Tertiary–Quaternary faulting and uplift in the northern Oman Hajar Mountains

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Abstract: Field mapping and remote sensing investigations reveal two new major fault sets cutting through Tertiary rocks, Quaternary terraces and a several-hundred-year-old irrigation canal system in the Hajar Mountains of northern Oman. They extend for tens of kilometres, forming fracture intensification zones several hundred metres wide. WNW- to NW-oriented faults run parallel to the mountain fronts in the plains adjoining the central Hajar range then obliquely crosscut the mountains in the north. Motion along these faults explains how Quaternary marine terraces became elevated 190 m above sea level. A second fault set strikes north to NNE. The associated juvenile topography suggests that they also accommodate recent uplift, subsidiary to the WNW-striking faults, with minor strike-slip and differential movement between various segments of the Hajar Mountains. Both fault systems, and the amount of Quaternary uplift (between 100 and 500 m), are similar to those in other active and ancient forebulge environments. Using the fracture patterns observed, it is proposed here that the Hajar range lies on the active forebulge of a collision zone between the NE margins of the Arabian plate, the Zagros fold belt and the Makran accretionary prism, which resulted in the recent uplift.

Keywords: Oman, Hajar Mountains, satellite images, plate collision, uplift.

Combined use of satellite imagery and targeted high-resolution field mapping is able to yield structural, lithological and other data over large regions that have the potential to yield clues to the tectonic setting and evolution of entire structural provinces.

This paper identifies and describes newly recognized fault sets that may have accommodated Tertiary–Quaternary uplift in the Hajar Mountains of northern Oman and the United Arab Emirates (UAE). A new structural map is presented that is compiled in a geographical information system (GIS) database using Landsat Thematic Mapper (TM), high-resolution SPOT images and Shuttle Imaging Radar (SIR-C) data as base maps. The maps also depict regional systematic relationships between several late fault sets that were previously unknown. Regional and detailed structural field investigations were conducted in areas throughout the Hajar Mountains to confirm satellite image interpretations and to assess the age of the mapped faults.

Some of the newly identified faults have mapable offsets of Tertiary units. They are characterized in the field as zones several metres to several kilometres wide where fault breccia separates less-deformed lozenges of rock and minor faults with striated surfaces. Some are very young features, associated with recent downcutting of drainage, faulting of cemented Quaternary wadi gravels, and in one case, even cutting a falaj (a local name for a man-made irrigation canal system used to tap water seeps from fracture zones). Other examples do not noticeably offset geological map units; therefore, they probably have relatively minor displacements. Owing to the regional dimension of these structures they are called fracture intensification zones in this paper.

The newly recognized fault and fracture zones were not mapped by earlier geologists in the field, possibly owing to a covering by younger deposits. The unique perspective offered through the analysis of satellite images, and the ground-penetrating ability of orbital radar, coupled with regional field investigations, however, has allowed the identification of geomorphological features related to these structures; thus, the discovery of the fracture intensification zones.

Structural setting

The Hajar (meaning solid rock) Mountains in northern Oman and the United Arab Emirates (UAE) are located on the NE margin of the Arabian plate (Figs. 1 and 2). This plate is bounded to the south and SW by the active spreading axes of the Gulf of Aden and Red Sea. On the east and west its border is marked by transcurrent fault zones of the Owen Fracture Zone and the Dead Sea Transform, respectively. On the north the plate is marked by a complex continent–continent to continent–ocean collision boundary along the Zagros and Makran fold and thrust belts (Fig. 1).

The mountains are made up of several major structural units ranging in age from Precambrian to Miocene (Fig. 2). These include a pre-Permian basement, the Hajar unit, the Hawasina nappes, the Samail ophiolite and metamorphic sole, and the post-nappe structural units. Of particular interest are the Quaternary fluvial and marine terraces that are preserved along the flanks of the Hajar Mountains. These can be divided into an older lower cemented terrace and an upper, younger and uncemented terrace group (e.g. Béchennec et al. 1992). They grade both northward and southward into coalesced alluvial fans forming the bajada that flanks the margins of the mountains (Fig. 3). The northern alluvial plains grade into a narrow coastal plain (the Batinah Plain) along the Gulf of Oman.

Rocks of the Hajar supergroup preserve a history of Permian to Cretaceous subsidence of the Arabian Platform on the margin of the Neo-Tethys Ocean (Glennie et al. 1974; Béchennec et al. 1992). Formations that now make up the Hawasina nappes have biostratigraphic ages of 260–95 Ma, and are interpreted to have been deposited on the continental slope and in abyssal environments of the Neo-Tethys Ocean (Glennie et al. 1974; Béchennec
et al. 1992). By about 100 Ma, spreading in the Neo-Tethys generated the oceanic crust of the Samail ophiolite, which was detached in the oceanic realm and thrust over adjacent oceanic crust soon after its formation. Metamorphic ages for the initiation of thrusting range from 105 to 89 Ma (Montigney et al. 1988; Nicolas 1989; Nicolas et al. 1996; Hacker & Liou 1999; Searle & Cox 1999).

The ophiolitic nappes moved toward the Arabian margin, forming the high-grade metamorphic sole during transport, and progressively scraping off layers of the Hawasina sediments and incorporating them as thrust nappes to the base of the ophiolite. The ophiolite reached the Arabian continental margin and was thrust over it before 85–75 Ma (Lanphere 1981; Nicolas 1989) as indicated by greenschist-facies metamorphism in the metamorphic sole and by deformation of the Arabian margin sediments.

Initial uplift of the dome-shaped basement cored antiforms of Jabal Akhdar and Saih Hatat (Fig. 2) may have been initiated during the late collision stages of the ophiolite with the Arabian passive margin, and may have been localized by pre-existing basement horst and graben structures (Le Métour et al. 1995). The location and geometry of these massive uplifts is probably controlled by basement ramps (Bernoulli & Weissert 1987). Uplift of these domes was pronounced during the Oligocene–Miocene, as shown by tilting of Late Cretaceous–Tertiary formations on the flanks of the domes (Glennie et al. 1974; Mann et al. 1990). Mount et al. (1998) have suggested that the uplift of the domes began in the Oligocene, resulting from the propagation of a fault beneath the southern limbs of the folds. Al-Lazki et al. (2002) presented evidence that the uplift of the domes includes a complex history, involving several different events. Some uplift of the domes continues today, whereas much of the Batinah coastal plain is subsiding.

In most of the Hajar Mountains, the Hawasina nappes...
structurally overlie the Hajar supergroup, and form a belt of north- or NE-dipping thrust slices. However, on the southern margins of Jabal Akhdar, Saih Hatat, and other domes (Fig. 2), the Hawasina units form south-dipping thrust slices (Fig. 2). Major valleys typically occupy the contact between the Hajar supergroup and the Hawasina nappes, because of the many, easily erodable shale units within the Hawasina nappes. Several very large (c. 10 km scale) allochthonous limestone blocks known as the ‘Oman Exotics’ are also incorporated into mélangé zones within the Hawasina nappes. These form light coloured, erosionally resistant cuestas including Jabal Kawr and several smaller mountains south of Al Hamra (Fig. 3).

South and SW of the belt of ophiolite blocks, sediments of the Hamrat Duru group are complexly folded and faulted in a regional foreland fold–thrust belt and then grade into the Suneinah foreland basin (Fig. 2; Boote et al. 1990). The Hamrat Duru rocks include radiolarian cherts, micritic limestones, turbiditic sandstones, shales and calcarenite, all complexly folded and thrust faulted in a 30 km wide fold–thrust belt (Fig. 2).

A belt of regional anticlinal uplifts brings up carbonates of the Hajar supergroup south of the main Hajar range, as exposed at Jabal Salakh (Figs 2 and 3). These elongate anticlinal domes have gentle to moderate dips on their flanks, and are cut by several thrust faults that may be linked to a deeper system (Al-Lazki et al. 2002). The folds have been attributed to flower structures developed over deep strike-slip faults (Boote et al. 1990). South of the Jabal Salakh fold belt, the surface is generally flat and covered by Miocene–Pliocene conglomerates of the Barzaman Formation, and cut by an extensive network of Quaternary channels of the active alluvial plain (Figs 2 and 3).

The Hajar Mountains locally reach over 3 km in height at Jabal Shams (Fig. 4). They display many juvenile topographical features, such as straight mountain fronts and deep, steep-walled canyons that probably reflect active tectonism resulting in mountain uplift. The present height and ruggedness of the Hajar mountainous area is a product of Cretaceous ophiolite obduction, Tertiary extension, and rejuvenated uplift and erosion, which was initiated at the end of the Oligocene (Mann et al. 1990) and continues to this day. The Sayq Plateau in Jabal Akhdar ranges from 2 to 3 km in elevation. Jabal Shams, on the margin of the Sayq Plateau, is the highest point in Arabia at 3075 m (Fig. 4). The mountains

Fig. 2. Simplified geological map of northern Oman that shows the Hajar Mountains and major structures. They are composed of several major structural units, ranging in age from Precambrian to Miocene. These include a pre-Permian basement, the Hajar Unit, the Hawasina nappes, the Samail ophiolite and metamorphic sole, and the post-nappe structural units.
decrease in height northward, reaching 2 km in the Musandam Peninsula, where the mountain slopes drop directly into the sea (Fig. 4).

**Data and methods**

Landsat TM and SIR-C radar data are used to produce a new structural map of the Hajar Mountains (Fig. 5) assisted by field observations and SPOT data analysis. Eight Landsat scenes are used in this study; the path and row numbers are: 157–045, 157–044, 158–045, 158–044, 159–045, 159–044, 159–043 and 159–042. Six L-band and 6 C-band SIR-C scenes are used; the processing run numbers are: 13144–13147 (April 1994 images) and 42794–42797, 46407–10 (October 1994 images). One high-resolution SPOT image is used with a path and row number of 169–304.

Landsat TM data have a resolution of 28.5 m². They reflect the lithological and mineralogical variations of exposed rocks and soils by separating the solar reflected energy into six spectral bands. Thermal emitted energy is also collected in a separate band. TM bands 7 (2.08–2.35 µm), 4 (0.76–0.90 µm) and 2 (0.50–0.60 µm) are used in this analysis because they have low correlation and produce high-contrast images suitable for geological interpretation. In this study, band 2 is helpful for rock discrimination, band 4 for land–water contrasts, and band 7 for discrimination of mineral and rock types (Jensen 2000, p. 194). The ability of Landsat data to aid in the identification of rock types distinguishes them from radar data, which discern different lithological units because of different surface roughnesses (e.g. Robinson 1998; Inzana et al. 2003).

SIR-C data are processed using CEOS-READER (Committee on Earth Observation Satellites) software (obtainable from the Jet Propulsion Laboratory, Pasadena, CA). The resulting images have a resolution of 25 m. Images for all bands (L and C) and polarizations were generated. The application of histogram equalization stretches and edge filters (either simple 3 × 3 Laplacian filters or modified subtraction filters) is particularly useful in the enhancement of SIR-C data (e.g. Robinson et al. 1999).

Recognition of tectonic features in radar images is dependent on viewing geometry and incidence angle. If these circumstances are favourable, then radar images can be used to identify regionally extensive
linear features that are otherwise not clearly depicted in TM data (e.g. Sabins et al. 1980; Robinson 1998; Robinson & Kusky 1998; Kusky & Ramadan 2002). This is because the surface albedo in these images varies much more than in optical imagery (as they respond to lithological, not mineralogical, characteristics). This means that if the fault scarps are oriented perpendicular to the radar look direction they appear brighter than those parallel to the look direction, because the radar wave is backscattered directly to the receiving antenna in this geometric configuration.

Principal structures are mapped in the field and using Landsat images (Fig. 3), supplemented by SIR-C image interpretation, where the latter are available. On-screen digitizing is applied to the satellite images to generate digital maps of structural features in vector format. The procedure uses geometrically corrected images as a template, which further allows the geolocation of the interpreted structural features. The spatial databases are created using ‘ESRI’s Arc/Info’ GIS software.

Principal youthful structural features are visible as distinct lines cutting rocks that are Miocene or younger in age. Gently dipping thrusts and shear zones, such as the basal thrust and metamorphic sole of the ophiolite, are not included in the new fault and fracture maps. However, these faults are mapped on the geological maps of the country (Directorate General of Minerals 1993), and are consulted while mapping the fault and fracture zones in the field and from the Landsat images. There is a general agreement between the geological maps and the new structural interpretation shown in Figure 5. Our new maps, however, show additional faults and fractures that are not included on the geological maps. These are discussed below.

Integrated image analysis and structural field mapping

The WNW–NW-striking Tertiary–Quaternary fault set includes numerous faults that parallel the mountain front in the central and eastern Hajar range, and cut the mountains obliquely in the northern Hajar region (Fig. 5). They comprise a major array of linked faults developed with c. 50 km spacing. The most notable of the north- to NNE-striking fault set run along the Samail Gap (Fig. 5). They too form a major group of faults characterized by c. 50 km spacing. Seven localities with examples of these faults sets, and the associated Tertiary–Quaternary movement, are described below.

1. Maradi Fault (WNW striking)

The Maradi Fault (centred on 22°15′N, 58°E) is one of the major WNW–NW-striking faults and is located in the Suneinah fore-
land basin to the south of the Hajar Mountains (Figs 1, 2, and 5). It is a major, 60 km long, NW-striking fault with 10–20 m of north-side-down, normal-sense displacement. It merges with a foreland fold belt to the NW, and disappears beneath the Quaternary alluvial plain to the SE (Fig. 5). It may re-emerge as the Saiwan–Nafun Fault in the Huqf area of central Oman (Fig. 2), or it may bend to become continuous with the north- to NW-trending Oman line to the NW (Fig. 1).

The fault is associated with a number of west-striking minor faults that intersect the Maradi Fault in a systematic fashion suggesting that they are pinnate fractures, formed by a component of sinistral shear (Fig. 5). It may also have older dextral or dip-slip displacements (Hanna & Nolan 1989) that are not directly observable from the satellite images (Fig. 6). The fault forms a NE-facing escarpment defined by the lower Hadhramaut group shelf facies (Fiqa Formation), with a reduced elevation of about 20 m on the NE side of the fault. The fault juxtaposes Eocene rocks on the SW (Hadhramaut group) with Campanian–Maastrichtian rocks on the NE (Barzaman Formation of the Fars group) indicating that it has a component of vertical displacement (Hanna & Nolan 1989).

Radar (SIR-C) data and field studies indicate that the Maradi Fault has had Tertiary, sinistral strike-slip displacements, in addition to the observable vertical displacement. SIR-C images illustrate its continuity (Fig. 6), compared with Landsat TM images, where identification is more difficult owing to extensive cover with a heavy clay signature. The SIR-C image shown in Figure 6 is collected in descending (left-looking) orbit at incidence angles between 36° and 43.7°. The relatively high angles enhance surface roughness effects and minimize slope effects, the necessary geometric configuration for imaging this regionally extensive fault. Subsurface imaging also occurs at these localities, because of the arid and gently undulating terrain that is covered only by fine-grained material (e.g. Robinson 1998).

Two features in the SIR-C images indicate that the fault has a component of sinistral motion, as well as its documented vertical displacements. First, a large, pre-Miocene, unnamed drainage
Fig. 6. L band SIR-C image overlain on a Landsat TM image of the area. The arrows point to the leftward displacement of an unnamed drainage channel. The Upper Fars Group Tertiary palaeo-surface across the fault is labelled. This indicates that the Maradi Fault experienced sinistral motion since the Tertiary. In the SIR-C image, drainage trends approximately NE compared with north–south in the TM image.

Fig. 7. Photograph of the Maradi Fault scarp (c. 10 m high). It shows Neogene gravels that are faulted (the label points to such an example) and Quaternary gravels that are not. Thus, movement along the fault must have been confined to the Tertiary.
channel is displaced in a left-lateral direction (Fig. 6). This river bed is more defined on the L band image than the C band image (Robinson & Kusky 1998), indicating that it exists below 50 cm and up to 2 m in the subsurface (Schaber et al. 1997). Further evidence of subsurface imaging at these locations comes from the radar drainage pattern that is shifted slightly from the surface drainage seen in the TM image at southerly locations (Fig. 6). In the SIR-C image, drainage trends approximately NE–SW, whereas the surface trend of drainage visible in the TM is dominantly north–south (Fig. 6).

The second piece of evidence supporting sinistral strike-slip movement on the fault comes from the Tertiary ferruginized and karstified palaeosurface of the Upper Fars group that is displaced to the left in the SIR-C image (Fig. 6), again supporting sinistral strike-slip movement of the fault. Thus, sinistral strike-slip displacements must have taken place along the Maradi Fault during the Tertiary period. This age determination is also supported by field observations showing that Neogene semi-consolidated non-marine gravels are cut by the Maradi Fault, but unconsolidated Quaternary gravels are not cut by fault-related structures (Fig. 7).

2. Quriyat and Tiwi region (WNW and NNE striking)

Clear evidence for young uplift of the Hajar Mountains comes from the Quriyat and Tiwi areas (Fig. 8). Both major sets of young faults are identified here. The regional picture shows that the WNW-striking set comprises a major group or array of linked faults occurring with c. 50 km spacing. The NNE-striking set also shows c. 50 km spacing between fault arrays, and is intersected by a third, NE-striking fault set that shows less well-developed 50–100 km spacing between arrays. All of these faults cut the Tertiary limestones and several cut Quaternary marine terraces.

Fig. 8. Structural map of the Quriyat–Tiwi region. It shows that both the WNW-trending and the NNE-trending faults form a major array of linked structures, with about 50 km spacing. All these faults cut Tertiary limestones and several cut Quaternary marine terraces, providing clear evidence for young uplift of the Hajar Mountains here.
Figure 9 shows a view of Pliocene–Quaternary terraces in the Tiwi area. The terraces occur at five main levels oriented WNW, parallel to the coast. These include terraces at 10–20 m, 30–50 m, 110 m, 140–150 m and 180–200 m above sea level. The terrace deposits consist of a few metres of calcarenite matrix conglomerate with *Pecten* and *Ostrea* mollusc shells lying on old marine platforms, with reworked Eocene foraminiferal microfauna (Wyns et al. 1992). The observation that these terraces are elevated well above the highest Pliocene–Quaternary eustatic sea-level highs (+80 m at 4–5 Ma) shows that the region has experienced considerable Pliocene–Quaternary uplift that exceeds 100 m. This uplift is attributed to differential motion on the WNW- and NNE-striking faults that cut the mountain front.

Near the coast, just north of Tiwi, a NNE-striking zone of fracture intensification strikes into the Gulf of Oman. On the map (Fig. 8), most of the fractures strike north–south, showing characteristics of very steep to vertical dips. However, NNE-striking fractures are the most abundant in the field, many of which have visible open karst features developed along them. Analysis of Landsat TM thermal band (band 6) data suggests that ground water is flowing through this fault and seeping out in large quantities offshore this location (Fielding et al. 2001). Two ages of faulting can be discerned at this fault. First, a pre-Tertiary fault system is well exposed near Hawyl Al Quwasim village (Fig. 8), where karst pinnacles and collapse features developed along the fault. These are filled with conglomerates made of the Hajar limestone, which is Tertiary in age. These conglomerates are cut by a second generation of faults, followed by karst dissolution along them, which led to the collapse of the Tertiary limestones into the newly formed sinkholes and graben.

Further evidence for very recent faulting is found in Wadi Dayqah in the eastern Hajars. Here a WNW-trending fault cuts a falaj in a down-to-north normal sense (Fig. 10; Kusky et al. 1998). The cement-lined channel of the falaj shows evidence of having been repaired and then fractured again. There is no quantitative knowledge of the age of this fault, but local villagers suggest it may be between 300 and 1000 years old. They also speak of a time several generations ago when the ground shook, destroying buildings in the village. It may be speculated that motion on one of the WNW-striking faults may have caused this historical earthquake.

Fig. 9. Photograph of the Pliocene–Quaternary terraces in the Tiwi area. Terrace surface in the foreground is 30–50 m above sea level, whereas the background shows several levels of terraces up to several hundred metres above sea level, eroded in the Cretaceous limestone of Jabal Bani Jabir. These terraces have been elevated by over 100 m above the Pliocene–Quaternary eustatic sea level, indicating that the region experienced considerable uplift during that time period.

Fig. 10. Photograph of a faulted falaj thought to be between 1000 and 300 years old. The fault trends NW and as it crosscuts this youthful structure it confirms that many of the NW faults mapped in Figure 5 may be youthful structures. For scale, the black arrow in the bottom points to a geologist.

3. Wadi Taww–Wadi Al Ajal area (WNW striking)

The Wadi Taww–Wadi Al Ajal area is located in a complex belt of Hawasina nappes in thrust contact against the northern margin of Jabal Nakhl (Fig. 11). This area is located along the possible westward extension of the listwaenite line, a late, heavily
mineralized fault that strikes WNW across the north end of Jabal Nakhl.

At Wadi Taww, Hawasina nappes and interthrust ophiolitic slices are overlain by several levels of Quaternary gravel terraces, with the lower terrace deposits being cemented and the upper terrace deposits being only partly cemented. A detailed map (Fig. 12) was made of the lower terrace that directly overlies the Hawasina Group, and a reconnaissance survey of other units in the area was also carried out to make structural measurements of faults cutting the different units. The detailed map clearly shows the complex deformation in the Hawasina nappes, but more relevant to this study is the observation that two sets of faults (WNW and NNE) cut both the Cretaceous Hawasina sedimentary rocks and the Quaternary gravels; therefore, these faults are demonstrably of Quaternary age.

4. Bahla–Bisyah region (NW and NNE striking)

The area around Bisyah is structurally complex in terms of faulting. It is situated at the extrapolated junction of two major late fracture zones, one striking NW and the other NNE (Fig. 13). The regional fracture intensification zone is not exposed in Bisyah because of the extensive alluvial cover of Wadi Sayfam and its tributaries. Two complementary approaches were taken in the field to better understand the NW- and NNE-striking fracture zones. First, field analysis of outcrops in rocks of the Hamrat Duru group exposed near Bisyah and in the mountains to the north and NW was aimed at locating and characterizing any minor structures that may be associated with the main faults. Second, time domain electromagnetic (TDEM) geophysical surveys were carried out, and seismic reflection profiles were obtained from the petroleum industry, both of which cross the alluvial channels and plains (Fig. 13). These geophysical techniques are directed at finding deep channels and buried fault traces.

With respect to the first approach, Figure 13 shows the orientation of fractures in the ophiolite (Fig. 13, plot a) and in the Hawasina units (Fig. 13, plot b) in the Bani Shukayl area of Bisyah. Fractures in both units have a wide range of orientations, but show two concentrations, the strongest of which relates to a NW-striking set and the other to a NNE-striking set (Fig. 13). These faults are generally open structures, although calcite veins
cut Cretaceous Hawasina sedimentary rocks and Quaternary gravels. The map shows that the WNW and NNE faults which control the Misfah gorge orientation (Fig. 15, plot b). West of Bahla, more closely spaced and wider strands of a NNE-striking fault system are present, suggesting closer proximity to a major fault (Fig. 13, plot d). The faults in the outcrop are similar in character to those at outcrop a, but also include some serpentinized ductile shear zones that splay into brittle fractures, which form pinnate joints of a dextral system. On the east side of Bahla, an outcrop of cumulate gabbro was examined (Fig. 13, location b), and this is cut by faults of both the NNE and the WNW sets.

Thus, structural data from the Bahla area suggest that a major NNE-striking dextral fault passes through the town and that this fault is associated with NNE- and WNW-striking minor faults.

Figure 14 shows an interpretation of seismic profiles across Wadi Sairam. These are important in that they show prominent faults extending to several kilometres depth, and the surface traces of these faults coincide with lineaments mapped from the TM images. This confirms that the NW- and NE-striking fracture intensification zones exist at depth and that they reach several hundred kilometres in length (Fig. 1).

5. Al Hamra area (NNE and NW striking)

Several areas on the southern flank of Jabal Akhdar preserve evidence of young faulting along both the north–NNE trend and the WNW–NW trend, as described below. For example, Al Hamra area features prominent trellis and parallel drainage that suggests association with fractures (Fig. 15). The SPOT image of the area SE of Misfah, near Al Hamra, shows a small swarm of NW-striking faults intersecting the main north–south fault.

In the field it is clear that a NE-facing escarpment south of Misfah is formed by erosion of one of the NW-striking faults that continues into Wadi Maq’al (Fig. 15). Many small caves are developed along this part of the fault system. At this location a, exposures of Cretaceous (Albian–Cenomanian) limestone of the Natih Formation are cut by NW- and NE-striking faults and joints (Fig. 15, plot a). It is observed that fractures of the NW-striking set are spaced at c. 50–100 cm, whereas those of the NE-striking set are spaced approximately every metre. Both sets are generally open, apparently young fractures, with apertures (at the surface) of several millimetres. At location b near Misfah village, the NE and NW faults and fractures are present, as well as an additional set of north-striking, vertical fractures that control the Misfah gorge orientation (Fig. 15, plot b).

6. Ghul area (north–south striking)

A north–south-striking fault with Quaternary displacements cuts through the Wadi Ghul–Wadi Nakhir region, along the southern flank of the central Hajar range (Fig. 16). It forms the western boundary to the ‘Grand Canyon’ of Oman, which offers more than 1000 m of vertical relief (Fig. 4). The juvenile topography of the Grand Canyon–Wadi Ghul area suggests that it formed by relatively recent uplift, and that erosion has not yet had a chance to develop a more mature landscape. Furthermore, fieldwork in the southern part of the area, SW of the modern Ghul village (Fig. 16), shows that a cemented Quaternary terrace in the wadi bed is preserved c. 10 m below a less cemented terrace. The older terrace is remarkable in that it is cut by a number of faults (Fig. 16, plot a), including several subparallel strands of a north–south-trending fault that is parallel to the major north–south fault mapped as the western margin of Wadi Nakhr and the Grand Canyon. The fault (Fig. 17) cuts some cobbles in the
conglomerate and curves around others, showing that it formed at very shallow levels.

7. Faulted Quaternary terrace in Al Ghail, UAE (WNW striking)

Field investigations were also carried out in the neighbouring regions of the UAE where the analysis of Landsat images suggests that some young faults may cut Quaternary fluvial terraces (Fig. 18). An area upstream from Al Ghail on the western slopes of the Hajar Mountains was investigated where the Landsat TM image shows a prominent NW-striking fault. Several areas with Quaternary terraces (estimated to be about 100 ka old) are exposed, providing an opportunity to investigate the age relationship between various sets of faults and terraces. A low cemented fluvial terrace at this location shows several
tectonic fractures, some of which cut clasts in the gravel. A large Quaternary fault that cuts both the cemented and the overlying uncremented terraces is exposed 10 km up the wadi from Al Ghail. The fault is one of the WNW sets that cut the mountain range in many places and consists of a zone about half a metre thick of brecciated gravel exposed as fault gouge. The fault cuts through the lower 15 m thick terrace, and continues into the overlying wadi terrace (Fig. 19).

**Fig. 14.** Interpretations of the seismic profiles taken across Wadi Sayfam. Profile ‘Bisyah’ is the southeasternmost profile; line ‘North of Bisyah’ is the northwesternmost profile. These show prominent faults that extend to several kilometres depth. The surface traces of these faults (indicated by vertical arrows on lines of section) correspond to the WNW and north–south fracture intensification zones mapped from the Landsat TM image.

**A model for the neotectonics of the Hajar Mountains, and tectonic controls on uplift, subsidence and the formation of the late fault sets**

The Hajar Mountains reside on the foreland margin of the active collision zone between the passive Arabian margin and the Zagros–Makran fold belts (Fig. 1). This collision involves the shallow subduction of continental crust of the Arabian Shield
beneath the Zagros Mountains in the west, with shallow waters of the Persian (Arabian) Gulf in the active foredeep (Glennie et al. 1990; Mann et al. 1990). East of the Dibba Line on the Arabian margin, and the Zendan Fault in Iran, the collision includes stretched continental crust grading into sea floor in the Gulf of Oman (White & Klitgord 1976), which is being subducted beneath the Makran accretionary wedge (Fig. 1).

The tectonic history of the northern Oman margin is complex, including the development of a Permian–Cretaceous carbonate platform on the southern margin of the Tethys, a remnant of which is preserved in the Gulf of Oman (Mann et al. 1990). Late Cretaceous deformation associated with the collision of the north Oman margin with a probable forearc environment terminated passive margin sedimentation, emplaced the Samail ophiolite (Glennie et al. 1973, 1974; Pearce et al. 1981), and initiated foredeep sedimentation in the Aruma foreland basin on the eastern edge of the Arabian plate (Robertson 1987). Emplacement of the Samail ophiolite was thus associated with closure of the Tethys, although the ophiolite is probably forearc lithosphere and not true Tethyan oceanic lithosphere. Ophiolite emplacement strongly deformed and imbricated the shelf sediments of the Hajar Group, oceanic and continental slope sediments of the Hawasina and Sumeini Groups, and formed metamorphic rocks of the dynamothermal aureole. The large basement-cored antiformal domes of Jabal Akhdar, Nakhl and Saih Hatat are probably related to movement of the entire thrust package over deep basement thrust ramps, deep duplexing, or blind thrust faults propagating under the domes in the Late Cretaceous (e.g. Hanna 1986; Coffield 1990; Al-Lazki et al. 2002). This deformation ended by Late Campanian (Glennie et al. 1974). Latest Cretaceous and Early Tertiary rocks record shallow marine, quiescent conditions.

Convergence between the north Oman margin and the Zagros–Makran appears to have been re-established by the Eocene (Coleman 1981; Mann et al. 1990). Contractual structures on Musandam have been related to Arabian–Zagros convergence, whereas Tertiary structures in the central Oman Mountains have been variously ascribed to gravity tectonics (Glennie et al. 1974) or down-to-the-basin normal faults along the Batinah coastal plain (Mann et al. 1990). Mann et al. (1990) and Nolan et al. (1990) showed how Maastrichtian–Oligo-Miocene structures have controlled the distribution of several of

Fig. 15. SPOT image (169–304) of Al Hamra, on the southern flanks of Jabal Akhdar. It shows a swarm of NW-striking faults that intersect the NNE-trending fault. The stereonets further confirm the prevalence of the NW and NE faults at locations a and b. Both fault sets are generally open, with apertures of several millimetres at the surface.
the Tertiary stratigraphic units, and that the Saih Hatat dome remained high during this period.

The contact between the Tertiary sedimentary sequence and the Samail ophiolite on the Batinah coastal plain is in many places a WNW-striking normal fault, downthrown toward the Gulf of Oman (Mann et al. 1990). Listric faults with roll-over anticlines are present, as are horsts and grabens, accommodation structures and antithetic normal faults (Mann et al. 1990). The Late Tertiary structures have a consistent down-to-the-north or -NE sense on the Batinah Plain, and appear to be continuous with extensional structures in the Gulf of Oman (White & Ross 1979). Although Mann et al. (1990) recognized the Tertiary extensional province on the Batinah plain, they were not able to provide any clear tectonic cause for the extension, suggesting that perhaps the structural culminations of Saih Hatat and Nakhl were collapsing, or that gravity tectonics initiated extension. We recognize that this extension has continued through the Quaternary, and present a new tectonic mechanism that explains the regional pattern of faulting.

The driving forces for Late Tertiary–Quaternary uplift in the northern Oman Mountains are most probably related to the contemporaneous collision between the NE margin of the Arabian plate and the Zagros fold belt and the Makran accretionary prism. The axis of recent uplift in the Hajar Mountains lies about 150 km from the active thrust front of the Makran prism, suggesting that the NW and WNW faults may be outer-trench slope normal faults (e.g. Bradley & Kusky 1986) that accommodate uplift on the flexural bulge of this collision. The NNE-striking faults are interpreted as tear faults separating blocks that have slightly different rotational histories. The inferred strike-slip motions of some of the WNW-striking faults are enigmatic. The geometry of the Makran–Arabia collision implies that these faults may have a component of dextral shear, as suggested by Hanna & Nolan (1989). However, new observations presented here suggest that the Maradi fault may also have experienced sinistral motions. Al-Lazki et al. (2002) presented deep seismic data that help resolve the conflicting kinematics inferred for the Maradi Fault. They showed that the Maradi Fault (Fig. 5) is a deeply penetrating thrust fault, which displaces the top of the Hajar Supergroup 900 m up on the NE side of the fault. The fault breaks into many splays near the surface, forming a flower structure, some strands of which show normal displacements and some of which show thrust and strike-slip displacements.

Geomorphological features of the Musandam Peninsula reveal that an east–west-striking flexure passes through the centre of the peninsula. The flexure marks a drainage divide, where wadis
to the north of the line flow to the north and those to the south of it flow to the south (see Fig. 20). The mountains are higher in the south, and become progressively lower and more subdued to the north. Valleys to the north of the drainage divide are drowned and flooded by the sea, whereas to the south the valleys are still alluvial.

We interpret these features to mark the position of the flexural bulge on the Musandam Peninsula. The area north of the drainage divide is dipping to the north and subsiding under the weight of the Zagros fold belt; hence, the drowning of the valleys and the gently north-sloping maximum elevation surface. The area south of the divide is on top of the flexural bulge, or just moving up to the maximum height as the bulge migrates southward. Numerous raised beaches have been recognized in this area (Ricateau & Richie 1980).

The flexural bulge axis is located considerably further south in the western and eastern Hajar Mountains, and we suggest that it is offset across the Dibba Zone (Figs 1 and 2), which apparently separates blocks of different types of lithosphere on the west and east. The southward displacement of the bulge axis also corresponds to the southward displacement of the thrust front (and load) from the Zagros to the Makran across the Zendan Fault (Fig. 1). The flexural lithospheric thickness and rigidity of the Arabian lithosphere must increase toward the SE, as the bulge axis appears to broaden and move further from the thrust front in this direction.

Conclusions

The present work integrates remote sensing, field mapping and GIS techniques to reveal evidence that two major sets of late
faults and fracture intensification domains are responsible for Tertiary–Quaternary uplift of the northern Oman Mountains. Evidence for the young age of uplift and faulting includes juvenile topography, faulted Quaternary marine terraces and a fractured falaj. The young faults occur as a WNW-striking set parallel to the Maradi Fault with a major group or array of linked faults occurring with c. 50 km spacing. A second set of dextral faults striking NNE shows less well-developed 50–100 km spacing between arrays. It is suggested that the two late fault systems described here may have accommodated Tertiary–Quaternary uplift of the northern Oman Mountains, and can account for the previously unexplained juvenile topography.

A new tectonic mechanism is proposed to explain the regional pattern of faulting and the Tertiary–Quaternary extension. The driving forces for Late Tertiary–Quaternary uplift in the northern Oman Mountains are most probably related to the contemporaneous collision between the NE margin of the Arabian plate, the Zagros fold belt and the Makran accretionary prism, suggesting that the axis of recent uplift in the Hajar Mountains lies about 150 km from the active thrust front of the Makran prism. This implies that the NW and WNW faults may be outer-trench slope normal faults (e.g. Bradley & Kusky 1986) that accommodate uplift on the flexural bulge of this collision. This is further supported by their similarity to those faults in active and ancient forebulge environments, including the amount of Quaternary uplift, estimated between 100 and 500 m. The NNE-striking faults are interpreted as tear faults separating individual blocks that have slightly different rotational histories.

The axis of uplift is offset to the north across the Dibba line (striking NE) to the Musandam Peninsula (Figs 2 and 20), suggesting that it marks a fundamental lithospheric break. The Dibba line is close to parallel to the Zendan Fault separating the Makran and Zagros fold belts in Iran, suggesting that this break has manifestations in both the upper and lower plates. The offset of the axis of uplift could be related to different lithospheric thicknesses or flexural rigidities of blocks on either side on the lower plate, or could be related to differences in the load geometry on the upper plate.

Implications for active tectonics and seismic hazards

Data presented here show that the Hajar Mountains of northern Oman and the UAE have undergone very recent to active deformation and uplift, and therefore the region has more serious seismic risks than previously appreciated. Global positioning system and seismic monitoring stations have recently

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**Fig. 20.** Drainage map of the Musandam Peninsula, showing the drainage divide with wadis flowing north and south on either side. This divide is thought to indicate a flexural bulge that resulted from a collision between the NE margin of the Arabian plate and the Zagros fold belt and the Makran accretionary prism in Late Tertiary to Quaternary time. The mountains are higher to the south of the bulge axis and progressively become lower and more subdued in the north (Fig. 4).
been set up in Oman under the Earthquake Monitoring Project, based at Sultan Qaboos University in Muscat. This effort is critical to further assess active neotectonics along the study area. Seismic monitoring coupled with further field and geological studies aimed at documenting Tertiary and Quaternary structures will lead to a greater understanding of the tectonics of the region, and a better ability to assess earthquake hazards and risk zones.

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