Kinematic interpretation and structural evolution of North Oman, Block 6, since the Late Cretaceous and implications for timing of hydrocarbon migration into Cretaceous reservoirs

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ABSTRACT

On the basis of structural style and differences in Late Cretaceous evolution, the carbonate platform in northern Oman and the allochthonous wedge comprising deepwater sediments and oceanic crust in the Oman Mountains form distinct structural domains. Imbrication associated with the emplacement of the Semail Ophiolite and predominantly SW-verging thrusting of the Arabian Platform margin culminated in the late early Campanian. The structural grain of NW-trending thrust faults and contractional folds contrasts markedly with the style and grain of the region immediately south of the Oman Mountains (our study area) and implies strong strain partitioning. Kinematic indicators from subsurface data, combined with the age of growth faulting, provide the basis for the interpretation that maximum horizontal stress was oriented NW-SE in this foreland region rather than NE-SW during the Campanian. The dominant tectonic control on the formation of faults is believed to have been an oblique “collision” of the Indian Continent with the Arabian Plate during the Santonian-Campanian. Deformation in this domain was dominated by distributed strike-slip and normal faulting. This period of faulting was significant for two reasons:

(1) The faults both enhanced existing structures and formed new traps. They also allowed vertical migration of hydrocarbons from Palaeozoic reservoirs (e.g. Haushi clastic accumulations) into Shu’aiba and Natih carbonates above. Until that time, some 75 Ma ago, oil was retained in Late Palaeozoic and older traps. This period of deformation is a “Critical Event” within the context of Oman’s hydrocarbon distribution.

(2) Faults with NNW and WNW orientations that developed at that time appear to be directly associated with important fracture systems that affect the productivity of several giant fields comprising Natih and Shu’aiba carbonate reservoirs (e.g. Lekhwair, Saih Rawl).

Following this tectonic event, late Maastrichtian to Palaeocene uplift and erosion in excess of 1,000 m, is recorded by truncation of the Aruma Group and Natih Formation, as well as part of the Shu’aiba Formation below the base Cenozoic unconformity. Seismic velocity and porosity anomalies from Lekhwair field in the northwest to the Huqf-Haushi High in the southeast, provide additional support for the areal distribution of this event. Around the Lekhwair and Dhuilmia fields, the circular to elliptical subcrop pattern below this unconformity does not support the notion of a peripheral bulge related to the emplacement of the allochthon.

The stress field changed during the late Cenozoic with the opening of the Red Sea and Gulf of Aden, and the collision of the Arabian Plate with the Iranian Plate. NE-SW-oriented maximum horizontal stress during the late Cenozoic led to the formation of major folds resulting in, for example, the surface anticlines over the Natih and Fahud fields as well as causing inversion along the Maradi Fault Zone. This may also have led to the uplift of the Oman Mountains. The regional northerly subsidence caused by crustal loading of the Arabian Plate gently tilted traps during the Pliocene-Pleistocene from Lekhwair to Fahud.
Figure 1: Location map and simplified geological map with principal structural elements. Inset map indicates coverage of 3-D seismic.
INTRODUCTION

The aim of this paper is to provide a synthesis of structural styles observed in the northern part of Petroleum Development Oman (PDO) Block 6 in north Oman. This synthesis is based on kinematic information derived from an extensive 3-D seismic data set, which now covers over 40% of the study area (Figure 1).

The observations presented here focus on the structural development during the Late Cretaceous. Seismic data locally permit a differentiation between these structures and structures of Cenozoic age. Timing is defined by growth history and associated unconformities. The Campanian event is emphasised here primarily to illustrate its significance to fault and fracture distribution in north Oman oil and gas fields. This is only one of several tectonic events we describe since the time of deposition of the Permain Gharif Formation to the present-day, but appears to have considerable significance to the hydrocarbon distribution in north Oman.

Previous structural analyses of northern Oman (Searle, 1985; Hanna, 1990; Mount et al., 1998; Al-Lazki et al., 2002) have tended to concentrate on the evolution of the Oman Mountains and the emplacement of the Permain-Cretaceous allochthon during the Late Cretaceous. The shortening associated with this Cretaceous event and subsequent folding of Palaeogene strata during Miocene and younger times, have dominated structural thinking in this area with the conventional interpretation that the tectonic transport direction and maximum horizontal stress was oriented NE-SW. For the Oman Mountains, there is considerable evidence to support this conclusion (Hanna, 1990) judging from fold-axis orientations and thrust traces of Late Cretaceous age (Figure 1). However, subsurface data in the adjacent foreland record a distinct structural regime with different characteristics.

The implications of these differences in character are significant to developing a better understanding of the structural evolution of north Oman and important for developing fracture-fault relations at reservoir scale.

The limit of the allochthonous wedge of Late Cretaceous nappes (Figure 1) and the sole or “frontal” thrust can be traced immediately west and south of its outcrop in the Oman Mountains and just to the north of Block 6 (Glennie et al., 1974; Boote et al., 1990; Warburton et al., 1990; Mount et al., 1998). The trace separates domains of strikingly different structural character. To the northeast, an imbricate stack consisting of continental margin and deepwater sediments as well as oceanic crust is now exposed at the surface. In contrast, south and west of this domain there is little evidence for Late Cretaceous, N-S or NE-SW-oriented shortening within Block 6. Instead, the structural grain in the northern part of Block 6 is oriented approximately NW-SE and comprises normal or strike-slip faults. At about the same time as the nappes in northern Oman were being emplaced (Santonian-Campanian), the Masirah Ophiolite to the east (Campanian to earliest Palaeocene) was also obducted (Ries and Shackleton, 1990; Shackleton and Ries, 1990; Shackleton et al., 1990; Marquer et al., 1995; Schreurs and Immenhauser, 1999; Immenhauser et al., 2000). In this paper, we present the evidence for, and discuss the link between, the structures in the northern part of Block 6 and the emplacement of the Masirah Ophiolite.

During the late Cenozoic (mid-Miocene to Pliocene-Pleistocene) the Arabian Plate broke apart from Africa. Rifting and sea floor spreading in the Red Sea and Gulf of Aden was mirrored by collision with the Iranian Plate along the Zagros Suture. This contractional event, which led to the development of thrusts in the Musandam and possibly to uplift of the Oman Mountains, can also be recognised in the form of folding of late Cenozoic sediments in the northern domain of Block 6 (post-Fars Formation according to Boote et al., 1990; Miocene-Pliocene according to Carbon, 1996; Glennie et al., 1974) and is clearly distinct from Late Cretaceous Hawasina Nappe emplacement.

The contractional structures are the expression in the foreland of the compression associated with the Zagros Collision (Hessami et al., 2001; Boote et al., 1990) that had resumed in the Eocene farther north in Iran and the Gulf of Oman. The relation between collision along the northern margin of Oman and the United Arab Emirates with the Iranian Plate and the early to middle Miocene initiation of rifting of the Gulf of Aden and Pliocene spreading of the Red Sea, has been discussed by Boote et al. (1990) and Allen and Jackson (2002). The impact of this later event appears to have been felt as far south as
This paper

Figure 2: Simplified stratigraphic column for Oman illustrating main unconformities and hydrocarbon reservoirs discussed in this paper.
the Fahud and Natih fields with inversion of the Fahud Fault. Folded Cenozoic sediments have been mapped some 50 km to the SW and west of the trace of the Late Cretaceous frontal thrust from Fahud in the south to Jabal Hafit to the northwest and again farther north to Jabal Faiyah (cf. Noweir and Alsharhan, 2000).

The Fiqqa, Natih, Shu’aiba to Gharif formations (Figure 2) are all affected by moderately to closely spaced faulting. The overlying Shammar, Rus and Dammam formations are locally folded with only a minor record of faulting. Below, we provide a summary of the structural observations made in selected areas using 3-D seismic data from northwest to southeast across the northern part of Block 6. Our synthesis and interpretation places these observations into a tectonic framework. The kinematic interpretation and structural evolution have important implications for the timing of hydrocarbon migration and charge in northern Oman.

**LATE CRETACEOUS AND CENOZOIC STRUCTURAL STYLES FROM SUBSURFACE DATA IN NORTH OMAN, BLOCK 6**

Regional structural interpretations have been made at key horizons (Figure 2) utilising both 2-D and 3-D seismic coverage in the PDO concession area (northern Block 6). These surfaces include the base Palaeogene (Figure 3), top Natih, top Natih E, top Kharaib, Akhdar Unconformity and top Gharif. In addition, fault lines were interpreted on both 2-D and 3-D data. Fault planes were constructed for regional faults (discussed in more detail below in the section on the present-day stress regime). Detailed fault-orientation analysis was conducted on fault line interpretations from 3-D seismic data at near-top Kharaib (Figure 4) and near-top Gharif (Figure 5) levels, as well as regional fault planes constructed from the major fault lines. Below we discuss the main structural observations using mapped 3-D seismic data at Natih E or Shu’aiba level. In addition, uplift and erosion, following the main fault generating event, is also described where detectable.

**Lekhwair Area**

In the Lekhwair area (Figure 6), there are two fault families, both equally well developed. The faults are steep and cut from the Fiqqa Formation (where still present, having been eroded from the main part of the Lekhwair High), through the Natih and into the Shu’aiba formations. Fault throws reach a few metres typically with visible offset on seismic data of approximately one seismic wavelength (10 m, 25 msec two-way time) or less. Fault orientations fall into two families: 305–125° and 340–160°. Uplift and erosion prior to the deposition of the Palaeocene Shammar Shale, removed some 500 m of Fiqqa and 500 m or more of the Natih Formation. The Shammar Shale now lies unconformably on the Shu’aiba Formation, at the centre of the uplifted region. The subcrop of the Natih Formation can be established from well data to the southeast and east of the Lekhwair and Dhulaima fields, as well as truncation of Natih and Shu’aiba reflections from 3-D seismic data. The truncations of the members of the Natih Formation, below the “base Cenozoic unconformity”, strike approximately 45° (Figure 7).

Subsequently, during the Pliocene to Pleistocene, the parallel-bedded Rus and Dammam formations, exhibiting little or no change in thickness over the Lekhwair field to the north, were tilted to the NNE by about 0.5–1.0°. Some 80–100 km further to the north, the Palaeogene Dammam and Fars formations are also folded into asymmetric broad and tight folds (e.g. at Jabal Hafit in the United Arab Emirates and at Ibr; Boote et al., 1990; Al-Ain, Noweir and Alsharhan, 2000). The folding has been related to the Zagros Collision (Hessami et al., 2001) and the tilting due to crustal loading.

**Yibal and Al Huwaisah Areas**

The eastern flank of the Al Huwaisah field is bounded by an array of NW-SE-oriented faults at Natih and Shu’aiba level (Figure 8). The array of right-stepping faults trends approximately N-S to NNW-SSE above an earlier lineament at Gharif and deeper levels. The inferred sense of movement is sinistral on this array. The Al Huwaisah structure itself is elongate, with long axis trending NE-SW and cut by two families of faults. The older set of faults is oriented NW-SE and the younger set is oriented NE-
SW. The relative age of the faults has been established by abutting relations. Locally, the NW-SE fault family also forms N-S trending en-echelon arrays with an inferred sinistral, oblique movement sense. On WNW-ESE-oriented en-echelon fault arrays, a dextral sense of displacement is inferred.

Minor uplift and erosion of approximately 200 m over the Yibal field at the end of the Cretaceous exposed the Shargi Formation below the Arada (Figure 7) probably as a result of salt movement.
Figure 4: Surface illumination at near-top Kharaib Formation based on 3-D seismic data only. Fault families have been created to highlight fault orientations in accompanying rose diagrams.
Figure 5: Upper surface illumination at near-top Gharif Formation based on 3-D seismic data only. Fault families have been created to highlight fault orientations in accompanying rose diagrams.
Fahud Area

The Fahud Fault is the main bounding fault of the Fahud and Haban fields at Natih and Shu’aiba levels (Figures 9 and 10). The main Fahud Fault extends from the Fiqa Formation down to the Palaeozoic and the top of the salt of the Ara Group. The trap is a tilted fault block with the shallower footwall on the north side of the fault. The fault is composed of several linked segments oriented WNW along its southeast half and trends almost east along its western segment. The Fahud Fault was clearly active during the Late Cretaceous (Figure 10). Growth on the fault was accommodated during the Campanian based on biostratigraphic interpretations from nearby well data (e.g. Sufrid-1 and Ibtihaj-1). Total vertical displacement amounted to 1 km with a minor strike-slip component probably equivalent to the vertical displacement. The Fahud Fault does not appear to offset the post-Cretaceous sediments either as imaged on seismic or surface data. Subsidiary faults in the hanging wall of the main growth fault, form en-echelon arrays and can be interpreted to have accommodated a limited dextral strike-slip movement.

These arrays of subsidiary faults extend through the Natih and Shu’aiba formations and into the Ghariif (Figure 10), at which level most of the fault displacement is no longer discernible on seismic data. Faulting is not visible in the Haima clastics below. The arrays of faults, most of which trend NW, sub-parallel to the main fault form en-echelon sets of fault pairs defining narrow grabens, some 250–500 m wide. The fault arrays are oriented NW to NNW. The en-echelon arrays suggest sinistral movement. These faults do not cut across the entire Fiqa Formation and are interpreted to be late Santonian to late Campanian in age and contemporaneous with the growth of the Fahud Fault. Locally, weakly developed en-echelon arrays, trending WNW, are also discernible at Kharaib and Natih levels, with a dextral sense of displacement.
At the end of the Cretaceous, prior to the deposition of the Shammar Shale, a narrow zone of uplift around the Fahud Fault has been mapped utilising well and seismic data (Figures 7 and 10). The uppermost part of the Shargi Member and the Arada Member are truncated both to the NE and SW of the trace of the fault in the subsurface, with increasing erosion towards the main Fahud Fault. Limited well data to the south of the fault does not allow the mapping of the exact location of the erosional limit in this area. The maximum uplift is estimated to have been up to about 300 m prior to erosion and deposition of early Palaeogene strata.

Figure 7: Base Cenozoic subcrop map in north Oman based on well data. The subcrop is mapped at the base Cenozoic west of Maradi Fault Zone and at the base of Miocene conglomerates east of the fault zone. In the latter area, the top of the Arada Formation and Palaeogene sediments are missing, probably eroded. Uplift estimates over the Lekhwair High in the northwest of Block 6 are based on measured (undecompacted) thicknesses from well data.
Subsequently, the Rus and the Dammam formations were deposited with minor change in thickness over the Fahud and Natih areas. In both Natih and Fahud folding of the Rus and Dammam to form the asymmetric, surface anticlines took place during the latter part of the Palaeogene to Neogene. The steep limbs of the folds dip to the northeast (Figure 10).

Musallim-Makarem Slope Area

The Musallim-Makarem Slope is less intensely faulted than the Lekhwair, Al Huwaisah and Fahud areas (Figure 11). The entire Cenozoic (Tertiary) section dips gently to the north (Figure 12). Faults in two fault families affect the Natih and Shu’aiba to Gharif formations. Faults are arranged in arrays

Figure 8: Surface illumination map at Natih E level from the Yibal-Al Huwaisah 3-D seismic data sets. Two systems of en-echelon faults developed along E-W and N-S trends. Rose diagrams based on fault lines interpreted at Natih and Gharif levels are presented. A sketch of the kinematic interpretation based on the main structural features is added to summarise the late Cretaceous deformation.
Figure 9: Surface illumination map at Natih E level from the Fahud SE 3-D seismic survey. En-echelon faults are well developed along a NNW-SSE lineament. Minor, subsidiary faults associated with the Fahud Fault, oriented WNW-ESE, suggest a modest amount of strike-slip movement occurred on what is principally a normal, growth fault. Neogene, NNE-SSW-oriented faults (010° to 050°) have not been included in the rose diagram.

Figure 10: NE-SW-oriented seismic section illustrating the thickening (growth) in the hangingwall of the Fahud Fault during the Campanian (approximate vertical exaggeration 2:1).
that form conjugate pairs of grabens. The faults in these arrays are segmented and form en-echelon pairs. The faults do not extend below the Haushi Group (Gharif and Al Khlata formations).

Uplift and erosion in this domain is limited (Figure 7) and the tilt to the north of the base Palaeogene and younger units is not pronounced (Figure 3). To the south and SW, the tilt diminishes further so that in central Oman, the Mesozoic and Palaeogene strata are almost flat-lying.

**Burhaan Area**

The main Burhaan Fault is oriented 150–155° and is sub-parallel to the Maradi Fault Zone, some 10 km to the east (Figure 13). The fault has considerable vertical offset, up to 200 m. The Fiqa Formation thickens towards the main Burhaan Fault and growth was accommodated during the Campanian (Figure 14).
Figure 12: Seismic section illustrating the nature of the fault sets in the Mesozoic carbonate platform sediments. Faults are steep, extending from the Fiqa Formation through to the Gharif Formation, but rarely enter the Haima Supergroup sediments. Often the faults form in pairs (bounding narrow grabens) and the fault intersection marks the limit of displacement either in the Mesozoic carbonates or in the Haushi Group.

Subsidiary faults to the south of the main fault are arranged in en-echelon arrays. The faults in these arrays strike approximately 150° (SE). The right-stepping geometry of the Burhaan and subsidiary faults to the south suggest a sinistral sense of displacement on this fault system. A secondary fault set and subsidiary faults, forming an apparently conjugate set in map view, are oriented 95° (c. east) and 125° (southeast, Figure 14).

The Burhaan Fault extends from above the top of the Natih Formation to the Gharif and below, but does not offset the base of the Palaeogene. The smaller faults cross the Natih and Shu’aiba formations. Most of the displacement on the faults terminates before reaching the top of the Gharif Formation (Figure 14). At or near the top of the Palaeozoic clastic section the graben-forming faults connect at a sub-horizontal branch-line. Displacement does not appear to continue into the Haima Supergroup. There is little or no tilt of the Cenozoic strata towards the north in the Burhaan area (Figure 3).

Maradi Fault Zone (MFZ)

The Maradi Fault Zone (MFZ) extends from the Huqf-Nafun area in the east-central area of Oman and has a traceable length of over 300 km in both subsurface and surface data (Figure 1). The fault can be traced at surface by ridges of Cenozoic and Late Cretaceous rocks dipping both to the east and west, for example, near Wadi al Awaifi (Hanna and Nolan, 1989). The fault zone separates the north Oman Musallim Slope from the Afar region. On the east side of the fault zone, the base of post-Mesozoic lies, on average, some 100–200 m shallower than the base of the Palaeogene to the west of the Maradi Fault Zone (Figure 15). Most or all of the Paleogene, on the east side of the fault, appears to have been eroded, based on analysis of cuttings from well penetrations.

The MFZ comprises steeply dipping faults that cut through the Fiqa Formation and entire Mesozoic section down to the Haima Supergroup where it cannot easily be traced seismically. There is little
evidence on seismic data for Mesozoic displacement along the fault, other than the obvious expansion during the deposition of the upper part of the Fiqa Formation (Figures 16 and 17). Locally this increase in thickness indicates that the fault had accommodated substantial extensional offset during the (late) Santonian and Campanian. The thickness of the Fiqa Formation approximately doubles relative to its normal thickness from about 700–900 m outside the fault zone, to some 1,600–2,000 m in the deepest mini-basins within the fault zone (Figure 18).
Kinematic indicators from 3-D seismic data at Natih level, e.g. splay faults and “horse-tails” along the trace of fault zone and on both flanks indicate that the fault had a sinistral movement during the Late Cretaceous (Figure 17). Further south, the MFZ forms the eastern and western margins of a deep, Late Cretaceous “rhombic” graben that also confines the Ghaba Salt dome and is left-stepping in character (Figure 18). Extensional faults bound the northern and southern margins, the separation of which provides a direct estimate for Late Cretaceous movement on the MFZ of some 10 km. The left-stepping nature suggests that at an earlier time, the faults had initiated with a dextral sense of movement. This movement pre-dates the deposition of Gharif Formation and possibly the Haima Supergroup, as little evidence can be observed for thickening of these units within the fault zone.

The base of the Palaeogene deposits and sediments as young as Neogene (Hanna and Nolan, 1989) now rise steeply over the central part of the fault zone from both east and west flanks, thus indicating that inversion of the MFZ took place as recently as late Neogene (Pliocene-Pleistocene). The sense of fault movement based on kinematic indicators from surface data is recorded as dextral (Hanna and Nolan, 1989). The amount of Neogene dextral motion is believed to be relatively small with a maximum strike-slip displacement of some 100 m as estimated by Hanna and Nolan (1989), compared to late Cretaceous sinistral motion of some 10 km. Our data supports this interpretation: the Ghaba East pull-apart graben shows little evidence of contractional structures that would be expected from significant (km-scale) Neogene, NE-SW-oriented compression in the “jog” associated with dextral motion on the MFZ (Figure 18).

**Kauther 3-D – Afar Area**

The Afar Area is bounded in the north by the Salakh Arch (Figure 3), in the west by the Maradi Fault Zone separating the area from the Makarem-Mussallim Slope, and to the south by outcrops exposed in the Huqf-Haushi High. The area south and east of the Salakh Arch is covered to a depth of some 250 m by (possibly latest Miocene) Pliocene and younger wadi gravels (Maizels and McBean, 1990). There is no evidence, from biostratigraphical and lithological analysis of drill cuttings, of any pre-Miocene sediments above the Aruma Group. Towards the southeast, more than 500 m of the Aruma...
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Group, Fiqa and Arada formations, have been removed during the Late Cretaceous and possibly in the early Palaeogene. The Late Cretaceous tilt of the Huqf-Haushi High was to the NW (Figure 15) and the strike of the eroded units is WSW as defined by 3-D and 2-D seismic data as well as the subcrop of the Arada and Shargi Members below the base Palaeogene.

Most faults trend northwest. Fault arrays trend approximately east above deeper-seated, possibly basement faults. These arrays suggest a minor dextral strike-slip component.

The Habiba-Khatmah Ridge, a broad anticlinal feature, bounded to the northwest by a steep reverse fault and to the southeast by both normal and reverse faults, strikes NNE-SSW (Figure 19). The axis of the uplift can be traced across the Salakh Arch to the north forming the Khatmah Ridge (Figure 3),

Figure 15: Base Fars subcrop map in north Oman based on well data. Uplift estimates are based on measured (undecompacted) thicknesses from well data.
also striking NNE. The Habiba-Khatmah Ridge formed during the Campanian with greater erosion of Fiqa Formation over its axis. Following its initial rise in the Campanian and partial erosion during the early part of the Palaeogene, the ridge was reactivated with the erosional base of the Miocene forming a low-relief fold of some 30–50 m amplitude also striking NNE.

The Salakh Arch and the jabals to the east (Madmar) and west (Qusaybah and Nahada) were uplifted during the later part of the Palaeogene, probably since Miocene times (Hanna and Smewing, 1996), late Miocene-Pliocene (Carbon, 1996; p. 145), early Pliocene (earliest wadi gravels noted by Maizels and McBean, 1990) or Pliocene-Pleistocene (Hanna, 1990). The Natih Formation, and locally the Nahr Umr Formation, are exposed at the present-day surface. The uplift brought the Natih Formation some 1,000-1,500 m above its regional level. The Salakh Arch and related structures (Jabal Qusaybah, Jabal Nahada, and Jabal Madmar) post-date the formation of the Habiba-Khatmah Ridge (Figure 3).

**STRUCTURAL INTERPRETATION**

**Late Cretaceous Structural Styles in the Carbonate Platform of North Oman**

The stratigraphic sequence in north Oman can be subdivided into six geomechanical units (Figure 20). The fault frequency is highest in the brittle or incompetent Mesozoic carbonates of Unit III. Fault density decreases both downwards and upwards from the top Natih. Some 30% fewer faults are
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observed at top Gharif and less then 5% continue upwards to offset the base Palaeogene at the top of the Natih Formation. Only the largest faults with vertical offset exceeding 200–1,000 m as mapped on 3-D and 2-D seismic data (e.g. Fahud Fault, Maradi Fault Zone, Burhaan Fault, Habiba-Khatmah and Faults) affect the entire succession from post-Fiqa to the Palaeozoic Haima Supergroup.

Many of the smaller faults mapped with 3-D data within the carbonate sequence, appear to form “conjugate” sets (Lekhwair and Dhulaima fields, Makarem High) with fault intersections or branch-lines oriented sub-vertically and sub-horizontally. Many of these faults occur in pairs bounding narrow grabens. The sub-parallel, steeply dipping faults coalesce within the carbonate sequence or above the Gharif Formation. Strains, measured in terms of vertical offset, at the top of the Natih are greater than at the top of the Gharif. However, strains are relatively small; the larger faults accommodate approximately 0.5% average strain (extensional component) across the northern part of Block 6 to central Oman (some 400–500 km). Including smaller faults, average strains reach 3% measured in a NE-SW direction across north Oman. Distributed extension with strike-slip deformation is prevalent across this “foreland” domain. However, with the exception of the Maradi Fault Zone, the horizontal displacement is probably less than or equal to the vertical displacement. This interpretation is based

Figure 17: Surface illumination map at Natih E level along the Maradi Fault Zone. Subsidiary faults oblique to the main bounding faults on either side of the Maradi Fault Zone (MFZ) as well as fault “horsetails” are indicative of a component of sinistral movement on the MFZ during the late Cretaceous. Timing of movement is defined by growth of the Fiqa Formation in grabens along the fault zone (see Figure 16).
on the fact that the vast majority of the observed fault geometries are still broadly segmented and linear rather than connected and sinuous as expected in zones with substantial strike-slip components (Richard et al., 1995).

Three major fault-orientation families can be defined:
Figure 19: Surface illumination map at Natih E level from the Kauther 3-D (south of the Salakh Arch). En-echelon faults have developed along an E-W lineament with a dextral sense of displacement. The Maradi Fault Zone is contemporaneous and had a sinistral sense of displacement (see Figures 17 and 18). The Habiba ridge formed as an anticline together with NE-SW faults in the Paleogene.

1. en-echelon, left-stepping arrays with minor dextral strike-slip displacement oriented E to ESE;
2. a complementary set of en-echelon, right-stepping arrays with minor sinistral strike-slip oriented NNW to N. The acute angle between these arrays is approximately 65-70°; and
3. faults oriented northwest.

For the majority of these Late Cretaceous (Campanian age) faults mapped with 3-D seismic data, the orientation of maximum horizontal stress is inferred to have been 125-135° (southeast, Figure 4).
Distributed faulting and more restricted folding took place from the end of the Santonian through the Campanian (a period of some 20–25 my), and locally continued until the early part of the Palaeogene, as evidenced by the slight undulation in the base Palaeogene unconformity in the Kauther area, for example (cf. Marzouk and Abd El Sattar; 1995; and Immenhauser et al., 2000). The maximum horizontal stress was oriented NW-SE probably until the early Miocene (Table 1). Farther west, Al-Mehsin et al. (2002) described fault orientations in the Asab field primarily in two families NNW and WNW. These families are similar to the trends observed across the northern region of Block 6. Marzouk and Abd El Sattar (1995), however, reported a more E-W orientation of the maximum horizontal stress in Abu Dhabi).

The deformation in the Mesozoic carbonates (Unit III, Figure 20) is effectively detached above the underlying Haushi and Haima clastic units. Deformation in these deeper units, as well as in the Ara Salt, was probably accommodated by ductile strain.

### Table 1: Summary of Structural Styles, Kinematic Indicators and Interpretation in the Northern Part of Block 6, Oman.

| Region         | Kinematic Indicators                                                                 | Interpreted oriented orientation of Late Cretaceous S\(_{\text{max}}\) | Shu'aiba-Natih Fault orientation families | Gharif Fault orientation families | Evidence for timing                                                                 |
|----------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------|----------------------------------|-------------------------------------------------------------------------------------|
| North Oman Platform |                                                                                      | Mode: 125°<br>Secondary peaks: 005°, 035°                                | Mode: 125°<br>Secondary peaks: 005°, 035° | No data                          | Pre-Shammar truncation of Fiqa and Natih formations post-dates faulting; uplift of Lekhwair High also post-dates folding |
| NW Lekhwair    | "Conjugate" pairs of steep faults                                                   | 140°                                                                   | Set 2: 125°<br>Set 3: 160°              |                                  |                                                                                      |
| Al Huwaisah    | Fault array of NNW-oriented faults arranged on N-S basement lineament                 | 125°                                                                   | Set 1: 095°<br>Set 2: 120°<br>Set 3: 140°<br>Set 4: 020° | Set 2: 115°<br>Set 4: 055°<br>Set 5: 035° | Faults cut Gharif through Natih and partly into Fiqa; faults do not enter Tertiary |
| Natih          |                                                                                      | 120°                                                                   | Set 1: 095°<br>Set 2: 120°<br>Set 3: 145°<br>Set 4: 020° | Set 1: 095°<br>Set 2: 120°<br>Set 4: 050°<br>Set 5: 175° | Natih reverse fault causes Tertiary fold                                           |
| Fahud SE       | En-echelon fault arrays of NNW-SSE faults arranged along NNW-SSE lineaments           | 120°                                                                   | Set 1: 095°<br>Set 2: 125°<br>Set 3: 145° | Set 1: 095°<br>Set 2: 120°<br>Set 4: 050°<br>Set 5: 175° | Santonian-Campanian extensional growth faulting; Later Fahud fault inversion causes Tertiary fold |
| Musallim       | "Conjugate" pairs of steep faults oriented NNW-SSE and WNW-ENE                       | 120°                                                                   | Set 1: 095°<br>Set 2: 120°<br>Set 3: 145° | Set 1: 105°<br>Set 2: 125°<br>Set 3: 145° | Faults cut Gharif through Natih and partly into Fiqa; growth of Fiqa               |
| Burhaan        | "Conjugate" pairs of steep faults oriented                                          | 125°                                                                   | Set 1: 095°<br>Set 2: 125°<br>Set 3: 150° | Set 1: 105°<br>Set 2: 125°<br>Set 3: 155° | Santonian-Campanian extensional growth faulting                                    |
| Maradi         | NNW-ESE fault system with NW-SE-oriented splay                                       | 125°                                                                   | Set 1: 095°<br>Set 2: 125°<br>Set 3: 150°<br>(Main Fault) | Set 1: 095°<br>Set 3: 145°<br>(Main Fault) | Santonian-Campanian extensional growth faulting                                    |
| SE Kauther     | En-echelon fault arrays of NW-SE oriented faults arranged above E-W oriented lineaments | 120°                                                                   | (Set 1: 095°)<br>Set 2: 125°<br>Set 3: 145°<br>Set 4: c. 045° | Set 2: 135°<br>                                                                 | Santonian-Campanian extensional growth faulting                                    |
In this section we briefly describe the result of a transtensional sandbox experiment to support our kinematic interpretation of the fish-net pattern of conjugate faults observed in north Oman. We also illustrate with a cross-section the results of a plain strain experiment conducted under an X-ray tomograph. It shows how the faults converge at the interface between the brittle and more ductile layers (from Filbrandt et al., in preparation).

The sandbox models consisted of a 2.4 cm sand layer (0.1 mm grain size) overlying a layer of low viscosity putty 0.8-cm-thick. Sand and putty provide good analogues for modelling both the brittle behaviour of the upper crust (e.g. Natih and Shuaiba carbonates) and more ductile units (e.g. Palaeozoic clastics and salt) within it, that behave as detachment layers. A discussion of the experimental scaling is beyond the scope of this paper but is discussed in detail by Hubbert (1937), Ramberg (1967), Horsfield (1977), Vendeville et al., (1987), Richard and Cobbold (1990) and Richard (1991).

The transtensional strain was applied to the model by stretching a rubber sheet beneath the putty layer at a constant velocity (4.6 cm/hr). The stretching was obtained by a combination of extension and shear (Figure 21). Scaling is such that 1 cm in the model represents about 0.5 km in nature, and the strain rate is equivalent to 1 cm/yr at crustal scale.

The transtensional strain applied to the model resulted in a conjugate set of transtensional faults (Figure 22). Both sets were active simultaneously (Figure 22a). The central part of the experiment was dominated by NW-SE faults while the northern and southern parts of the experiment were dominated by NNW-SSE faults. This is explained by the boundary conditions of the model. The NW-SE and NNW-SSE-oriented faults accommodate right-lateral and left-lateral transtensional deformation, respectively. With increasing deformation, the graben structures are clearly visible due to increasing vertical offset (Figure 22b).

In cross section, the faults initiated at the free surface of the model and converged at the sand-silicone interface where they intersected to form narrow grabens. Figure 23 illustrates the vertical growth...
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Figure 21: Experimental configuration for detached transtensional deformation. A thin rubber sheet (0.2 x 120 x 120 cm) attached to two metal plates lies on a flat horizontal rigid table divided in two halves. The rubber sheet was stretched by simultaneously withdrawing the metal plates and moving laterally one-half of the table past the other half, to create a shear component. To maintain a constant sheet length perpendicular to the resulting extension direction, the two other sides of the rubber sheet were fixed to a series of rings sliding along rigid bars.

Figure 22: Sequential top view of transtensional sandbox model. (a) At an early stage of the deformation a conjugate set of transtensional faults developed in the central part of the model. (b) With increasing deformation the transtensional nature of the faults is clearly marked by narrow grabens accommodating increasing vertical displacement.
process of the fault in a plain strain experiment with similar rheology (from Filbrandt et al., in prep).

CENOZOIC (TERTIARY) SHORTENING

A small number of faults with minor offset on sub-surface data within Block 6 oriented between 10-50° (average orientation 30-35°) was mapped and identified as distinct late Palaeogene fault-orientation families (e.g. Figures 9 and 17).

These sets are interpreted to have formed at the end of the Palaeogene period, under a NNE-SSW-oriented, regional stress regime. This regime also led to the formation of the Fahud and Natih folds and the Salakh Arch and is broadly orthogonal to the mapped trend of fold axes. The frequency and density of these fault sets decreases with distance from the Natih field from north to south. In addition, the fold axial trend of the Al Jabal al Akhdar and Saih Hatat uplifts and related unroofing may have been a result of this contractional event.

Farther north and east of Block 6, Eocene to Oligocene syn-depositional movement on the North Ja’alan Fault (Filbrandt et al., 1990; Carbon, 1996) and kinematic interpretation suggest sinistral displacement with maximum horizontal stress oriented NW-SE to E-W. Evidence for this event in Block 6 is possibly observed in the Kauther area (Figure 19) with the folding of the base Miocene.

Later E-W to ENE-WSW-oriented compression led to the reactivation of pre-existing faults with a small strike-slip component (e.g. North Ja’alan Fault; Carbon, 1996; p. 261).

Regional Uplift since Late Cretaceous Times (Post-Natih Formation)

Uplift in north Oman has been estimated in two ways.

(1) Total residual uplift was determined at well locations using seismic velocity or well log-derived porosity data for the lower part of the Shargi Shale (Fiqa Formation, Santonian–Campanian age), Natih and Shu’aiba formations and the Nahr Umr Formation. These data were combined and provide a regional overview of the uplift observed relative to burial trends (Figure 24). Burial-related base-line trends were semi-quantitatively constructed for each data set and compared with seismic data and subcrop maps constructed from well data (Figure 24).
Figure 24: Uplift in north Oman. (a) Distribution of uplift in north Oman. Regional uplift reaches 500 to 1,500 m and is mainly restricted to the northern part of Block 6 and along the zone of salt piercements in the Ghaba Salt Basin. The magnitude of uplift is based on seismic velocity anomalies in lower Fiqa pelagic shales, and porosity anomalies in the Natih and Shu'aiba limestones and Gharif sandstones. (b) Examples of velocity data and trend used to determine the uplift.
(2) Subcrop maps were prepared based on detailed identification of formations in wells below regional unconformities. Regional tilt was established by estimating the amount of erosion relative to the total (undecompacted) thickness of the formations in basinal positions.

The unconformity at the base of the Fiqa Formation (Coniacian to Santonian) is associated with limited regional uplift in northern Oman (Figure 25). From the thickness distribution and the preserved thickness of the Natih Formation, it appears that minor uplift occurred at that time (Coniacian), in the order of 100-200 m, in the northern part of the area. In the central and southwestern area towards central Oman, the entire Natih sequence has been preserved (Figure 25). Locally, channels erode deeply (up to 200 m) into the Natih Formation (Figure 26), for example over the Yibal, Fahud or Natih fields. On Yibal field, sufficient well data coverage is available to clearly define a major N-S-oriented, Coniacian or Santonian channel on its eastern flank with several minor erosional scours on the central and eastern flanks. Similarly, over Fahud and the Natih fields, well data allow the construction of subcrop maps that suggest there was fault movement probably associated with salt migration. A similar degree of erosion (approximately 100-200 m) of the Natih Formation is observed towards the east, approaching the Huqf High.

Uplift at the end of the Cretaceous was more pronounced and localised (cf. Lekhwair High, Figure 7) and the greatest amount occurred in the far west of Block 6. At the scale of our map, the subcrop pattern, east of the Maradi Fault Zone (MFZ), does not provide an unambiguous indication of the stress field at the time. However, the elongation of the Lekhwair High (approximately NE-SW) could be interpreted to have been caused by NW-SE-oriented maximum horizontal stress. The MFZ separates two domains (Figure 7 and 15): in the west the Palaeogene is preserved below the Fars Unconformity, whilst in the east the Neogene rests directly on Late Cretaceous sediments. We infer that the MFZ may have been active at least at the end of the Palaeogene (late Eocene and Oligocene), probably under the same stress system as the North Ja’alan Fault (Filbrandt et al., 1990).

During the Palaeogene, the regional tilt was reversed (as compared to the Late Cretaceous-early Palaeogene) with increasing uplift and erosion towards the Huqf High (Figure 15).

**Distribution of Total (Residual) Uplift**

On a regional scale the uplift of central Oman and southwestern parts of north Oman was much more limited in comparison to the eastern (Huqf) and northeastern (Al Jabal al Akhdar) margins of the Arabian Plate. These margins were uplifted several hundred metres, probably reaching well over 3,000 m in the central parts of Al Jabal al Akhdar, since the Late Cretaceous (Figure 24). Further work, e.g. illite crystallinity of the Muti and Fiqa shales in the Oman Mountains, is required to constrain the amount of inversion and erosion more precisely.

A narrow zone of uplift (generally less than 5 km wide) can be defined along the Maradi Fault Zone, Salakh Arch and localized areas associated with the salt domes in the eastern part of the Ghaba Salt Basin. Uplift in these areas reached 2 km and most uplift occurred during the Miocene and Pliocene-Pleistocene (Figure 24) with a more limited amount at the end of the Cretaceous. NE-SW-oriented compression caused the inversion of Fiqa-aged faults and Palaeogene deposits in the Fahud and Natih fields during the later part of the late Palaeogene and Neogene. This Neogene localized uplift was probably associated with the collision of the Arabian Plate with the Iran and Eurasia Plate.

**SUMMARY OF STRUCTURAL EVENTS**

The weight of evidence derived from kinematic indicators interpreted from 3-D seismic data in Block 6 of north Oman, strongly suggests that the maximum horizontal compressive stress was oriented approximately NW-SE during the Santonian-Campanian. The persistence of this orientation until the Palaeocene to Oligocene is supported by the SW-NE-oriented uplift over the Lekhwair High, localized deposition of the Simsima Formation and inversion of the Habiba-Khatmah Ridge east of the Maradi Fault Zone, as well as sinistral movement of the North Ja’alan. A similar structural fabric
has been reported in the United Arab Emirates and northern parts of Saudi Arabia (ADCO Staff, 1986; Marzouk and Abd El Sattar, 1995; Al-Mehsin et al., 2002; Sadler, 2002; Strohmenger et al., 2002).

South of the present-day trace of the frontal thrust at the base of the Hawasina Nappes there is limited subsurface evidence for S- or SW-directed thrust-related structures of similar age (Campanian). The stable Late Cretaceous carbonate platform between the Central Oman High and the Natih field (close to the northern boundary of PDO’s Block 6 concession) appears unaffected by contractional structures. This is remarkable as the Semail Ophiolite and associated Hawasina Nappes are exposed only a few kilometers to the north of the structural domain described.

Figure 25: Base Fiqa (base Santonian-Coniacian) subcrop map based on well data illustrating general thinning and uplift towards the north, northwest and southeast at the end of carbonate deposition.
Between about 85 to 70 Ma, the Indian block (and possibly the Afghan continental blocks) moved northward (Figure 27). The emplacement of the Masirah Ophiolite fragment and westward-verging folds in basinal sediments, east of Jabal Ja’alan, provide evidence for a Late Cretaceous to early Palaeocene collision event (e.g. Mountain and Prell, 1990; Shackleton and Ries, 1990; Shackleton et al., 1990; Marquer et al., 1995; Pilcher et al., 1996; Immenhauser et al., 2000). We distinguish the two “events” to emphasize the strong difference in structural character (fault geometries, kinematics) within the two domains resulting from inferred stress systems that appear to have been orthogonal to each other at similar times.

The combined effect of the Semail Ophiolite obduction and nappe emplacement in the north, together with the obduction of the Masirah Ophiolite in the east, provided the boundary conditions to form the fault structures, mainly during the Campanian, as evidenced by growth on faults in north Oman. It is also interesting to note that, with the exception of deformation associated with salt dome growth in the Ghaba Salt Basin, this Late Cretaceous deformation was probably the first, basin-wide tectonic event of significance to have affected the carbonate platform sediments since the Late Palaeozoic. New traps were formed and existing structures accentuated while the faults provided vertical migration pathways for hydrocarbons into the prolific Natih and Shu’aiba reservoirs.

Miocene and younger fold orientations (Boote et al., 1990; Al-Mehsin et al., 2002) provide evidence of NE-SW-oriented maximum horizontal compression. The post-Fars tilt of 0.5-1.0° of the Palaeogene foreland of the Zagros Collision is most pronounced in northern Oman and west of the Musandam Peninsula and is dated as early Miocene (Boote et al., 1990; Robertson et al., 1990).

**IMPLICATIONS FOR HYDROCARBON MIGRATION AND FRACTURE GENERATION**

The initiation and growth of faults during the Santonian and Campanian provided local pathways between pre-existing intra-Permian and deeper accumulations, and shallower Cretaceous reservoirs. Vertical migration from the Gharif first into the Shu’aiba and then the Natih formations took place along faults acting as conduits and by reservoir-carrier bed juxtaposition (Figure 28). Vertical migration from Gharif traps (Figure 29) and carrier beds by fault juxtaposition, first to Shu’aiba and then to Natih reservoirs, was achieved across fault with throws that exceeded the thickness of the Khuff Formation top seal (Richard et al., 1998). In the North Oman fields investigated in this study, the Khuff ranges in thickness from about 100–900 m. Throws of this scale are associated only with the
largest Late Cretaceous faults: for example, Fahud, Natih, Burhaan, Saih Rawl grabens and one or both sides of the grabens forming part of the Maradi Fault Zone. These faults were active during the latest Santonian (about 84 Ma) to Campanian (71 Ma) times and probably represent the earliest and perhaps the only entry points for hydrocarbons to migrate into the overlying, hitherto unfaulted, Mesozoic carbonate platform. This mechanism would have allowed only localized access for hydrocarbons derived from infra-Cambrian source rocks into shallower reservoirs (Terken et al., 2001).

Transfer of hydrocarbons from fault-bounded traps in the Shu’aiba Formation, or carrier beds to the overlying Natih Formation, may have occurred by juxtaposition of reservoir against reservoir for fault throws that exceed 60–100 m (the thickness of the Nahr Umr top seal in north Oman). Vertical migration to the reservoirs of the Natih Formation, thus, depends on a relatively small number of faults (as indicated by fault throw analysis), and is one of the reasons why closures at this level are not always charged (Figure 30). Local, lateral (not vertical) charge of Natih reservoirs in the Fahud field, for example, by Natih source rocks is restricted to the northernmost part of Block 6. Here the Natih kitchen is more deeply buried (Nederlof et al, 1994) and the source rocks reached the oil window in the later part of the Cenozoic. Late Cenozoic faulting resulted in breaching of Natih and Shu’aiba traps along the Maradi Fault Zone.

Active faults that do not juxtapose carrier beds against another carrier bed or reservoir interval, may also act as vertical conduits (Wiprut and Zoback, 2000; Ferrill and Morris, 2003). Active slip associated...
Fault throw determined at Gharif level. Some of the main hydrocarbon entry points from the Gharif into overlying reservoirs are highlighted by arrows. Only the largest faults are illustrated. The size of the circle is defined by vertical offset on the faults. The majority of faults were emplaced during the Campanian and provide the first entry points for hydrocarbons to migrate into carbonate reservoirs at shallower levels. Present-day discoveries and fields at Gharif level are illustrated, and were the probable source of hydrocarbons for migration. The faults and fields are overlain on the Aruma Group isochore map (i.e. base Tertiary to top Natih A Formation). Note that Tertiary displacement associated with inversion on the Fahud, Natih and Maradi faults has not been restored. The thickening of the Aruma Group increases towards the north. Locally, erosion at the base Tertiary unconformity removed substantial amounts of the Aruma Group.
with fault activity causes dilation on fractures related to the fault zone. Dilation and maintenance of partially open fractures may allow permeation and ascent of hydrocarbon fluids from deeper to shallower reservoirs vertically up the fault zone conduit.

Figure 30: Fault throw determined at Natih level. Some of the hydrocarbon entry points illustrated by arrows on faults mapped at Natih level. Only the largest faults are illustrated. The size of the circle is defined by vertical displacement on the faults. The majority of faults were emplaced during the Campanian times, and provide the first entry points for hydrocarbons to migrate into carbonate reservoirs from deeper levels. Entry points for hydrocarbons from Shu'aiba traps into the overlying Natih Formation are indicated. Present-day discoveries and fields at Natih level are illustrated. “Dry tests” are indicated in blue and are located at relatively large distances from faults.
It is likely that both juxtaposition and dilatant fault conduits associated with a relatively small number of faults provided access for charge only since the Campanian into post-Gharif reservoirs, principally the Aptian Shu’aiba and Albian Natih formations. The dilatant conduits were likely to have closed as displacement stopped, as the minimum horizontal stress (oriented NE-SW) increased or as the maximum horizontal stress decreased (oriented NW-SE) at the end of the Cretaceous and early Palaeogene times. The orientation of the maximum horizontal stress rotated from NW-SE (Late Cretaceous) to NE-SW in the late Palaeogene and early Neogene.

Timing of Hydrocarbon Migration into Shu’aiba and Natih Reservoirs

Fault activity in north Oman during the Late Cretaceous is restricted to the interval late Santonian to late Campanian, a period of some 10 to 15 my. By the Maastrichtian or Palaeocene, fault activity in north Oman appears to have largely ceased.

Hydrocarbon ascent and vertical migration could be achieved by juxtaposition of carrier beds and reservoirs from the Gharif to the Shu’aiba and Natih formations (a vertical path of some 2,000 m), and local conduits formed by active fault movement. The access of hydrocarbons by cross-fault juxtaposition into shallow (Shu’aiba and Natih formations) traps that were formed during the Santonian and Campanian was potentially limited by available hydrocarbon supply from deeper Gharif traps and source rock maturity.

Shallow traps are at risk of underfill, particularly for those that are at significant distances from fault entry points (Figures 29 and 30). The distribution of known Natih and Shu’aiba fields in north Oman is strongly correlated with the presence of faults with large throws. The most likely entry points can be established through fault throw and juxtaposition analysis. Thus, the charge access risk in prospects can be evaluated according to fault throw and fault activity along mapped fault segments.

IN-SITU STRESS ORIENTATION

Borehole breakouts and induced fractures in Oman suggest that the orientation of the present-day first-order maximum horizontal in-situ stress is oriented NE-SW (Figure 31). Drawing on a data set of over 30 wells, 70% of data (excluding intra-salt determinations) support this interpretation. A minor proportion of wells indicate that at least locally, perhaps associated with active faults, the maximum horizontal in-situ stress is re-oriented to NW-SE or E-W. This regional stress direction is probably induced by ridge push from the Red Sea and Gulf of Aden, relative converging motion of the Arabian and Iranian Plates (McClusky et al., 2003), and slab pull related to the subduction of oceanic plate in the Makran Zone.

Slip Tendency (Ts) and In-Situ Stress

Fracture permeability can be enhanced by shear failure along active faults where slip results in rupturing and opening of fault planes and associated fractures, hence causing episodic fluid flow (Sibson, 1992; Heckman et al., 1995; Barton et al., 1995). In recent years, prediction of fault reactivation has become an integral part in the work flow of assessing fault-sealing potential (e.g. de Ruig et al., 2000 in the Timor Sea; Wiprut and Zoback, 2000 in the northern North Sea; Finkbeiner et al., 2001 in the Gulf of Mexico). One method to investigate the potential of fault reactivation is through the concept of slip tendency (Morris et al., 1996). The analysis is used to assess the tendency of critically stressed pre-existing faults to slip, as a function of magnitude and orientation of the current in-situ stress field. Fault properties including cohesive strength (Co) and coefficient of friction (µ) are used in the analysis.

Slip-tendency analysis was used to assess which large faults are critically stressed and likely to undergo re-activation under the current in-situ stress regime in north-central Oman. Reactivated faults and associated fractures act as potential fluid pathways for hydrocarbon and therefore the slip-tendency analysis identifies which of the faults is potentially a conduit for hydrocarbon migration.
The average magnitudes of the present-day stresses in north-central Oman are 24.3 kPa/m for vertical stress ($\sigma_v$), 19.4 kPa/m for minimum horizontal stress ($\sigma_h$) and 34.3 kPa/m for maximum horizontal stress ($\sigma_H$) (PDO-GMI Internal Report, 2004). This means that the present-day regional tectonic stress regime in north-central Oman is strike-slip (maximum and minimum stress horizontal; intermediate stress vertical). The carbonate reservoirs in north-central Oman are at hydrostatic pressure. Hence, fluid pressure ($P_f$) gradient is assumed to be 10.0 kPa/m. The overall orientation of the present-day maximum horizontal stress in north-central Oman is NE-SW as supported by breakouts and induced fractures from bore hole images. The analyses are based on a compilation from various depths carried out by GMI, Baker Atlas, Schlumberger on behalf of PDO, and summarize data from different formations in each well.
The average magnitude and orientation of present-day stress were used in the slip-tendency analysis. The fluid pressure was assumed to be hydrostatic and faults were assigned a coefficient of friction ($\mu$) of 0.6. The result of the analysis (Figure 32) suggests that today faults or fault segments that are oriented W to WNW and N to NNW have the highest slip potential (Slip Tendency of 0.8). Under the present-day stress regime there is a risk that fault-dependent traps, whose fault orientations lie close to the W to WNW and N to NNW trends, may have been breached. Campanian-aged faults, oriented at the critical angle relative to the present-day stress, have a higher slip tendency and are more likely to have been reactivated in this stress regime. These faults (red color in Figure 32) may have acted as conduits for hydrocarbon migration since early Neogene time. Sections of the MFZ, particularly in the north (Figure 32), are presently close to critical stress (high slip tendency, red on Figure 32).

The combination of juxtaposition of reservoirs and carrier beds together with temporally distinct Late Cretaceous and Neogene activity on the Maradi Fault Zone makes it a significant pathway for hydrocarbon migration over the last 85 Ma. Other faults were either only intermittently active, or did not have sufficient throw to allow cross-fault flow through reservoirs and carrier beds. Their relative importance as entry points for hydrocarbons, or subsequent loss from traps, is lower than the Maradi Fault Zone.
The Late Cretaceous and late Palaeogene-Neogene collisions imparted a consistent fault and fracture pattern in the Mesozoic carbonates in north Oman. Both subsurface and surface data can be combined into a conceptual model of fault and fracture distribution in the foreland area south of the Oman Mountains and the frontal thrust of the Late Cretaceous nappes. Fault and fracture systems of a similar age, density, frequency and geometry can be readily examined on Al Jabal al Akhdar, north Oman in the Natih Formation (Figure 33) both on a sub-metre scale and on a kilometre (oil field) scale. However, we are cautious to draw specific conclusions about fracture fill and diagenesis due to the considerably greater burial depth below the overburden of nappes, including several kilometers of obducted oceanic crust on Jabal Akdhar. The framework below provides a summary of these fault families and related fractures in the carbonate platform south of the Oman Mountains that could be used as an initial model in fractured reservoir studies in Mesozoic carbonates, especially the Natih and Shu’aiba formations.

1. Two fault families, oriented between 100–110° and 130–160°, are related to the Late Cretaceous collision with the India Plate. These are most likely calcite filled (see Figures 34–36) and closed or at best partially open. On electrical borehole image (BHI) logs, the fractures related to these faults are seen as predominantly electrically resistive and commonly interpreted as non-fluid conductive or closed features. These fractures can form barriers or baffles in reservoirs and inhibit or restrict flow leading to potential compartmentalisation of the reservoir perpendicular to their strike direction. The fault zones may still act as flow conduits parallel to their strike when they are only partially cemented.

2. NE-SW-oriented compression and inversion during the Miocene to Recent collision of the Arabian Plate with the Iran/Eurasia Plate(s) probably induced the formation of new fractures. On resistivity-based BHI logs, the NE-SW fractures are seen as predominantly...
Figure 34: Aerial photograph of fault planes intersecting the top of the Natih Formation on the southern slopes of Al Jabal al Akhdar. Fault orientations are dominantly 100° with a secondary set oriented 130°. The faults cut down from the top of the Natih Formation to the base of the Mesozoic carbonate section (see Figure 36), and appear to converge within the Salil and Rayda formations (i.e. towards the base of the Kahmah Group). For location of figure see Figure 33.

Figure 35: (a) Locality 5 km east of Tanuf (Al Suwaihariah, north side of Tanuf-Nizwa road on southern slope of Al Jabal al Akhdar) illustrating faults emerging at the top of the Natih Formation. The fault at right has a maximum throw, $T_{max}$, of c. 3 m and fault arrays suggest a small component of sinistral strike-slip on the fault zone; note the development of subordinate, en-echelon, minor faults and fractures between the two larger faults (at left and right of the figure). Fractures are concentrated over a width of about 1 m around the slip surface and oriented approximately 100°. Later joints are oriented NNE-SSW. (b) Conjugate, calcite filled-fractures in en-echelon arrays associated with damage zone at tip of fault in the Natih Formation.
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**Figure 36:** Faulted limestones of the Salil Formation (some 1,000 m below the Natih Formation on the southern slopes of Al Jabal al Akhdar in Wadi Nakhr). Note the conjugate system of faults along which a calcite/dolomite breccia and gouge have developed. A damage zone of approximately 0.5 m has formed on the fault with a throw of 10 m.

**Figure 37:** A conceptual model for fault and fracture systems that occur in the Mesozoic carbonates south of the Oman Mountains and in Block 6. Late Cretaceous (Campanian) faults and fractures formed mainly in two families: E-W to WNW-ESE and NW-SE to NNW-ESE. NE-SW oriented compression as a result of continued contraction in the Makran and on the Zagros fault zones created late Tertiary faults and pervasive joint sets of similar orientation. The contractional regime caused local inversion of pre-existing normal faults (e.g. Fahud Fault) and dextral movement on the Maradi Fault Zone.
electrically conductive. These fractures are commonly interpreted as open features and form important conduits to fluid flow in, for example, gas-oil gravity drainage or water flood field development. Faults associated with this fracture orientation are relatively rare, but have been observed on, for example the Natih (Figure 17 and Table 1) and Fahud fields.

A synopsis of the conceptual model for the fault and fractures systems is presented in Figure 37. We recognise that this simple framework will be modified by uplift (predominantly regional, late Palaeogene and Neogene inversion) associated with probable contraction of the limestone reservoirs. This effect will be particularly pronounced in the area north of Block 6, in the Oman Mountains and foothills, as well as around salt domes in the Ghaba Salt Basin (we have deliberately excluded discussion of these in our model).

CONCLUSIONS

The observed fault geometries of Late Cretaceous age in the carbonate platform, south of the Oman Mountains, and our kinematic interpretation suggest that the maximum horizontal compressive stress was oriented NW-SE during the late Santonian and Campanian (possibly until the early Palaeogene) in the northern part of Block 6 (PDO concession). This interpretation contrasts with the direction of emplacement of the Turonian Semail Ophiolite immediately to the north of the concession. Shortening of the Arabian continental margin as well as the northern part of the carbonate platform related to the obduction culminated in the Campanian. We relate the NW-SE compressive stress to an oblique collision between the Indian–Afghan continent with the Arabian Plate during the Santonian to Campanian period some 85 to 75 Ma ago. We believe this stress field also affected the northern edge of the Arabian Plate, now exposed in the Oman Mountains. The characteristics and structural grain (thrusting in the north, strike-slip farther south) of the two domains belonging to the two events overlap there. Emplacement of the Masirah Ophiolite from the E-SE is believed to have taken place during the Maastrichtian to early Palaeocene (Schreurs and Immenhauser, 1999; Immenhauser et al., 2000). However, the pervasive nature of the faulting across northern Block 6 and striking similarity in geometry strongly suggest that tectonic activity may have begun at the eastern margin of the Arabian Plate in Campanian and continued into the Campanian. Accurate dating of fault activity in the Huqf – Haushi region would provide a key piece of evidence to test this hypothesis.

We have noted that there is little or no evidence on seismic data for major fault movement in north Oman prior to the late Santonian since and after the deposition of the Khuff carbonates or Gharif clastics other than around salt domes in the Ghaba Basin. Indeed, the major faults (Fahud, Burhaan, Saih Rawl and Maradi) can be shown to have accommodated significant growth only in the Campanian. Thus, the Mesozoic carbonate platform in north Oman remained largely stable, undisturbed by faulting and subsided gradually until that time.

The oblique collision along the eastern margin of the Arabian Plate with India caused the partial foundering of the platform across north Oman as growth faults, with a component of strike-slip, were emplaced in the Mesozoic carbonates. This event created fault-bounded traps (e.g. the Fahud and Burhaan fields) and allowed hydrocarbons to migrate for the first time from pre-existing traps in Gharif reservoirs, along faults, into reservoirs of the Shu’aiba and subsequently into the Natih Formation. The Fiqq shale, top seal to Natih traps, would have reached several hundred metres in thickness by late Campanian time. Areas with low fault densities and faults with small throws, that do not exceed the thickness of the Khuff and the Nahr Umr seals, have a high charge risk.

Localized uplift, around Lekhwair, the Maradi Fault and the Huqf High occurred prior to the deposition of the Palaeocene Shammar Shale. Uplift in excess of 1,000 m has been estimated locally over the Lekhwair High. The southwest part of the study area, from the Musallim Slope to the Central Oman High, appears to have remained a relatively stable block displaying limited or no uplift.

During the Oligocene and Miocene, the collision between the Iran/Eurasia Plates and the Arabian Plate resulted in NE-SW-oriented compression, supported by interpretation of borehole breakouts and induced fractures. Although deformation associated with this event was more widespread to the north of Block 6 (Oman Mountains, Saih Hatat and foothills), in our study area the effect was more localised and restricted to the northern part. The well-known folds associated with the Fahud...
and Natih faults developed at this time, enhancing the relief of existing structures and providing additional trap volume for these world-class fields. Along the Maradi Fault Zone, however, Miocene and later fault slip led to breaching of existing fault traps. Further structural analysis on Cenozoic outcrops at the northern and eastern margins of Oman would help to constrain the timing of the reorientation of the stress field from NW-SE (Late Cretaceous) to NE-SW.

The fracture systems associated with these two events provide distinctly different contributions to carbonate field development in north Oman. A simple framework is proposed in which fractures oriented NNW-SSE or WNW-ESE associated with Late Cretaceous faulting are now mainly closed. This system was superposed by mainly open fractures oriented NE-SW during the later part of the Palaeogene through to the present-day.

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