) developed in the platform succession (Figure 12c). Burial veins filled with blocky calcite and ferroan saddle dolomite, precipitated from warm geothermal fluids, also formed during this stage. In the Sumeini slope unit, the burial was limited to ca. 2,000 m (to a maximum 3,000 m) and the tectonic compression was translated into tectonic stylolite development (TS in Figure 12c) and syn-tectonic crack-seal veins from the post-TS syn-tectonic period (Figure 6).

The main compression ceased in the Late Maastrichtian. In the foreland there was still some flexural sedimentation (Figure 12c). This was the beginning of a short period of tectonic relaxation. Flexural subsidence was still active in Palaeocene to Eocene times. A successor foreland basin (Pabdeh foredeep) developed in front of the uplifted Musandam Platform (Searle, 1988b; Figure 12c). Slab detachment probably occurred before the Oligocene, accounting for unflexing of the foreland lithosphere and slight erosion of former foredeep deposits in Oman in the south, as well as in the Strait of Hormuz (Jahani, 2008).

Musandam Culmination: Neogene

Major shortening of the platform resumed during post-Eocene times, coeval with the Zagros Orogeny. Break-back thrusting was initiated (Figure 12d). Breakback thrusts cut through a stack of thrust sheets and inverted the stacking order by placing lower, later thrust sheets on top of higher, earlier ones (Searle, 1988a, b).

The culmination of the Musandam shelf carbonates was established by thrusting of the Permian to Cenomanian shelf carbonates 15 km westwards along the Hagab Thrust on top of Hawasina cherts. These Hawasina cherts were previously stacked on top of the Musandam Platform during the late Cretaceous thrusting event (Figure 12d; Searle, 1988a, b). A frontal fold developed on the leading edge of this thrust fault and internally the platform series were affected by reverse faulting (Figure 12d).

The contact between the Dibba Zone and the Musandam shelf is marked by a late stage listric normal fault. Extensional normal faulting was associated with the culmination collapse of the Musandam sequence (Searle, 1988b).

The direct tectonic shortening on the Musandam shelf carbonates caused tectonic pressure solution and the development of vertically oriented tectonic stylolites (TS in Figure 12d). This was also the period when the observed Hagab Thrust fluid-flow system was active with migration of hydrothermal brines along the steep reverse faults and infiltration in the footwall blocks (Figure 12d). The syn-tectonic veins (e.g. from Wadi Ghalilah) and syn-tectonic dolomites (e.g. from Wadi Bih and Wadi Batha Mahani), which belong to the post-TS syn-tectonic stage, were the resulting diagenetic products in the Musandam Platform (Figure 5).

Geographic positioning data (GPS) data are not available so as to precisely document the present kinematic evolution of the northern UAE. Uplift and erosion resulted in the present-day topography. Post-TS telogenetic meteoric infiltration and karstification, with post-tectonic calcite precipitation, has been documented during these last stages in both the Musandam Platform and the Sumeini slope.
carbonates (Figures 5, 6 and 12d). In Wadi Batha Mahani, for instance, caves with stalagmites originate from this second karst phase. A fluid circuit with infiltration of meteoric fluids which resurface at moderate temperatures is inferred in the Musandam carbonates (Figure 12d) from the study in Al Khatt.

Recently the Musandam Peninsula was tilted northeastward, as indicated by the occurrence of wadi terraces and raised beaches on its western side. The northeastern coast has subsided ca. 60 m in the last 10,000 years (Searle, 1988b).

**IMPLICATIONS FOR RESERVOIR CHARACTERISTICS AND HYDROCARBON SCENARIOS**

In the studied outcrops of the carbonate platform and slope deposits in the Musandam Peninsula and Dibba Zone, no traces of hydrocarbons were found. There are no oil shows present and no bitumen was found along stylolites or fractures. The total lack of hydrocarbons in this outcropping unit is surprising since, even though the Musandam Platform has been thrust and uplifted, one would expect relics of bitumen (e.g. in Albania, Vilasi et al., 2006) if hydrocarbons had been formerly trapped in these rocks and subsequently were washed out or biodegraded.

The discovery of green fluorescent oil-containing fluid inclusions in calcite veins in the Musandam 2–3 limestones in Wadi Batha Mahani, however, confirms the existence of an oil kitchen at depth. The exact source rocks cannot be determined but marine source rocks (type II kerogen) in the platform series are most probable (Alsharhan, 1989; van Buchem et al., 2002). According to petroleum modelling there is still gas or condensate potential in the Musandam Platform units, which occur beneath the allochthonous fault-bounded Sumeini and Hawasina rocks. Another possibility of oil potential relates to the trapping of early oil in cold reservoirs of growth anticlines and overlying allochthonous units, on the condition that there has been no remigration during more recent tectonic movements.

Since the lithostratigraphy of the para-autochthonous carbonates cannot be calibrated with well data, it is uncertain if the carbonate platform strata extend beneath the Dibba Zone or if these strata are Sumeini slope-type deposits. Therefore these two potential reservoir systems should be considered in further exploration. These potential reservoirs can be compared with the Sajaa and the Margham fields in the foothills (Figure 1). In these fields, gas condensates are produced from Thamama Group carbonates in hanging wall anticlines of the thrust (Alsharhan, 1989).

The diagenetic processes and the evolution of the fluid-flow system and may have an influence on the potential reservoirs in the carbonate platform and Sumeini slope strata. Due to deep burial and the lack of framework-stabilising components, the platform and slope carbonates in the study area did not preserve their primary matrix porosity. Secondary porosity development in FFTB’s relates to the open-system circulation of extra-formational fluids that are not in chemical equilibrium with the host rocks and which are often channelled along permeable strata near vertical conduits such as normal faults and thrusts (Swennen et al., 2003; Roure et al., 2005).

The effect of the fluid flow system with migrating brines along the Cenozoic reverse faults, which infiltrate in the footwall rocks, was in the outcrop locations limited to hydraulic fracturing and cementation. When combined with hydrocarbon migration, hydraulic fracturing can create pathways for the hydrocarbons to further infiltrate in the reservoir rocks. Here the described compartmentalisation can be of importance. By analogy with the case study in Wadi Ghalilah (Breesch et al., 2009), the fluids might only infiltrate in the footwall and the fault can act as a seal above the reservoir. Therefore the subthrust footwall units in the vicinity of reverse or thrust faults of Cenozoic age are potential exploration targets.

Circulation of extraformational fluids can cause host rock and especially saddle dolomitisation. The ferroan saddle dolomites in several studied outcrops and the pink saddle dolomite in Wadi Bih are present as cement in fractures and molds in limited volumes. Consequently these dolomites do not have an important influence on the porosity development. Only the replacement of limestones or the recrystallisation of fine-crystalline dolomites can create additional porosity, since crystalline dolomite...
occupies less space than calcite. In Wadi Bih host-rock dolomitisation has taken place in the vicinity
of a reverse fault and has created secondary porosity. This is again on a rather small scale (zone of
maximum 50 m wide). The only regional-scale event of dolomitisation, recorded in the study area,
is the dolomite recrystallisation in Wadi Batha Mahani (Breesch et al., 2006, 2010). These dolomites
are not saddle dolomites but fine-crystalline dolomites, which have been recrystallised by hot brines.
Due to intercrystalline pores and the brecciated nature of the rocks, the total porosity of the dolomite
patches is larger than in the bedded limestone strata. Subthrust exploration can therefore also be aimed
at the transition zone of the carbonate platform to the slope, where these dolomite breccias occur in
Wadi Batha Mahani. It must be noted, however, that the distribution of these potential reservoirs is
quite unpredictable in patches of variable size (from 10s of metres to 1 km wide). Moreover they do
not possess a good areal connectivity (Breesch et al., 2010).

CONCLUSIONS

The comparison of the results of the diagenetic study in the different outcrop areas in the northern Oman
Mountains with each other and with similar studies carried out in other FFTB’s in the world yielded
some interesting conclusions concerning the evolution of the fluid-flow system and implications for
petroleum exploration. As a result of the northern Oman mountain belt formation in two successive
but separate compressive tectonic stages, burial stylolites could develop at two different times in the
Musalndam Peninsula. The tectonic stylolites in the Musalndam Peninsula appear to be much younger
than those in the Dibba Zone. Another consequence is the fact that the hydraulic and crack-seal veins
post-date the tectonic stylolites in contrast with classical FFTB’s. This is probably also partly due to
the association of the hydraulic fracturing with fault activity which took place in the post-TS period.

In the Musalndam Peninsula, a large-scale fluid system is inferred with migration of hot brines with a
H$_2$O-NaCl-CaCl$_2$ composition along Cenozoic reverse faults. These brines were sourced via the
Hagab Thrust from deeper formations or even from the basal decollement. The reverse fault acted
as a permeability barrier towards the hanging wall. Consequently the brines only infiltrated in the
footwall blocks with compartmentalisation as a result.

It is likely that there are subthrust occurrences of the slope and platform deposits of Permian to early
Cretaceous age. These can be considered as potential hydrocarbon reservoirs as the source rocks
are known to be in the condensate or gas window. Two main exploration scenarios were proposed
based on the occurrence of diagenetic processes, which have improved the porosity of the potential
reservoirs:

1. Subthrust footwall units in the vicinity of reverse or thrust faults of Cenozoic age are potential
exploration targets. When the migration of hot brines along the Cenozoic reverse fault is combined
with petroleum migration, the footwall compartments also could act as potential reservoirs. The
fault, which only allows fluid flow into the footwall and acts as a barrier to the hanging wall, can
form a seal for these reservoirs.

2. The transition zone of the carbonate platform to the slope represents the second exploration
target. Recrystallisation of dolomites at the platform border is a possible process to create poorly
connected hydrocarbon reservoirs such as in Wadi Batha Mahani.

ACKNOWLEDGEMENTS

This research was financed by the Institute for Promotion of Innovation through Science and Technology
in Flanders (IWT-Vlaanderen). Part of the fieldwork was sponsored by the IAS (International
Association of Sedimentologists) and part by the “Dirk Vogelfonds” (fund in honour of Professor Dirk
Vogel, K.U.Leuven). We wish to thank the Ministry of Energy of the United Arab Emirates, especially
S. Al Mahmoudi, K. Ali Al-Hosani and A. Gahnoog for their support and R. Ellison (BGS) for his help
in the field and comments on the text. H. Nijs is acknowledged for preparing thin sections and wafers.
M. Joachimsky (University of Erlangen) is thanked for performing the stable isotope analyses on the
carbonates and T. Fallick (SUERC) for the oxygen isotopes on the quartz samples. The suggestions
and comments of three anonymous reviewers greatly improved the quality of the text. We also would
like to thank Moujahed Al-Husseini, Editor-in-Chief, and Assistant Editor Kathy Breining for their assistance with the manuscript, and Nestor “Niño” Buhay IV for designing the paper for press.

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Manuscript submitted March 11, 2009

Revised December 14, 2010

Accepted December 20, 2010

Press version proofread by authors February 8, 2011