GeoArabia, Vol. 10, No. 4, 2005
Gulf PetroLink, Bahrain

Comment on "Aptian faulting in the Haushi-Huqf (Oman) and the tectonic evolution of the southeast Arabian platform-margin" by C. Montenat, P. Barrier and H.J. Soudet

Marc Fournier, Philippe Razin, Olivier Fabbri and Jean-Paul Breton

On the basis of field observations in the Huqf area in eastern Oman, Montenat et al. (2003) defined an extensional phase of faulting of Aptian age in the Arabian platform (see also Montenat and Barrier, 2002). We recently revisited the fault exposures of the Wadi Sha'bat al Tawraq from which this conclusion has been drawn (location in Figure 1a). Our observations contradict those of Montenat et al. (2003), and consequently our conclusions are different. Here we review the conflicting observations and discuss the different interpretations.

Geological Setting

In an area of about 10 square kilometers encompassing the Wadi Sha'bat al Tawraq, two major faults referred to as F1 and F2 are exposed (Figures 1 and 2). Both are normal faults, striking northwest-southeast, dipping about 60° towards the southwest, and offsetting the limestones of the lower Aptian Qishn Formation (corresponding to the Shu'aiba Formation of northern Oman). Figure 2a shows a schematic cross-section of this area with the two faults. F1 is the fault depicted in Figures 6, 9, and 10 of Montenat et al. (2003), and F2 is the fault depicted in their figure 11 (see location of their figures in Figure 1c). Both faults are expressed in the field by fault scarps a few meters high (less than 5 m) and several hundred meters long (Figures 2b and 2c). The faulted blocks are slightly tilted and dip gently towards the northeast. Secondary faults are found in the vicinity of F1 and F2 (Figure 1c): two normal faults limit a small graben in the hanging-wall of F1, and several normal faults are observed in the footwall of F2.

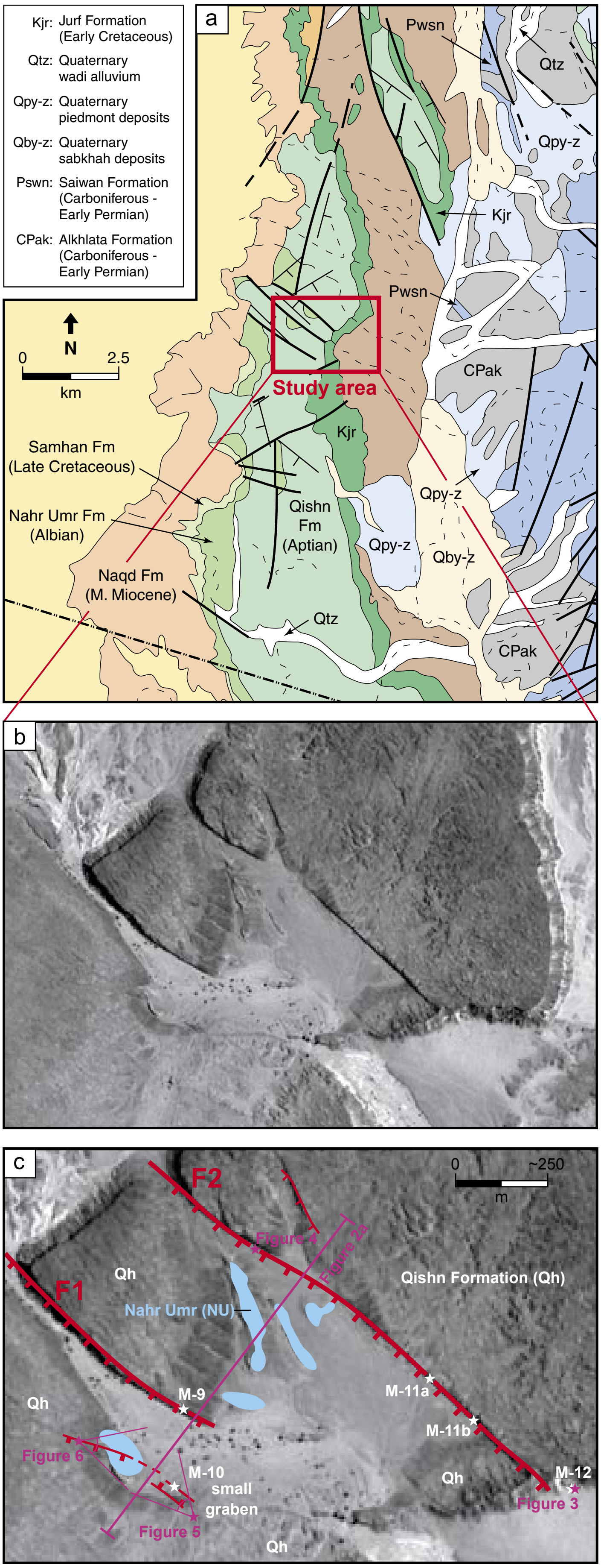
Montenat et al. (2003) present a series of field observations and interpretations related to F1 and F2: (1) to assess the synsedimentary or syndiagenetic character of normal faulting; and (2) to infer a pre-Albian age of faulting. In the following, we review these observations and propose alternative interpretations.

Post-lithification Normal Faulting of the Aptian Qishn Limestone

Montenat et al. (2003) put forward sedimentological and tectonic observations to argue that faulting occurred prior to complete lithification of the carbonates of the Qishn Formation. They first describe the upper part of normal fault scarps as showing indications of near-surface, soft-sediment deformation with "*small sinuous faults smoothed as a result of sediment creeping, boudinage and collapse of the cohesive muddy sediment*" (their figures 9 and 10). This "*jumbled deformation* [is] *due to the softness and plasticity of the unlithified sediment*". We disagree with this interpretation. The lithofacies of the Qishn limestone is not a mudstone but a coarse grainstone comprising rudist debris, i.e. a material that is non-cohesive before lithification and with no plastic rheological behavior. Moreover, the *small sinuous* fractures cut the rudist bioclasts and therefore postdated the lithification of the limestone.

Montenat et al. (2003) observed that the F2 fault plane is locally covered with patches of breccia with an irregular nodular aspect (their figure 11b). They indicate that the large breccia clasts "*show pre-lithification deformations, such as stretching and pillowing,* [and that] *the carbonate mud between the clasts has a flow structure*". We do not confirm these observations. The breccia is a typical cemented fault breccia with rigid clasts. Its irregular nodular (not pillowing) aspect results from dissolution and weathering. We note that the same nodular aspect is observed in the limestone of the footwall of the fault, and we conclude that it is not related to the fault or to syndiagenetic deformation.

In their figure 11a, Montenat et al. (2003) show a so-called clockwise-rotated block at the foot of the F2 fault scarp. They state that a "*part of the fault scarp collapsed and slid down with a clockwise rotating motion during or shortly after faulting*". The rotation is defined about an axis perpendicular to the



fault plane and the clockwise sense is inferred from a series of fractures in the fallen block that Montenat et al. (2003) misinterpreted as the bedding plane. In fact, the bedding plane in the fallen block is sub-parallel to the bedding plane in the footwall of the fault. The fallen block is completely rigid and does not show any evidence of soft-sediment deformation. We cannot see any reason to assert that this block collapsed *"during or shortly after faulting"*.

Montenat et al. (2003) show one outcrop of supposedly synsedimentary faulting in the Qishn limestones in their figure 12 (reproduced in Figure 3). According to their interpretation, a continuous calcirudite bed seals the main fault of this outcrop. This observation is erroneous. Indeed, the fault crosscuts all strata and is never sealed by any bed on the outcrop. In this example, faulting clearly postdated the deposition and lithification of the Qishn Formation.

Lastly, the occurrence of slickolite striations (i.e. stylolites formed by pressure solution process along the fault plane) on normal fault planes (Figure 4) demonstrates that the Qishn limestones were indurated

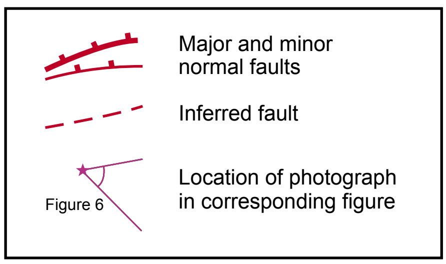


Figure 1: (a) Location of the Wadi Sha'bat al Tawraq area on the 1:250.000 geological map of Oman, sheet Duqm and Madraca (Platel et al., 1992). (b) Aerial photograph of the study area. (c) Geological and structural interpretation of aerial photograph of the study area. The two main faults F1 and F2 are shown. Locations prefixed with the letter M (e.g. M-11a) refers to figures of Montenat et al. (2003).

before deformation started. All this field evidence indicates that faulting was post-lithification of the Qishn limestone, and not syndiagenetic.

Normal Faults not Sealed by Top Qishn Formation Hardground

The top-Qishn Formation is capped by a ferruginous hardground, which represents a hiatus of more than 5 my (Platel et al., 1992; Immenhauser et al., 2000, 2004). The top-Qishn Formation surface is non-angular with respect to the underlying strata at the outcrop scale, but it is an unconformity at the regional scale (Dubreuilh et al., 1992; Platel et al., 1992). The two fault planes F1 and F2 are partly covered by a thin (1 mm to 1 cm) ferruginous crust. Montenat et al. (2003) claim that this crust is the same as the top Qishn hardground, and seals the extensional faulting. We disagree with these interpretations. First, the iron-stained top-Qishn Formation hardground has an irregular undulating surface perforated by borings that cut through the fabric of the underlying rocks, whereas the ferruginous crust on the fault planes is totally devoid of perforation. The two ferruginous surfaces are therefore different. Second, a fault scarp, even indurated by a ferruginous crust, would not have resisted to post-Qishn Formation emersion and would have been eroded. Third, the stratigraphic sections of the base of the Nahr Umr Formation, on either side of the F1 fault, are perfectly identical. Had the fault scarp predated the deposition of the Nahr Umr Formation, the base of the formation would have displayed lateral variations. Fourth, striations on fault planes (including slickolites of Figure 3) are systematically found under the ferruginous crust, implying that the crust postdated fault slip. The linear features borne by the so-called "striated" ferruginous surface depicted in figure 10 of Montenat et al. (2003) are definitively not tectonic striations. These linear features, developed in

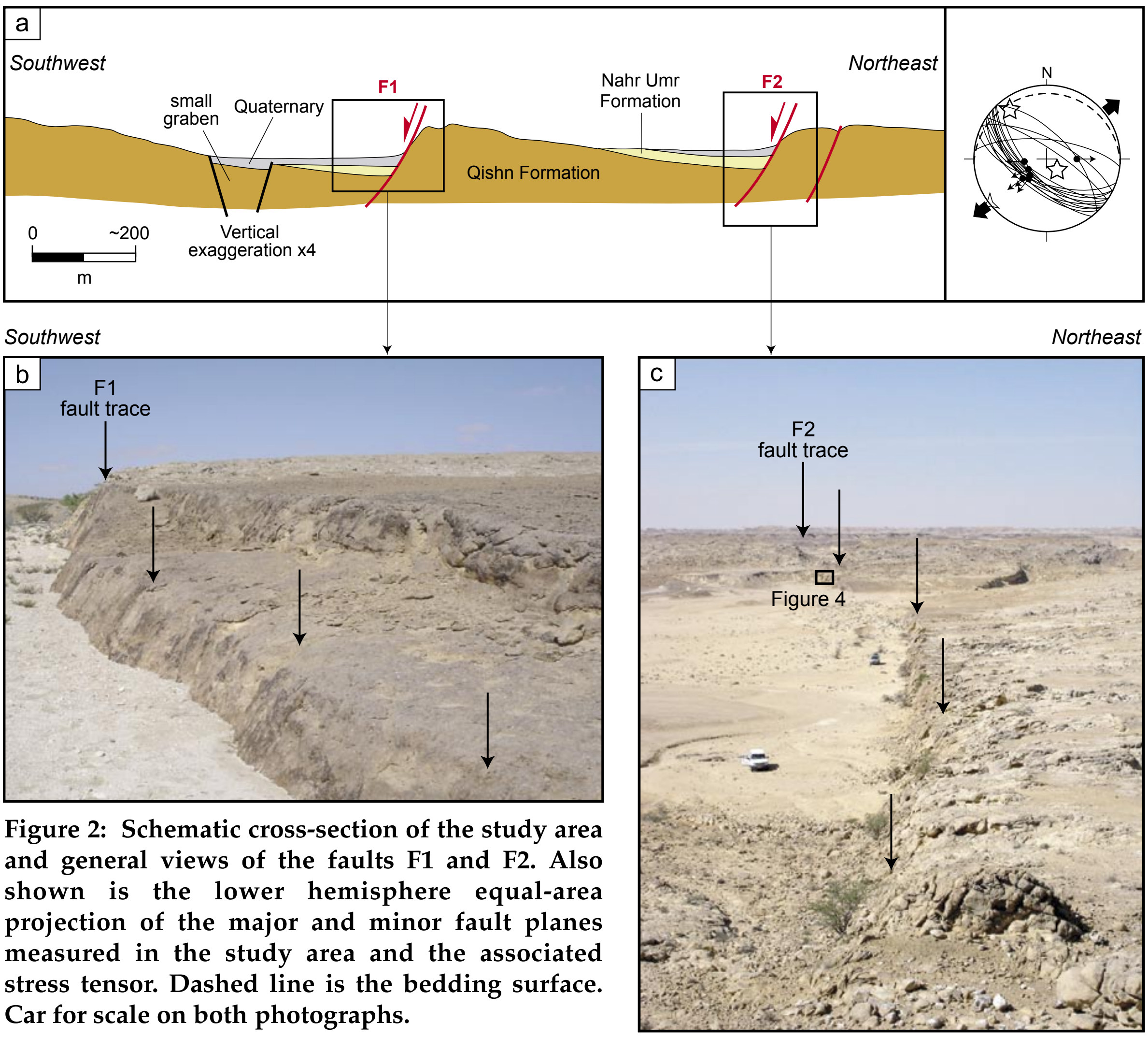


Figure 2: Schematic cross-section of the study area and general views of the faults F1 and F2. Also shown is the lower hemisphere equal-area projection of the major and minor fault planes measured in the study area and the associated stress tensor. Dashed line is the bedding surface. Car for scale on both photographs.

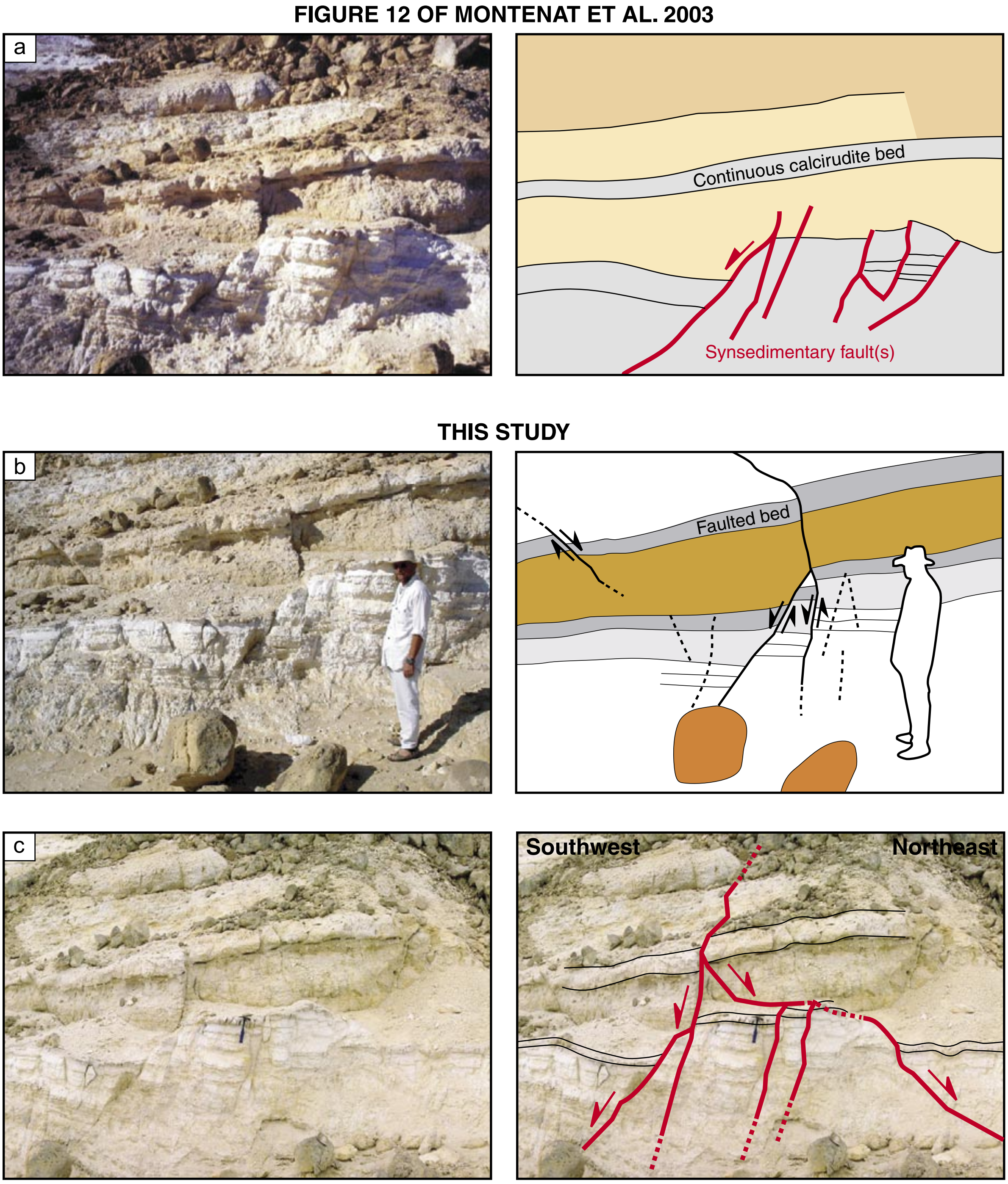


Figure 3: Normal faulting in the Qishn Formation in the footwall of F2 (location in Figure 2c). Comparison of Montenat et al.'s (2003) interpretation (a) and ours (b). The main fault crosscuts the strata and is not sealed by any bed. (c) Larger view showing that the apparent difference in thickness of the bed underlying the "continuous calcirudite bed" is due to the existence of a normal fault nearly parallel to the outcrop.

the ferruginous crust, result from erosion and weathering of the crust by meteoric water, and are not the result of mechanical damaging of the fault plane by hard objects. Fifth, most fault planes in the Huqf region, including fault planes cross-cutting Upper Cretaceous formations that are younger than the Qishn Formation, are covered by a ferruginous crust similar to that observed on fault planes in the Wadi Sha'bat al Tawraq.

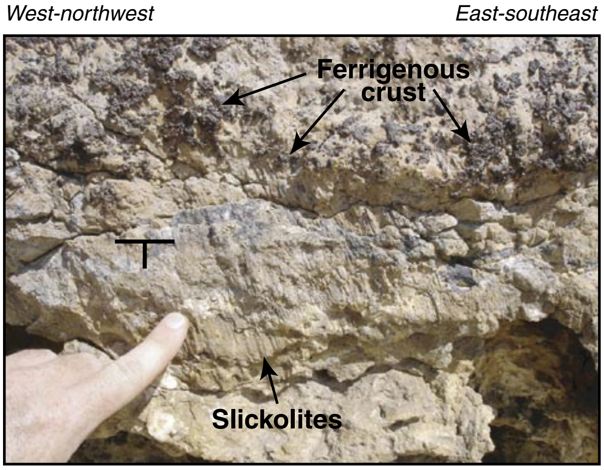


Figure 4: Slickolites borne by F2 in the Qishn Formation and showing oblique normal slip. The Qishn limestones were indurated before faulting occurred. Note the ferruginous crust present upon the striated fault plane. Location in Figure 2c.

All these observations indicate that the ferruginous crust on fault planes is not equivalent to the top Qishn hardground and that it postdates normal faulting.

Normal Faulting Affects the Albian Nahr Umr Marls

Figure 6 of Montenat et al. (2003) reproduced in our Figure 5 suggests that the Albian Nahr Umr marls seal the small graben affecting the Qishn limestones in the hanging-wall of F1. This interpretation is incorrect. Our observations show that Quaternary fluviatile deposits rest directly upon the Qishn limestones (Figures 2a and 5) and hide the contact between the limestones and the nearby Nahr Umr marls. Moreover, the dip of the Nahr Umr marls is in exact accordance with the dip of the underlying Qishn limestones, which implies that tilting postdated the Nahr

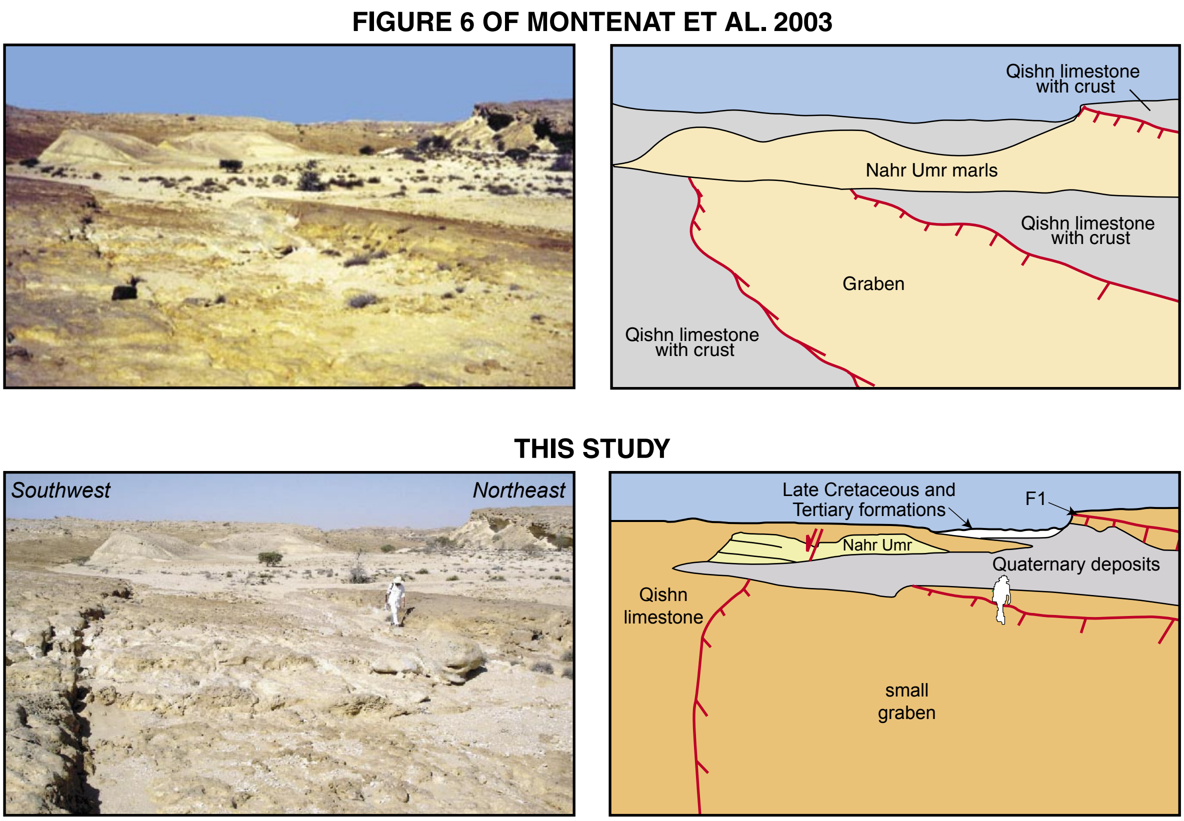


Figure 5: Two contradictory interpretations of the same view. Above: the Nahr Umr marls seal normal faults bounding a small graben in the Qishn limestones (Montenat et al., 2003). Below: Quaternary deposits seal the small graben and prevent the observation of the contact between Nahr Umr marls and Qishn limestones. Note the accordance between the Nahr Umr marls and Qishn limestones dips, suggesting that F1 faulting and related tilting are younger than the deposition of the two formations.

Umr marls deposition. This observation strongly suggests that F1 normal faulting and associated tilting are younger than the Nahr Umr marls.

This interpretation is further confirmed by the existence of a normal fault cutting the Nahr Umr beds in the vicinity of F1 (Figure 6). The fault trends N110°E, dips toward the southwest, and cross-cuts the strata of the Qishn and Nahr Umr formations. This fault, which is of the same type and the same trend as F1 and F2, most probably formed during the same extensional episode after the deposition of the Nahr Umr marls.

Moreover, the 1:250,000 scale geological mapping of the Huqf area (Figure 1a; Platel et al., 1992) shows that F1 and F2, among other faults with the same strike, affect the Nahr Umr Formation and are sealed by Middle Miocene limestone (Naqd Formation).

These lines of field evidence consistently indicate that normal faulting postdated the Nahr Umr Formation. Hence, our field observations lead to the following chronology: (1) deposition of the Qishn limestones and the Nahr Umr marls; (2) post-Albian normal faulting; and (3) formation of the ferruginous crust.

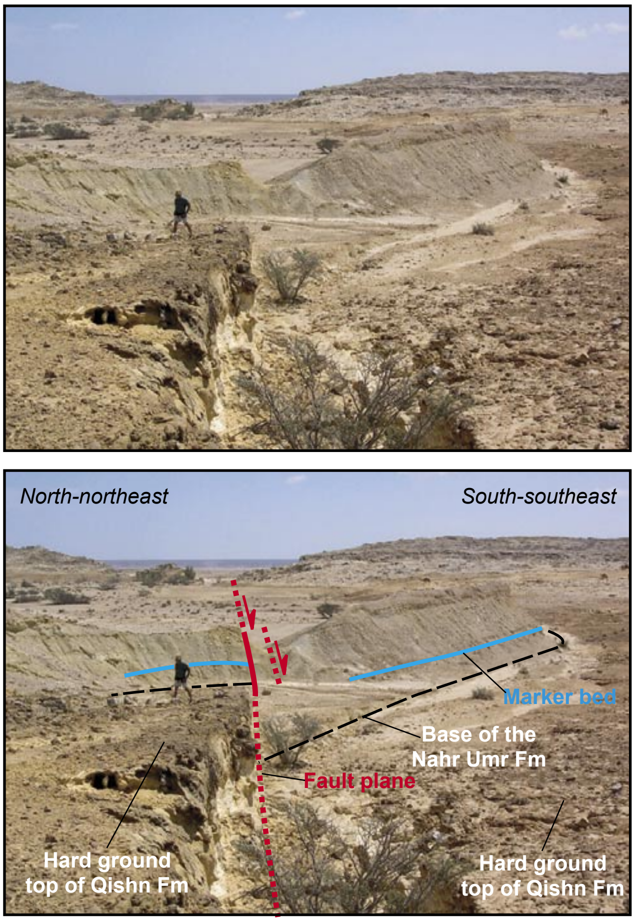


Figure 6: Normal fault cutting the strata of the Qishn and Nahr Umr formations (with the same throw). Location in Figure 1c.

CONCLUSION

The preceding discussion casts doubt on the field arguments used by Montenat et al. (2003) to define a late Aptian tectonic event in the Huqf region. According to our observations, the top-Qishn Formation hardground does not seal any tectonic event. We conclude that there is no late Aptian extensional tectonic phase in the Arabian platform documented in the Wadi Sha'bat al Tawraq. The exact age of normal faulting is not known, but it occurred between the late Albian and the Middle Miocene. It could be related to the NE-SW extensional event that was active during the Oligocene to Lower Miocene rifting of the Gulf of Aden, and whose effects are widespread in southern Oman (Lepvrier et al., 2002; Fournier et al., 2004).

ACKNOWLEDGMENTS

This study was supported by the MEBE program devoted to the Middle-East Basins Evolution. We are grateful to Dr. Hilal Mohammed Al-Azri and Dr. Salim Al-Bu Saidi from the Omani Directorate General of Minerals, Ministry of Commerce and Industry of Oman, for their support.

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