

Pre-Permian uplift and diffuse extensional deformation in the High Zagros Belt (Iran): integration in the geodynamic evolution of the Arabian plate

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Abstract The High Zagros Belt includes exposures of Lower Palaeozoic rocks in the core of several thrust anticlines developed during the Cenozoic Zagros orogeny. The structural style and tectonic evolution of this area during the Palaeozoic remain poorly understood due to the complexity of the subsequent deformation. We present the preliminary results of a field study focusing on the structural geology of Palaeozoic rocks in this area. We confirm the existence of an angular unconformity below the Lower Permian Faraghan formation. In the geological literature, this unconformity is reported as the “Hercynian Unconformity” suggesting a relationship with the Hercynian (Variscan) orogeny, which affected Western Europe and westernmost Africa during the Carboniferous. Surprisingly the only observable structures sealed by this unconformity are N to NE trending normal faults and tilted blocks without any evidence of compressional deformation. This pre-Permian extensional deformation,

which is general at the scale of the HZB, raises questions about the geodynamic significance of the “Hercynian unconformity” in the study area and, more generally, in the Arabian plate.

Keywords High Zagros Belt (Iran) · Palaeozoic · Arch · Hercynian unconformity · Normal faulting

Introduction

Throughout the Arabian plate, a more-or-less significant sedimentary hiatus separates the continental early Permian sequence from the older sedimentary formations (e.g. Konert et al. 2001; Johnson 2008). This hiatus and related unconformity is generally referred to the “Hercynian unconformity” (see a recent synthesis by Faqira et al. 2009) suggesting a relationship with the Hercynian (Variscan) orogeny, which affected Western Europe and north-western Africa during the Carboniferous (e.g. Simancas et al. 2009; Michard et al. 2010). Our field work in the central and eastern High Zagros Belt confirms the existence of an angular unconformity below the Lower Permian Faraghan formation. Surprisingly the structures sealed by this unconformity are normal faults and tilted blocks without any evidence of compressional deformation. This observation, which is general at the scale of the High Zagros Belt, raises the question of the significance of Hercynian unconformity in the study area and, more generally, in the Arabian plate. After a short description of the geology of the High Zagros Belt, we will present field data illustrating both the attitude of the pre-Permian unconformity and the geometry of inherited normal faults and tilted blocks in both the central and eastern High Zagros Belt. We will conclude with a

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discussion on the implications at the scale of the Zagros orogeny and the Arabian plate more commonly.

Geological setting: geology of the High Zagros Belt, correlation of the Palaeozoic sequences

The High Zagros Belt (HZB; Fig. 1) belongs to the Zagros Fold-and-Thrust Belt (ZFTB), which extends over about 2,000 km from south-east Turkey through southwest Iran down to the Strait of Hormuz (Fig. 1; Stocklin 1968; Falcon 1974; Berberian and King 1981; Alavi 1994; Sherkati et al. 2006). The ZFTB represents the southern palaeo-margin of the Neo-Tethys Ocean, involved in the Zagros orogeny (see a recent synthesis by Frizon de Lamotte et al. 2011). The HZB was first introduced as a continuous narrow NW-SE thrust zone with the highest rate of topography, uplift and rainfall (Berberian 1995). The HZB is bounded to the south by the NW-SE High Zagros Fault (HZF), which we define as the southernmost principal thrust-fault carrying out Lower Palaeozoic strata (other than Hormuz salt) over Mesozoic or Cenozoic rocks, and to the north by the Main Zagros Thrust (MZT), which corresponds to the fundamental limit (Neo-Tethys suture) with the internal Sanandaj-Sirjan domain pertaining to the Eurasian plate. Following this definition the HZB does not exist everywhere along the ZFTB but correspond to elevated domains in two specific areas: the central and eastern Zagros (Fig. 1).

In the central High Zagros a complex network of branching faults combining pure reverse faults in association with right-lateral strike-slip faults allow large exposures of Palaeozoic rocks (Fig. 2). In the eastern Zagros, the HZB (Fig. 3) is made up by three giant anticlines bounded to the

SW by basement faults interpreted as segments of the HZF (Molinaro et al. 2005). Lower Palaeozoic rocks are out cropping in the core of two of them, namely the Kuh-e-Faraghan and Kuh-e-Gahkum anticlines (Fig. 3). An isolated outcrop of Palaeozoic rocks also exists in the core of the Surmeh anticline, located in the external part of the Fars Arc (Fig. 1). Elsewhere in Zagros, the Palaeozoic is only known from sparse wellbore penetrations.

The litho-stratigraphy of Palaeozoic sequences has been established in the ZFTB by James and Wynd (1965) and subsequently revised by Setudehnia (1972), Koop and Stoneley (1982), Motiei (1993), Ghavidel-syooki (2003), Alavi (2004) and Ghavidel-syooki et al. (2011; Fig. 4). At the bottom of the sedimentary pile, the Hormuz salt of Late Precambrian–Early Cambrian age was deposited in an evaporitic basin located mainly on the site of the present Fars Arc (Fig. 1; Jahani et al. 2009). A branch of this basin seems to follow the trend of the central High Zagros Belt as indicated by the presence of several salt plugs underlying the main thrust faults in this domain (Fig. 2). From a structural point of view, this salt layer and its lateral equivalents form the main décollement in the area decoupling the overlying sedimentary pile from probable pre-Hormuz sediments of unknown age and from the Panafrican basement (e.g. O'Brien 1950, 1957; Berberian 1995; Alavi 2004; Sherkati et al. 2005; Mouthereau et al. 2007; Jahani et al. 2009; Vergès et al. 2011). This was followed by the development of epi-continental basins from Early Cambrian up to Late Devonian (Setudehnia 1972).

In the central High Zagros Belt, because of widespread uplift and erosion, which is generally interpreted as a far effect of the Hercynian orogeny or locally as result of Hormuz salt movement (Letouzey and Sherkati 2004; Sherkati 2004), only Cambrian and Ordovician sequences are out cropping

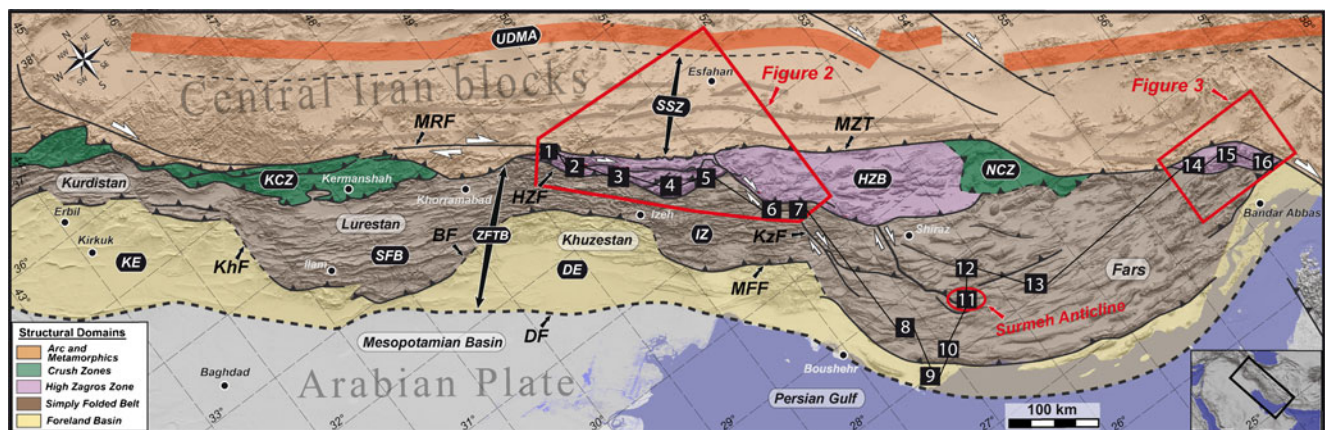


Fig. 1 Structural map of the Zagros Fold-Thrust Belt (ZFTB) emphasizing the position of the High Zagros Belt. UDMA Urumieh-Dokhtar Magmatic Arc, SSZ Sanandaj-Sirjan Zone, KCZ Kermanshah Crush Zone, NCZ Neyriz Crush Zone, ZFTB Zagros Fold-Thrust Belt, HZB High Zagros Belt, SFB Simply Folded Belt, IZ Izeh Zone, KE Kirkuk Embayment, DE Dezful Embayment, MZT Main Zagros Thrust, MRF Main Recent Fault, HZF High Zagros Fault, KzF Kazerun Fault, MFF

main Frontal Fault, KhF Khanaqin Fault, BF Balarud Fault, DF Deformation Front. The red lines mark the areas of Figs. 2 and 3 and Surmeh anticline. Note to the location map of 16 selected Paleozoic surface and borehole logs in central High Zagros, Fars Arc and eastern High Zagros. Connection line shows the trace of the stratigraphic correlation diagram (Fig. 5)

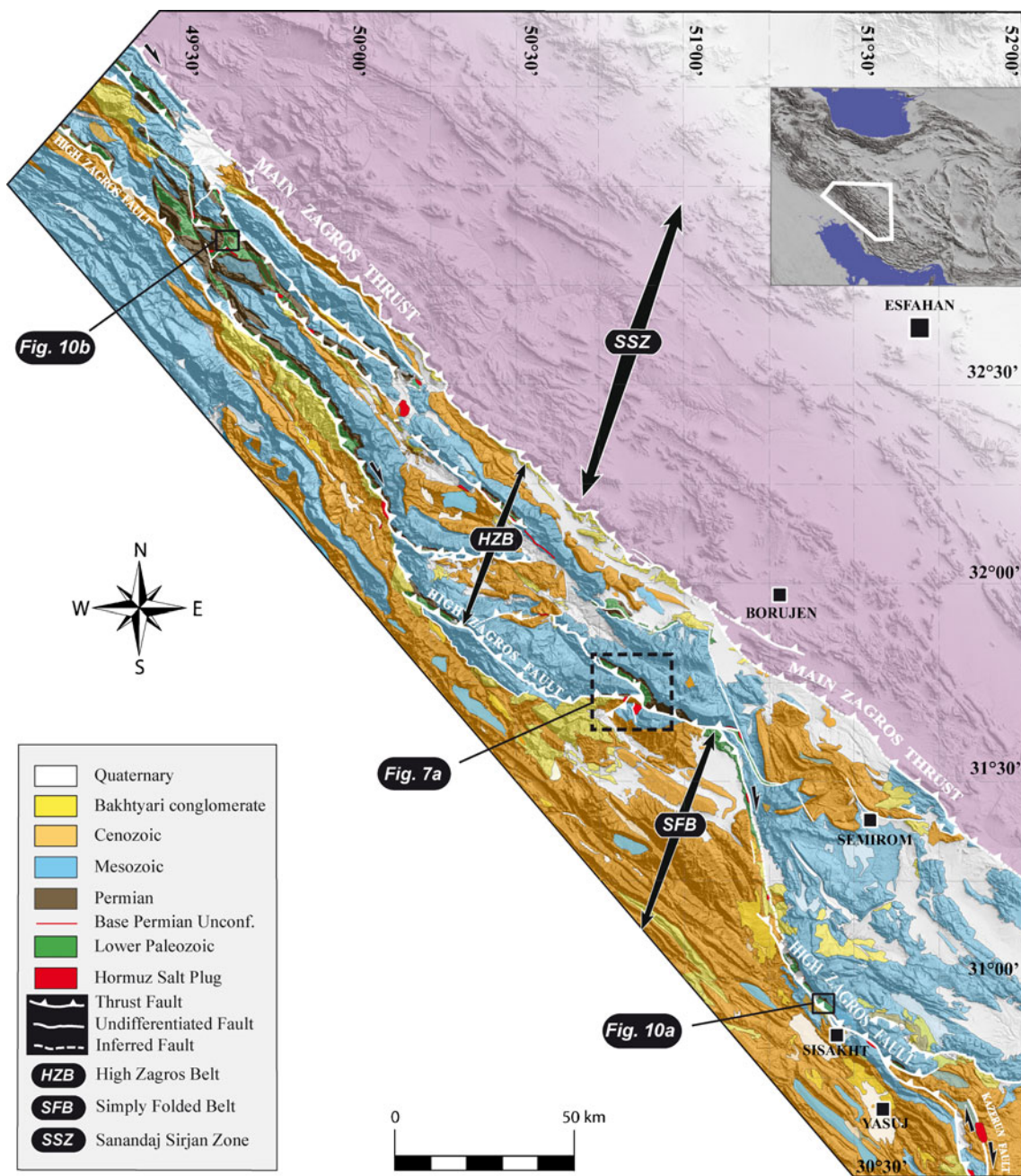


Fig. 2 Structural map of the central High Zagros Belt (HZB). This map has been compiled using SRTM, Landsat images, available geological maps published by the Geological Survey of Iran and NIOC and our field investigations. See location on Fig. 1

(Setudehnia 1972; Kheradpir and Khalili 1972). More precisely, Setudehnia (1972) recognized and dated the sandstone of the Lalun formation as well as the Mila trilogy, both of Cambrian age, in the Kuh-e-Dena and the olive shale of the Ilbek formation (Ordovician) at Zard-Kuh (Figs. 4 and 5).

Silurian and Devonian strata have not been reported and are likely absent in the central High Zagros. By contrast, they are out cropping in the eastern HZB at Kuh-e-Faraghan and Kuh-e-Gahkum anticlines (Fig. 3). These anticlines expose a quite complete lithostratigraphic succession from

Lower Ordovician (Floian) to Upper Devonian (Frasnian) (see Fig. 5). More precisely, Ghavidel-syooki et al.'s (2011) study in Kuh-e Faraghan recognized the Floian to Katian Syahoo formation, Hirnantian Dargaz Sandstones and diamicrites, the Silurian black shales of the Sarchahan formation and finally the clastic sequence of the Devonian Zakeen formation (Ghavidel-syooki 2003). The formations older than Middle Ordovician do not crop out in the Eastern Zagros, possibly due to a tectonic decoupling along the Syahoo formation (Fig. 5).

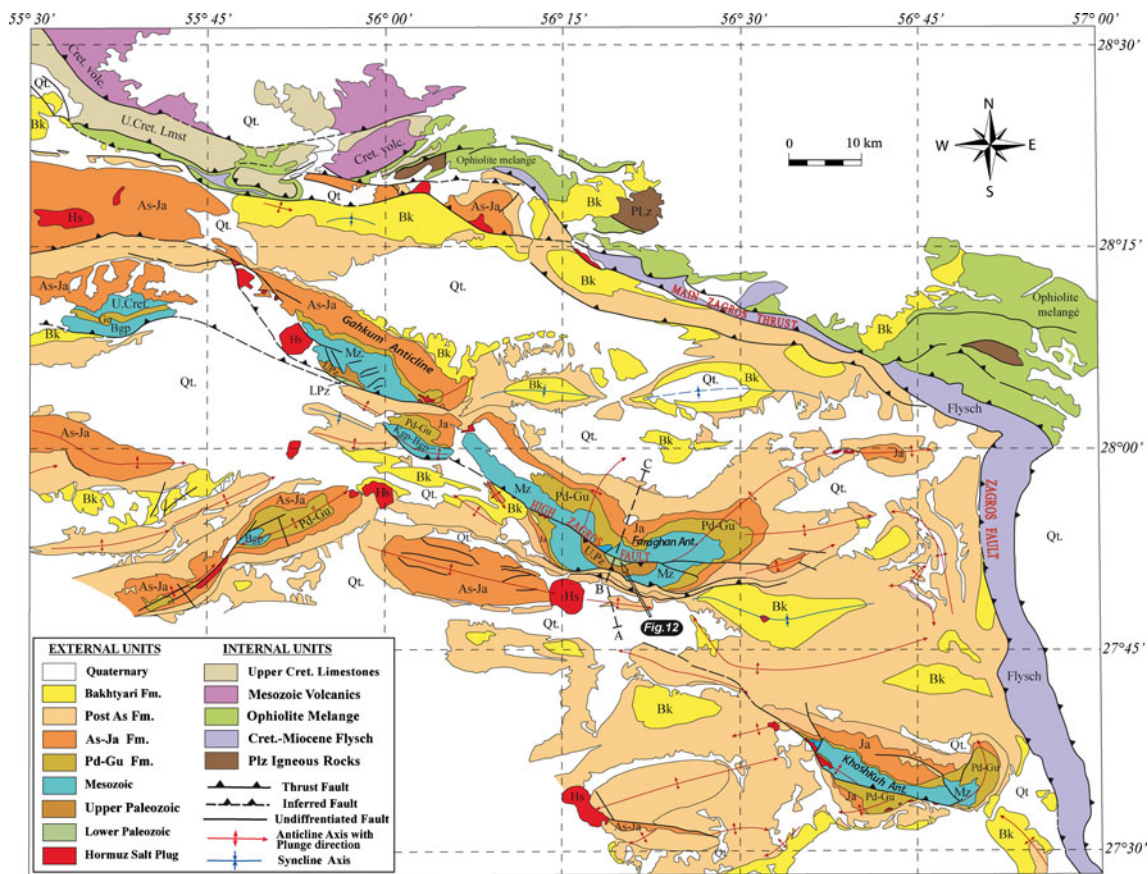


Fig. 3 Structural map of the eastern Zagros. This map has been compiled using various geological maps published by NIOC and the Geological Survey of Iran, Google Earth and Landsat imageries and our field investigations. See location on Fig. 1

Between the central and eastern High Zagros (i.e. in the Fars Arc, Figs. 1 and 6), the Palaeozoic sequences can be tentatively reconstructed using the outcrop of Surmeh anticline and a few well penetrations (Fig. 5). So, at the scale of the High Zagros Belt, we are able to rebuild long wavelength, low amplitude pre-Permian “folds” mimicking the so-called Palaeozoic “Arches” (or uplift) and intervening “Basins” well-known in Arabia (Konert et al. 2001; Faqira et al. 2009) or North Africa (Boote et al. 1998). More precisely, in the Arabian plate, Faqira et al. (2009) recognize three Arches, namely from west to east, the Levant, Al-Batin and Hadhramaut-Oman Arches and the two Basins, the Nafud-Ma’aniya and Faydah-Jafurah Basins located between the Arches (Fig. 6). Within the basins, some secondary Arches, like the Qatar Arch or the Ghawar High (Fig. 6), are present. The central HZB is located in the northeastern prolongation of the Al Batin Arch. The rest of our correlation line should be located in the Jafurah Basin and presents in its core a secondary dome (Gavbandi high), which could correspond to the northern prolongation of the Qatar Arch (Fig. 6).

Everywhere in the Zagros, Lower Permian coarse sandstone of the Faraghan formation deposited unconformably on the underlying more or less truncated beds (see below).

The deposition of this formation occurred after an intense erosion leading, in the central High Zagros Belt, to the removal of post Ordovician deposits and suggesting large scale vertical movements. It is followed by a carbonate epicontinental platform covering a large time period from Permian (Dalan formation) to Cenomanian (Sarvak formation). It is worth noting that the Iranian Faraghan and Dalan formations are the strict lateral equivalent of the Saudi Unayzah and Khuff formations, respectively (Insalaco et al. 2006). The age of the Unayzah formation has been reported as Upper Carboniferous–Lower Permian in Saudi Arabia (Konert et al. 2001), but based on NIOC palynology studies, the Carboniferous has not been recognized in Zagros and the Faraghan formation is attributed to the Lower Permian (Ghavidel-syooki 2005a).

Pre-Permian unconformity and sealed tilted blocks in the central High Zagros Belt

The central High Zagros has been recently the site of extensive geological work (Ehsanbakhsh-Kermani et al. 1996; Bosold et al. 2005; Gavillot et al. 2010). These studies focus

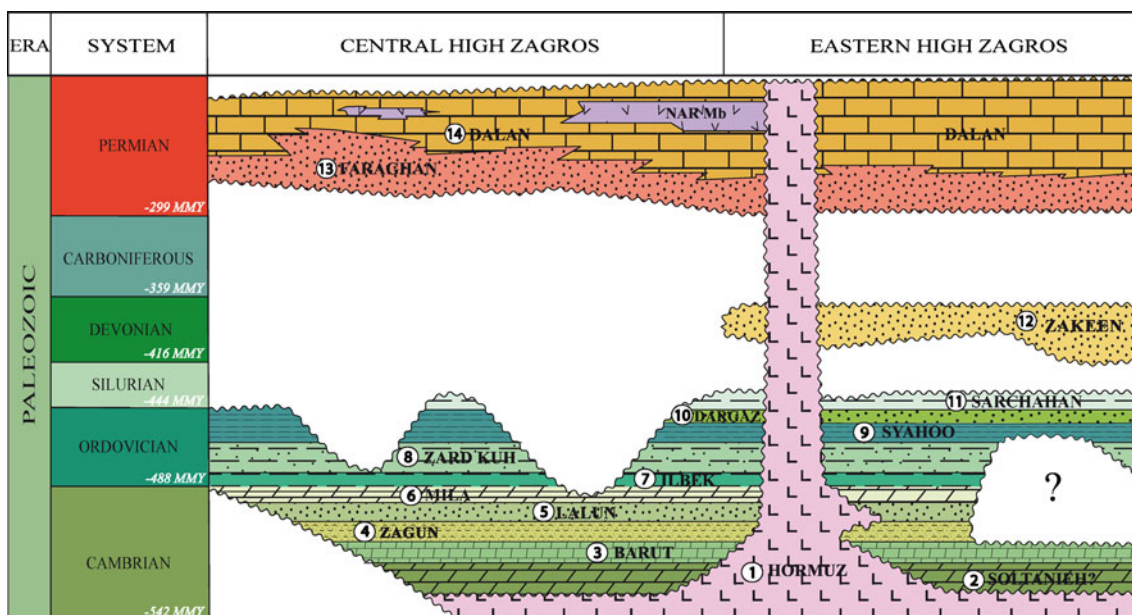


Fig. 4 General Lithostratigraphic chart for the Paleozoic sequence in the High Zagros Belt (modified after Motiei 1993). 1 Hormuz Fm halite, anhydrite, sandstone, shale, dolomite and igneous rocks. 2 Soltanieh Fm dolomite with shale beds. 3 Barut Fm dolomite with interbeddings of red shales. 4 Zagun varicoloured shale intercalated with fine sandstone on top. 5 Lalun Fm fluviatile reddish x-bedded sandstone and red shale on top. 6 Mila Fm limestone, dolomite and shale. 7 Ilbek Fm olive and black shale inter-bedded with sandstones. 8 Zardkuh Fm predominantly shale intercalated with beds of fine

grained sandstone. 9 Syahoo Fm greenish and black shale with subordinate sandstone, siltstone, conglomerate and limestone. 10 Dargaz Fm whitish sandstone and structureless to diffusely laminated diamictite. 11 Sarchahan Fm black shale and a few interbeddings of conglomerate, sandstone and carbonate. 12 Zakeen Fm sandstone with interbedded shale and subordinate dolomitic limestone. 13 Faraghan Fm inter-beddings of shale and sandstone. 14 Dalan Fm platform carbonate of limestone and dolomite

mainly on the geometry and kinematics of the major folds and thrust-faults, related to the Zagros orogeny, but deal only marginally with the Palaeozoic evolution. As an example, on the Ardal geological map (Ehsanbakhsh-Kermani et al. 1996) the Lower Palaeozoic strata have been drawn as a “layer cake” conformably overlain by Permian and younger rocks.

In fact and as indicated above, not only a considerable sedimentary hiatus separates the Lower Palaeozoic from the Upper Palaeozoic rocks but also the Lower Palaeozoic rocks have been tilted and truncated before the deposition of the Permian sediments. Among the different places where the pre-Permian unconformity is well exposed, the Kuh-e-Lajin is likely the most spectacular. From the revised geological map and associated cross-section (Fig. 7a, b), we can see that the Faraghan formation rests equally onto Lalun, Mila or Ilbek formations. Based on field observations, the mean dip of the Lower Palaeozoic rocks (45° ENE) is clearly higher than the dip of the Upper Palaeozoic (10° ENE; Fig. 8a, b). The unconformity is also visible in the Landsat TM satellite imagery (Fig. 8c). By contrast, it is worth noting the absence of an unconformity between the Upper Permian Dalan formation and the overlying Mesozoic rocks. Following along strike, the basal thrust of the Kuh-e-Lajin, which is a segment of the HZF, lateral missing of Ilbek formation and offset of the Lower Palaeozoic sequence are clearly observable (Fig. 7a).

It is due to a west-dipping approximately N-S oriented normal fault presently hidden beneath recent formations. This early normal fault, separating two east-dipping tilted blocks, is sealed by the Faraghan formation. The whole assemblage, i. e. the Lower Palaeozoic with its embedded normal fault and their unconformable Permian to Cenozoic cover, has been uplifted and thrust toward the WSW during the Zagros orogeny (Fig. 7a, b). A photo of the pre-Permian unconformity in Kuh-e-Lajin has been already published by Letouzey and Sherhati (2004). It was interpreted as a possible effect of a salt dome growth. In our opinion, the salt plugs existing in the footwall of the Lajin thrust (Fig. 7a, b) can explain neither the observed geometry nor the erosion preceding the deposition of the Faraghan formation.

Just south-west of the Kuh-e-Lajin is the Kuh-e-Bazman, an E-W trending faulted anticline in the core of which a small section of Lower Palaeozoic rocks is cropping out (Fig. 7a). The geology of the area is quite complex due to the vicinity of a plug of Hormuz salt. However a prominent unconformity between truncated Lower Palaeozoic formations (Lalun, Mila and Ilbek) and the Permian sequence is very well exposed in the field (Fig. 9). The eastward dip of the Lower Palaeozoic rocks suggests that, as in the Kuh-e-Lajin, this particular attitude could be controlled by a hidden west-dipping normal fault.

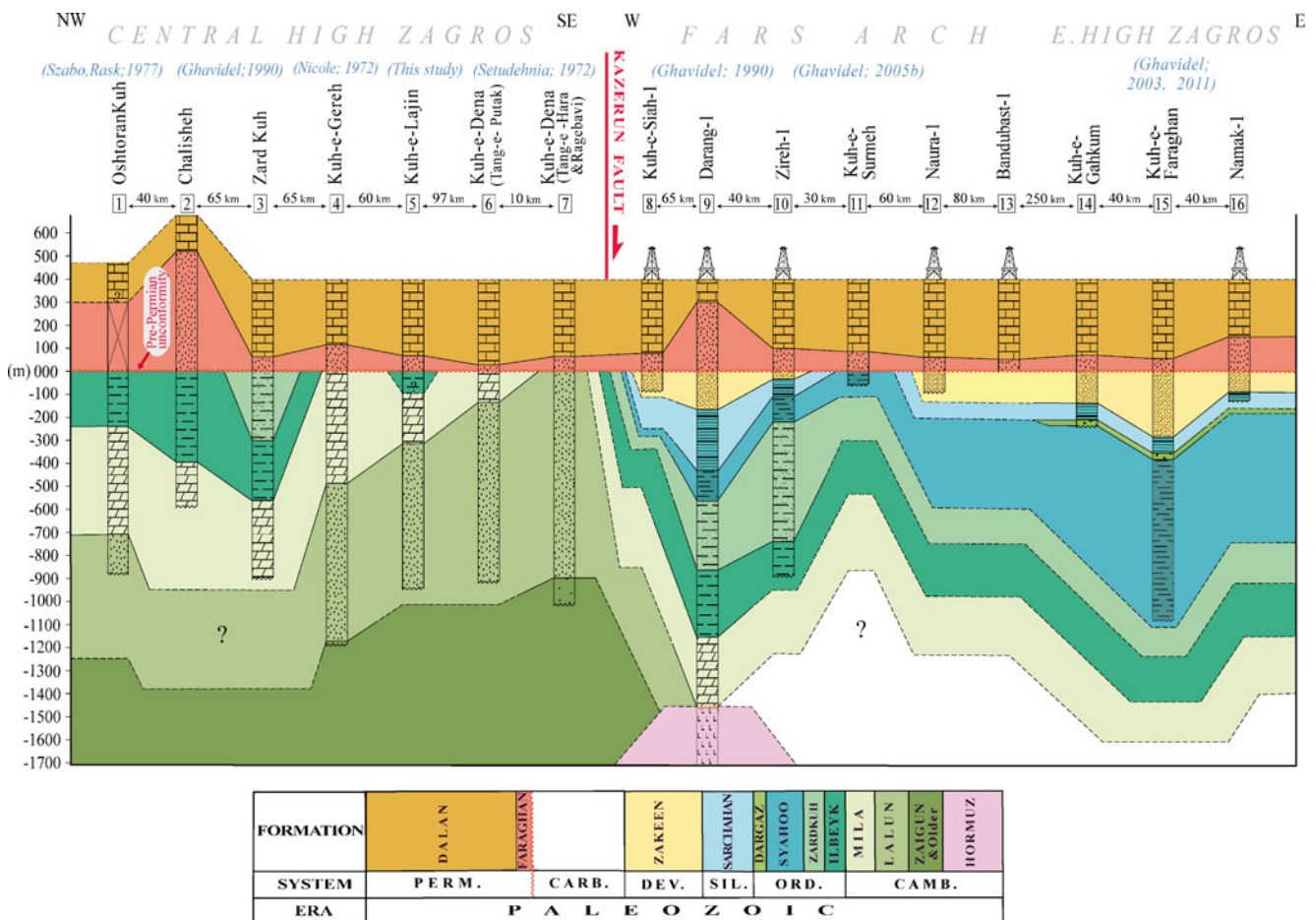


Fig. 5 Stratigraphic correlation diagram of pre-Faraghan Palaeozoic formations in High Zagros Belt. Datum: base Faraghan formation. (See Fig. 1 for location of the columns). Note to the references of the surface

Normal faulting restricted to Lower Palaeozoic formations has been observed in numerous other places within the central High Zagros Belt. The Fig. 10a, b present two examples, in Kuh-e-Dena and Baznavid area, respectively (see location on Fig. 2). All these normal faults are sealed by the pre-Permian unconformity.

Examination of preserved Palaeozoic stratigraphic sequence in the central HZB reveals different levels of erosion (and likely differential vertical movements) for the pre-Permian rocks (Fig. 5). In Dena mountains the basal Faraghan unconformity seals Cambrian, Lalun and Mila formations (Setudehnia 1972) whereas, towards the northwest (Zard-kuh area), the stratigraphic pile is more complete with presence of Ordovician Ilbek and Zardkuh formations (Setudehnia 1972; Fig. 5). In each place we observe the same geometrical relationships with pre-Permian rocks dipping towards the east or north-east beneath a more flat unconformable Permian cover. This configuration suggests a geometrical model of eastward tilted blocks over west-dipping normal faults. The hanging wall of each fault could preserve a more complete sedimentary sequence than the

stratigraphic logs in blue color. Borehole data are based on the well completion reports provided by NIOC

footwall, which suffered deeper erosion. Pre-Permian erosion (probably during the Carboniferous, see below) resulted in removal of huge thicknesses of Palaeozoic sequence (at least the whole Silurian and Devonian in the central HZB) before deposition of clastic Lower Permian Faraghan formation.

Pre-Permian unconformity and sealed normal faults in the eastern High Zagros Belt

In the context of the geological interpretation of the Palaeozoic rocks in Zagros, the eastern High Zagros Belt is important because it is the only place where Devonian and Silurian rocks are out cropping (Figs. 3 and 5). So, in contrast with the central HZB “Arch,” the eastern HZB is located rather in a “Basin” position.

Ghavidel-syooki et al. (2011) give a new stratigraphic appraisal of the Palaeozoic sequence cropping out in both the Kuh-e-Gahkum and Kuh-e-Faraghan anticlines (Fig. 3). Following the new stratigraphic data acquired by these

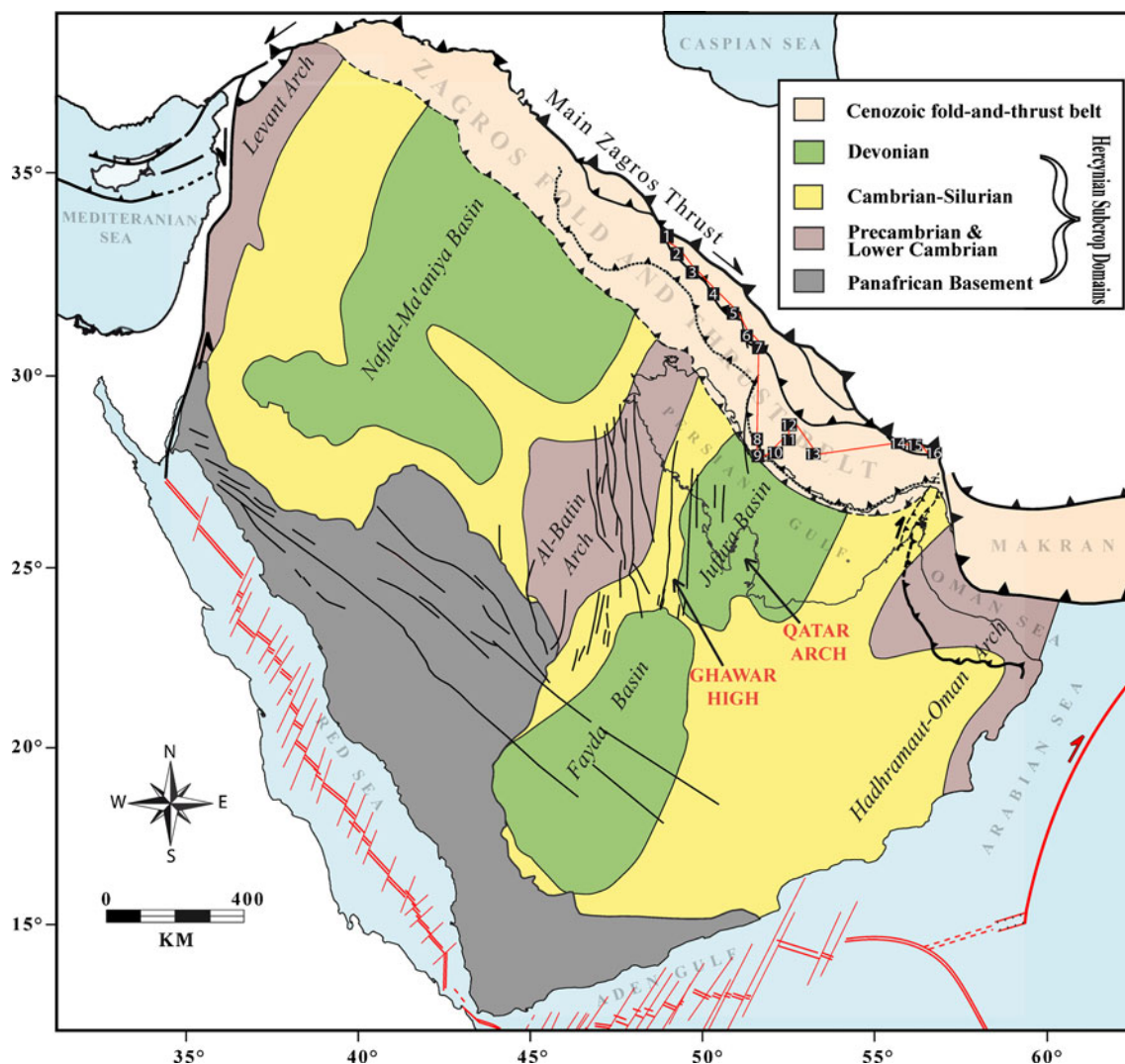


Fig. 6 Schematic structural map of the Arabian plate showing the main structural elements of the Zagros Fold-and-thrust Belt and Arabian platform. The Arabian platform is illustrated by an Hercynian

subcrop map (modified from Faqira et al. 2009) in order to underline the major Paleozoic Arches and Basins

authors, the oldest rocks are Hirnantian conglomerates in Gahkum anticline suggesting a strong de-coupling within Lower Palaeozoic rocks along the Syahoo shales. This matter has not been taken into account in previous tectonic interpretations (Jahani et al. 2009; Motamedi et al. 2011).

In Kuh-e-Faraghan structural section (Fig. 11), this decoupling led to the development of a major back-thrust (thrust faults labelled 1 on the Fig. 11) putting the Palaeozoic over the Mesozoic rocks (Jahani et al. 2009). Following our interpretation, this back-thrust initiated at an early stage of the development of the structure and is due to the activation of Ordovician ductile layers. Forward progression of deformation caused the occurrence of a low angle forethrust in the core of the Faraghan anticline (thrust faults labelled 2 on the Fig. 11). The whole sequence have been subsequently cut out by a late south-west verging

basement fault (thrust faults labelled 3 on the Fig. 11). Such an evolution can explain why the Cambrian and Early Ordovician rocks remain at depth and are not exposed in the field.

As in the central HZB and despite the restricted area where Palaeozoic rocks are out cropping, the Kuh-e-Faraghan presents beautiful examples of normal faults sealed by the Faraghan formation (Fig. 12a, b). This observation is of crucial importance for three main reasons: (1) it shows that normal faulting is not restricted to the Palaeozoic “Arch” as in the central HZB but developed also in the intervening “basins”; (2) it shows that the normal faults developed after the deposition of the Zakeen formation, which is dated as Early Devonian up to Frasnian (Ghavidel-syooki 2003) (Figs. 4 and 5) and (3) it shows (absence of the Carboniferous) that the pre-Permian uplift and related erosion

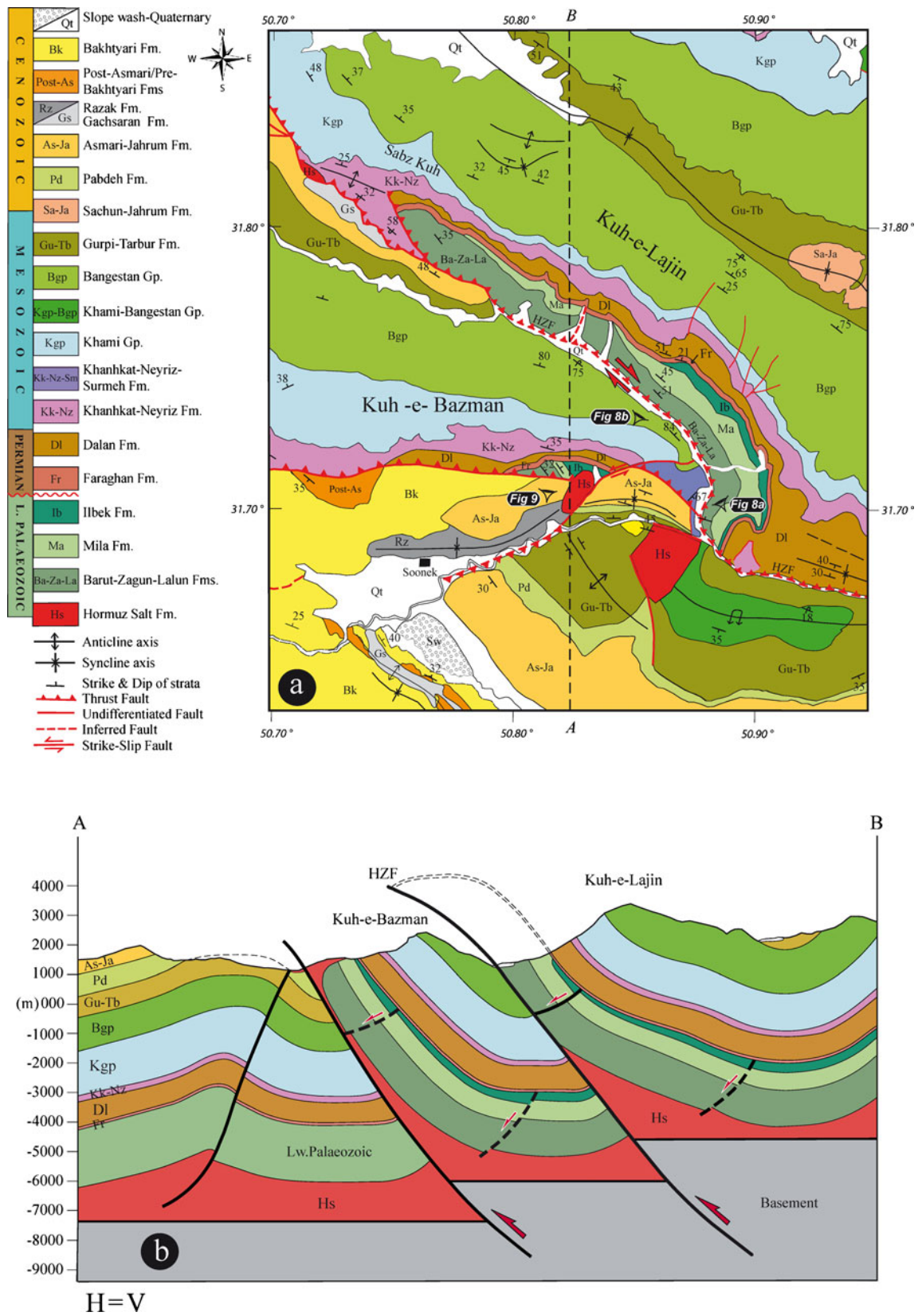


Fig. 7 **a** Geological map of the Kuh-e-Lajin, Kuh-e-Bazman and adjacent areas, modified from Ardal 1/100,000 map (Ehsanbakhsh-Kermani et al. 1996; see location on Fig. 2) with location of the section line. **b** Structural cross-section through the Kuh-e-Lajin (see location on Fig. 7a)

Fig. 8 **a** Helicopter view of the pre-Permian angular unconformity in Kuh-e-Lajin. **b** Detail of the unconformity in Kuh-e-Lajin. **c** Landsat image of the Kuh-e-Lajin illustrating the pre-Permian unconformity. Photos **a** and **b** are located on Fig. 7a

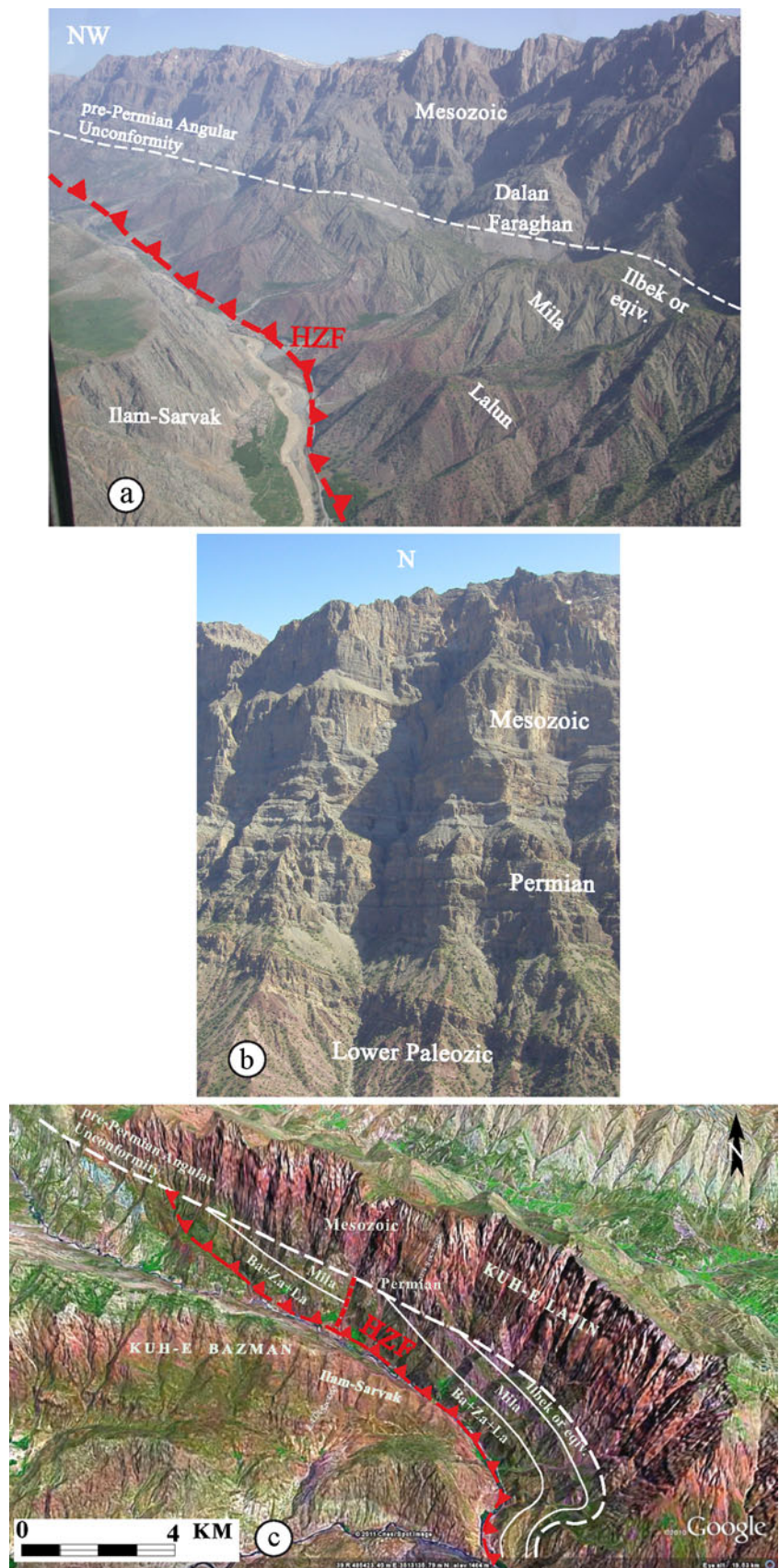


Fig. 9 The pre-Permian unconformity at Kuh-e-Bazman (see location on Fig. 7a). Note to the truncation of tilted Lower Palaeozoic formations by overlying Permian rocks

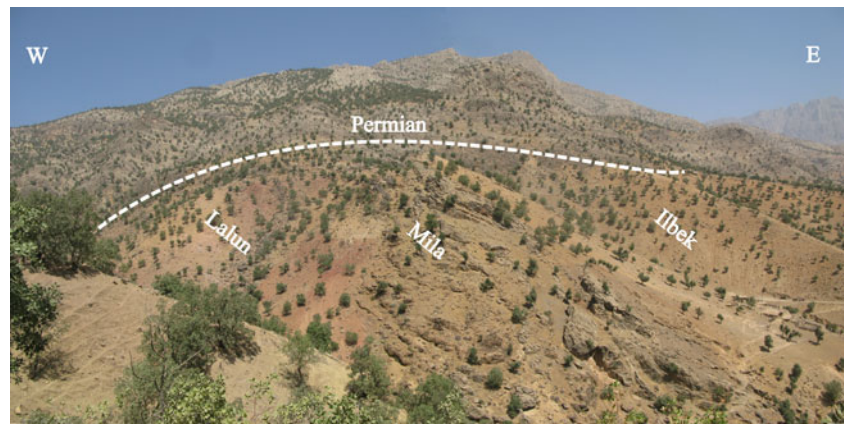
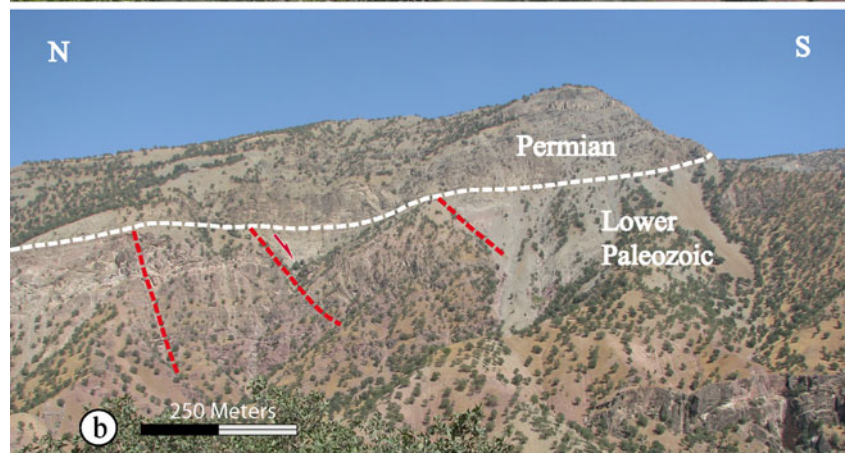
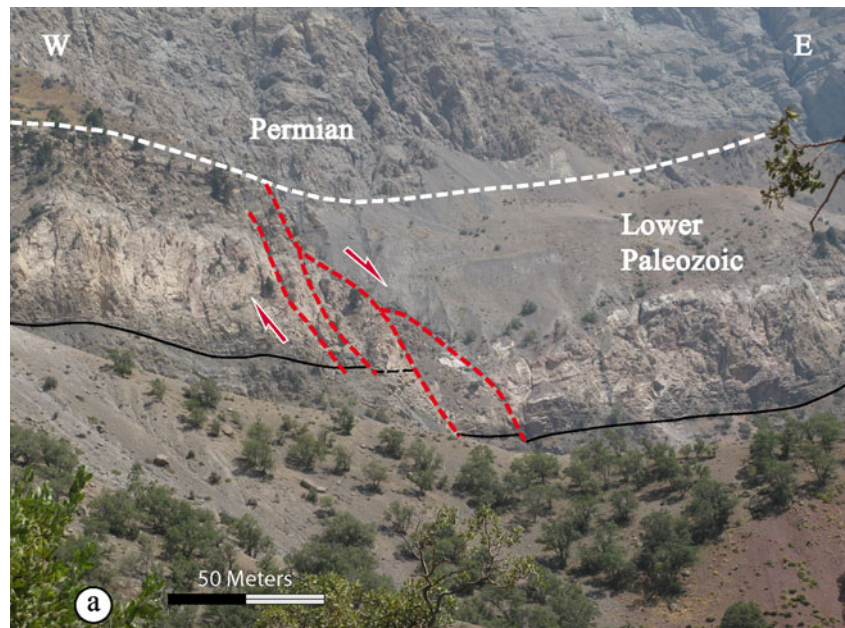


Fig. 10 Examples of pre-Permian normal faults. **a** Normal faults in Kuh-e-Dena sealed by Pre-Permian unconformity. In this case, the fault planes are dipping eastward. They are most probably antithetic faults by reference to the major normal faults. **b** Normal faults in Baznavid topped by Pre-Permian unconformity. Photos **a** and **b** are located on Fig. 2



is not restricted to the “Arch” but is general at the scale of the High Zagros Belt.

Discussion

Apart the direct border of the Arabian shield (Fig. 6), the HZB (Fig. 1) is the only place in the Arabian plate where the Lower Palaeozoic is out cropping. It is consequently of great interest for a better understanding of the Palaeozoic evolution of the whole Arabian domain.

Geometry of the Palaeozoic deposits and associated deformation

At large scale and after unfolding of the Cenozoic structures, the Palaeozoic section of the HZB presents NE trending pre-Permian long wavelength and low amplitude “folds” extending north of the Al-Batin Arch and the Jafurah Basin known in the Arabian foreland (Figs. 5 and 6; Faqira et al. 2009). These structures could be interpreted as the result of lithospheric folding. In this classical hypothesis, the normal faults observed in the central HZB should be extensional features developed in the outer stretched arc of the anticlines (Fig. 13a). However, the existence of these normal faults in the eastern HZB, which is in a “syncline” position (Fig. 5), cannot be easily integrated in such a scheme.

Our work suggests rather a gentle horst and graben geometry related to a weak extensional deformation (Fig. 13b). This deformation is accompanied by an important uplift

explaining the huge erosion observed in the Arches and the hiatus of the Lower to Middle Carboniferous observed in the Basins. The origin of this general uplift remains disputable. However, the lack of important normal faults within the post-unconformity deposits strongly suggests a sag geometry for these Basins and consequently a thermal origin for the subsidence. More precisely, the post-uplift cooling of the lithosphere should be responsible for thermal subsidence by the Late Carboniferous. The same geometry can be observed in the Arabian foreland of the Zagros where the Upper Carboniferous–Lower Permian Unayzah Fm is confined in the central parts of the Palaeozoic Basins whereas the Middle-Upper Permian Khuff Fm is on-lapping the “Arches” (Faqira et al. 2009).

Faqira et al. (2009) express some doubts about the causality relationships between the Arches building and the Hercynian orogeny, which developed 5,000 km away to the west. We share these doubts and go further. The question is to know if our conclusions on the HZB (i.e. the absence of pre-Carboniferous contractional deformation) can be extended to the Arabian plate and even to other parts of the north Gondwanian domain like Pakistan (Gee 1989). As a matter of fact, this entire domain presents a unified architecture with a series of broad Basins and intervening Arches. At its present stage, our work is too local to be affirmative. However, we can emphasize several important points. Most of the faults of the Central Arabian Domain are confined in the pre-Unayzah deposits (Wender et al. 1998; Johnson 2008). Despite recent high quality data, it is difficult to understand easily their kinematics because the faults appear

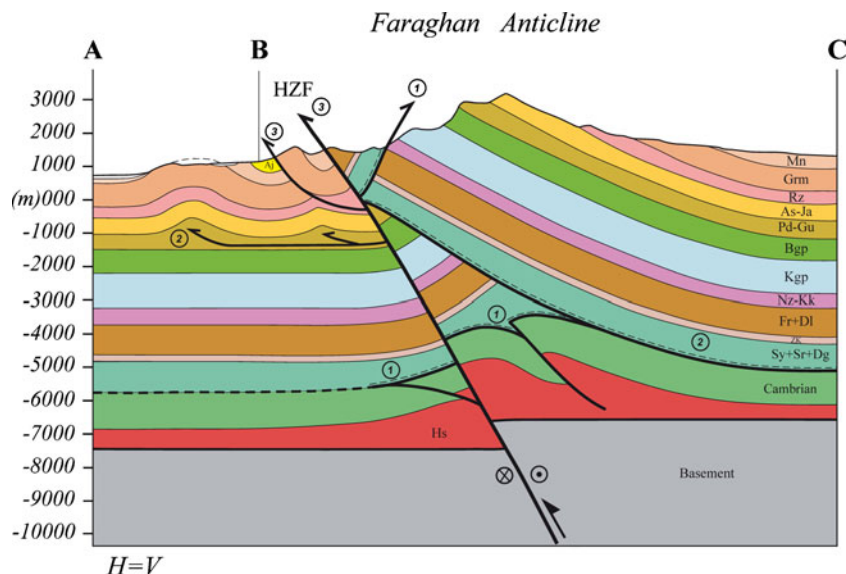
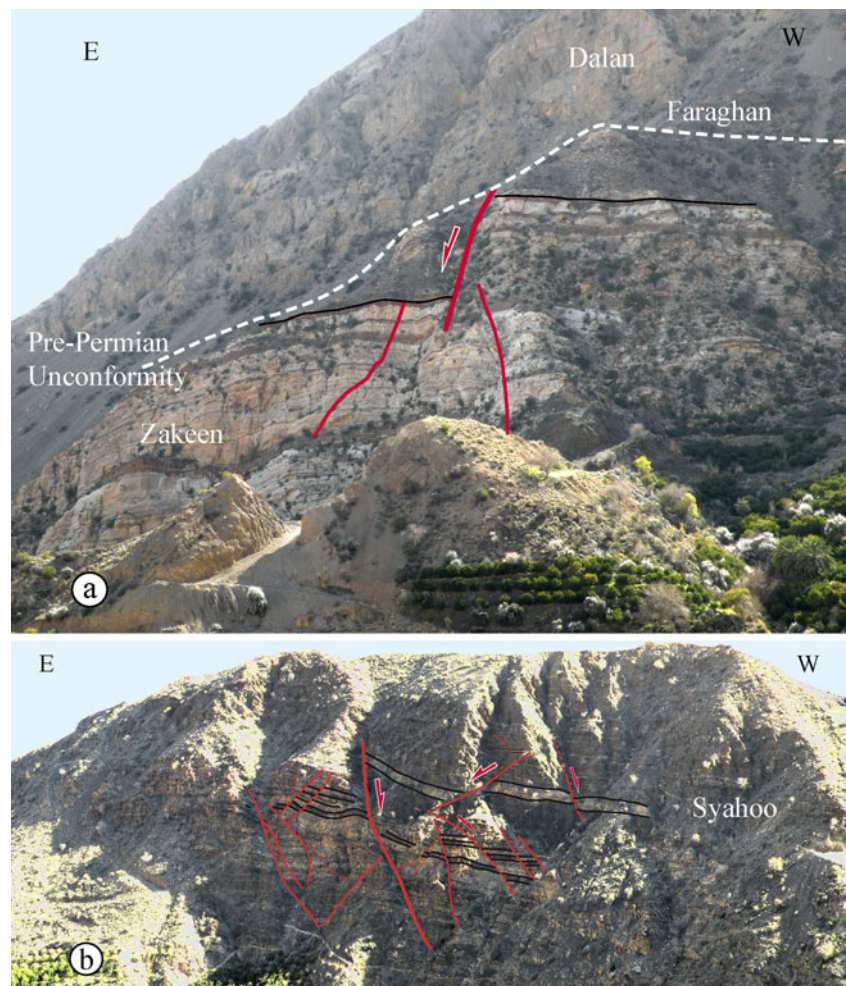


Fig. 11 Structural cross-section through Kuh-e-Faraghan (see location on Fig. 3). *Hs* Late Proterozoic to Infra-Cambrian Hormuz Salt, *Sy* Ordovician Syahoo Fm. *Dg* Hirnantian Dargaz Fm., *Sr* Silurian Sarchahan Fm., *Zk* Devonian Zakeen Fm., *Fr* Early Permian Faraghan Fm., *Dl* Permian Dalan Fm., *Kk* Triassic Khanehkat Fm., *Nz* Jurassic Neyriz

Fm., *Kgp* Jurassic-L.Cretaceous khami group, *Bgp* U. Cretaceous Bangestan group, *Gu* U. Cretaceous Gurpi Fm., *Pd* Paleo-Eocene Pabdeh Fm., *Ja* Eocene Jahrum Fm., *As* Oligo-Miocene Asmari Fm., *Rz* Miocene Razak Fm., *Grm* Guri member, *Mn* Miocene Mishan Fm., *Aj* U.Miocene Aghajari Fm. *Labels* show the sequence of thrusting

Fig. 12 **a** Tang-e-Zakeen (Kuh-e- Faraghan) illustrating normal faulting within Devonian Zakeen formation. The faults are sealed by Permian rocks (like in the Central High Zagros). **b** Conjugate sets of normal faults in Ordovician Syahoo formation exposed in the core of Faraghan anticline



in general as nearly vertical. In addition, there are strong difficulties in separating the effects of the pre-Unayzah development from the subsequent structural growth. This is particularly true for the Triassic and Upper Cretaceous periods, which are characterized by the development of normal and reverse faults, respectively (Konert et al. 2001; Faqira et al. 2009). In any case, it can be at least concluded that the so-called “Hercynian event” is quite complex and may be not expressed in the same way everywhere across the Arabian plate even if there are evident similarities between the main features of the Arabian Domain and what we have observed in the HZB. This is particularly clear for the Ghawar High (see Wender et al. 1998), which is located along the eastern flank of the Al-Batin Arch, about 800 km south of the central HZB (Fig. 6).

Timing of the processes

In the eastern HZB, the timing of the uplift and extensional deformation is quite well constrained by existing stratigraphic data as the younger formation situated below the pre-Permian unconformity has been dated as Frasnian in the

Kue-e-Faraghan (Ghavidel-syooki 2003). In the central HZB, the timing is poorly constrained by stratigraphic studies

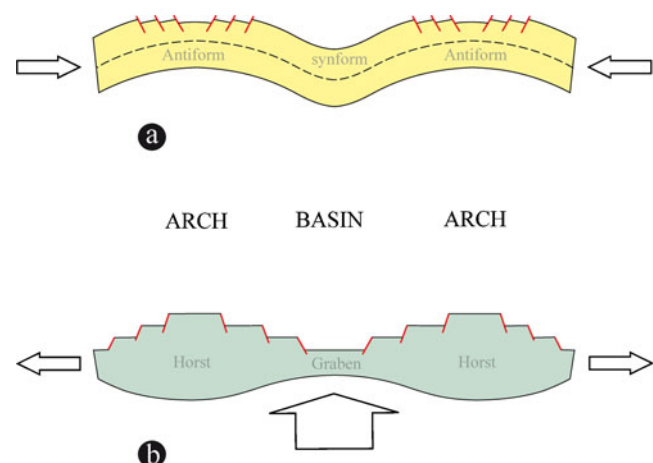


Fig. 13 Geodynamic interpretation of the Paleozoic Arches. **a** Compressive interpretation: in this classical explanation, the *Arches* represent lithosphere anticlines with possible normal faults in the extrados. **b** Extensional interpretation: in this latter (favoured in the present paper) explanation, the *Arches* are horst structures and the extension is diffused through the whole area

but the same post-Upper Devonian age is suggested by thermochronologic data. In this area, Gavillot et al. (2010) used (U-Th)/He thermochronology to date the recent thrust activity. The Palaeozoic history of the region was not the topic of their paper but they notice that a sample from the Mila formation (deposited about 500 Ma ago) was reset and then exhumed at 350 Ma (Late Devonian/Early Carboniferous).

The same exhumation age had been found by Kohn et al. (1992) in the north-western part of the Arabian plate. More precisely, the authors define a “major Late Devonian/Early Carboniferous thermotectonic event” responsible for uplift and huge erosion along a strip extending from the Gulf of Suez to north-east Syria and south-east Turkey, a zone corresponding to the Levant Arch in the terminology used by Faqira et al. (2009; Fig. 6). Using Zircon fission tracks of 17 Precambrian samples from deep boreholes and outcrops, these authors obtained 330–370 Ma ages. These ages indicate that (1) there was a total resetting of Zr fission track clocks (temperature required, $225 \pm 50^\circ\text{C}$), (2) the timing of exhumation (and related erosion) is Late Devonian/Early Carboniferous and (3) the thermal gradient was probably high (about $50^\circ\text{C}/\text{km}$) before the exhumation. It is worth noting that the same Late Devonian/Early Carboniferous age has been found by Bojar et al. (2002) in the Nubian shield of the Eastern Desert (Egypt). Again, we emphasize the convergence between ages of Arches building obtained in the HZB and elsewhere not only in the Arabian plate but also in a very large area of the northern Gondwana. In addition we note that the thermal origin for the generalized uplift of the Arabian Domain at that time has been already suggested by Fariqa et al. (2009).

Conclusion

In the central High Zagros Belt, there is no evidence of compressional deformation of Palaeozoic age. On the contrary, the only structures exposed in the field are normal faults leading to a system of tilted blocks. These field data from the central High Zagros seems consistent, at least partly, with what is shown in the Arabian domain (e.g. Wender et al. 1998; Johnson 2008; Faqira et al. 2009).

This first result raises the question about the significance of Variscan orogeny in the Arabian domain. In addition, thermochronologic data got by Kohn et al. (1992) in the north-western end of Arabia as well as the preliminary results by Gavillot et al. (2010) in the study area show that the uplift of the whole Arabia as soon as the Late Devonian is most probably of thermal and not tectonic origin. Moreover, the relief high wavelength ($\times 1,000$ km), the sag geometry of the post-unconformity deposits as well as the diffuse extensional deformation suggest a relationship with asthenosphere dynamics

rather than with a far compressive field. Quantification of these processes requires more data and more modelling.

Further thermochronologic work is required to reinforce this preliminary result. However, there is an increasing body of evidence suggesting that the pre-Permian geological history results from thermal uplift accompanying normal faulting and not from a far effect of the Variscan orogeny as classically assumed. The age of the uplift is not yet well constrained but seems to occur during the Late Devonian–Early Carboniferous. The subsequent cooling of the lithosphere should be responsible for thermal subsidence and deposition of the Faraghan-Unayzah formations by the Late Carboniferous.

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