Structures and timing of Permian rifting in the central Oman Mountains (Saih Hatat)

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ABSTRACT

We investigated remnants of Permian rifting sequences in the Saih Hatat metamorphic window (central Oman Mountains), part of the former Arabian continental margin which has been overthrust by the Semail ophiolite. In the less-deformed northwestern part of the Saih Hatat, well-preserved or inverted syn-sedimentary normal faults indicate ENE–WSW Permian extension. We propose new stratigraphic correlations with the more-deformed and metamorphosed parts of the Saih Hatat, based on lithostratigraphy and large-scale structures unfolding which indicate that breakup of the Permian platform resulted in sediment thickening and deepening towards the ENE. This rift event was coeval with within-plate volcanism that was widespread in all compartments of the margin, but marked by a single event in the stratigraphic record of the platform. In this part of the Arabian margin, rifting was restricted to a short time interval (less than 5 My) during the Murghabian, and volcanism can be correlated with the Panjal Traps event. We propose that this part of the Neotethyan margin formed as a volcanic rifted margin in a triple-junction setting.

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1. Introduction

The breakup of Gondwana occurred during the Permo-Triassic, leading to the opening of the Neotethys Ocean between the Gondwana and the Cimmerian continental blocks (Ricou, 1994; Stampfli and Borel, 2002; Stampfli and Kozur, 2006) and the formation of passive continental margins south of the Neotethys, on the northern edges of Indian and Arabian shields. Neotethys oceanic crust disappeared during the Cretaceous to Neogene convergence of Laurasia and Gondwana (Stampfli and Borel, 2002), and some remnants of continental margins were incorporated in Alpine belts in the Himalaya, Oman and Syria.

In Oman, the Late Cretaceous convergence that closed the Neotethyan realm resulted in obduction of the Semail ophiolite (Fig. 1a, Glennie et al., 1974; Coleman, 1981). This part of the Neotethyan continental margin was not the site of continent–continent collision and is better preserved than other margin segments. Palaeomagnetic data (e.g. Besse et al., 1998) and the occurrence of Middle Permian pelagic sediments associated with basaltic volcanism led several authors to propose that continental rifting and ocean spreading occurred during Middle to Late Permian (Searle and Graham, 1982; Blendinger et al., 1990; Pillevuit et al., 1997). Although the main aspects of the process are well understood, the following points require clarification.

- There is no agreement on the timing of the rifting because several stratigraphic unconformities are found within the Late Carboniferous to Permian succession of the southeastern part of Oman (Blendinger et al., 1990; Al-Belushi et al., 1996; Angiolini et al., 2003a,b) and because some pre-Permian volcanoclastic rocks occurs in the HP-LT units of the central part of Oman. They form tuffaceous layers outcropping beneath the eclogites in As Sifah (Fig. 1b), which yielded 298 ± 3 Ma U–Pb SHRIMP zircon ages (Gray et al., 2005). Despite unequivocal descriptions of a syn-rift succession, the onset of rifting was considered either as Late Carboniferous (Gray et al., 2005), Early Permian (Pillevuit, 1993; Angiolini et al., 2003a,b; Baud et al., 2001) or Middle Permian (Béchennec et al., 1988).

- There are disagreements about the tectonic style of the Neotethyan passive margins. Syn-rift structures such as tilted blocks or detachment faults which are common in paleomargins, for instance in the Alps (e.g. Lemoine and Trumpy, 1987; Froitzheim and Manatschal, 1996), are scarce in the Arabian parts of the Neotethys, and restorations of the margin are only constrained by stratigraphic correlations (e.g. in Oman: Searle and Graham, 1982; Béchennec et al., 1988; Blendinger et al., 1990; Pillevuit et al., 1997).

- The geodynamic significance of Middle Permian volcanism is also a matter of debate. Permian submarine basalts were first interpreted as syn-rift (Béchennec et al., 1991), then as witness of oceanic crust (Pillevuit, 1993). However, this volcanism displays plume-related geochemical signatures (Maury et al., 2003; Lapierre et al., 2004) which suggest that they were emplaced above thinned continental crust. Lapierre et al. (2004) proposed they represent remnants of a volcanic divergent margin in Oman.

This paper, based on field observations from the proximal part of the south Neotethyan margin in Oman (Saih Hatat area, Fig. 1b), provides a reappraisal of inverted rift-related structures at different

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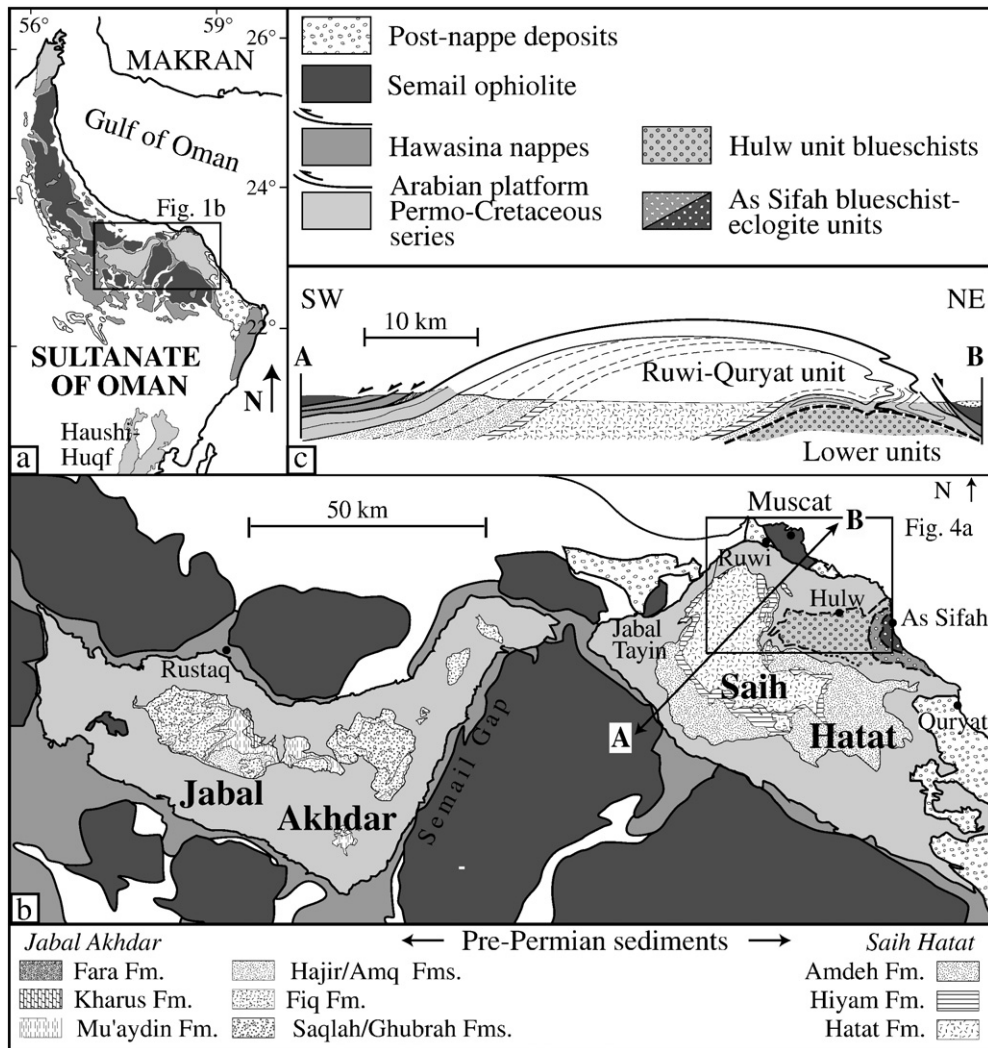E-mail address: francois.chauvet@univ-nantes.fr (F. Chauvet).

Fig. 1. a: Simplified geological map of the Oman Mountain range (after Glennie et al., 1974). b) Simplified geological map of the Jabal Akhdar and Saih Hatat tectonic windows with locations of the main structural units in the NE Saih Hatat area (after Rabu, 1987; Le Métour, 1987; Jolivet et al., 1998). c) Regional cross-section of the Saih Hatat tectonic window, modified after Warren and Miller (2007). Note the angular unconformity at the base of the Permian sediments of the Arabian platform.

scales and new constraints on rift style, orientation, timing and the relationship between rifting and Permian volcanism.

2. Geological setting

In Oman, the Arabian Platform and Hawasina Nappes are remnants of the proximal and distal parts of the south Neotethyan continental margin, respectively (Searle and Graham, 1982; Bernouilli and Weissert, 1987; Béchennec et al., 1988). The Hawasina Nappes were thrust over the Arabian Platform, which outcrops in the Jabal Akhdar and Saih Hatat tectonic windows below the Semail ophiolite (Fig. 1b). Permian to Cretaceous platform sediments unconformably overlie Neo-Proterozoic to Ordovician–Silurian folded and deeply eroded basement (pre-Permian sediments in Fig. 1b). Within Saih Hatat (Fig. 1b–c), the pre-Permian unconformity truncates northwards the Ordovician Amdeh Formation (2400 m) and the Hiyam (500 m) and Hatat (~2500 m) Precambrian formations (Lovelock et al., 1981; Le Métour, 1987). In Jabal Akhdar, only pre-Ordovician series are preserved below the unconformity (Rabu, 1987).

The significance of this regional pre-Permian unconformity is yet still unclear because the Proterozoic to Palaeozoic series have undergone successive compressive and distensive events. Indeed, the present structure of the pre-Permian series results from the addition of Neo-Proterozoic (Le Guerroué et al., 2005), Cambrian and post-

Ordovician (Le Métour, 1987; Rabu, 1987) deformation phases. The latter was classically associated to Hercynian motions (Glennie et al., 1974; Michard, 1982; Mann and Hanna, 1990) which are however suspected to have produced only large wavelength folding without cleavage (Rabu, 1987). Then, thickness and facies variations of pre-Permian sedimentary and volcanic formations show the dominant regional trend of pre-Permian structures in Oman is NE–SW to NS-oriented (Gorin et al., 1982; Le Métour, 1987; Rabu, 1987; Béchennec et al., 1993; Le Guerroué et al., 2005; Allen, 2007).

Thus, structuration of the pre-Permian substratum was polyphased and its peneplenation could be the result of successive episodes of continental abrasion (Rabu, 1987; Le Métour et al., 1990) and/or the result of rapid and deep erosion during the Neotethyan rift shoulder uplift (Rabu et al., 1990; Pillevuit, 1993; Al-Belushi et al., 1996). Al-Belushi et al. (1996) suggest that this pre-Middle Permian erosion was triggered by the Late Carboniferous to Early Permian glaciers, developed on the uplifted shoulders of the triple junction of the Neotethyan and Arabia–India–Madagascar rifts.

In the southeastern parts of Oman (Haushi-Huqf area, Fig. 1a) some Late Carboniferous to Early Permian siliciclastics overlie the unconformity (Al-Belushi et al., 1996; Angiolini et al., 2003a,b). They correspond to glacio-lacustrine to paralic environments (Al Khlata Fm., Fig. 2) and are unconformably overlain by late Sakmarian transgressive marine sediments (Saiwan Fm., Angiolini et al., 1997,

Int. stratigraphic chart			Tethys	Arabian platform formations

Fig. 2. Biostratigraphy of the Arabian platform Permian formations, with the international stratigraphic chart (Copyright © 2008 International Commission on Stratigraphy) and Tethyan time-scale (after Permophiles 36, p. 2, modified by Berthelin et al., 2003). Data are from (1) Broutin et al. (1995); (2) Berthelin et al. (2003); (3) Angiolini et al. (2003b); (4) Angiolini et al. (1997); (5) Angiolini et al. (2003a); (6) Rabu (1987); and (7) Le Métour (1987).

2003a). This first mega-sequence is unconformably overlain in turn by Kubergandian–Wordian fluvial to tidal sediments, followed by marine marlstones and limestones (e.g. Gharif and Khuff Fms., Fig. 2, Broutin et al., 1995; Angiolini et al., 2003b). This second Middle Permian platform mega-sequence is truncated topwards by Triassic to Jurassic paleosoils (Béchennec et al., 1993; Angiolini et al., 2003b). The two mega-sequences spanning from earliest Permian to Middle Permian times recorded in SE Oman a climate change from glacial to intertropical warm and humid. This paleoclimatic change is interpreted as a result of the northward drift of the Arabian peninsula from 50°S to 30°S during Carboniferous to Late Permian times. This implies the development of a very narrow Neotethyan oceanic floor during Permian times (Broutin et al., 1995; Crasquin-Soleau et al., 2001; Berthelin et al., 2003; Angiolini et al., 2003a,b).

In the central part of Oman Mountains, the pre-Permian substratum is overlain by Middle Permian clastic and volcanoclastic rocks, followed by a thick carbonate succession (Fig. 2, Murghabian to Dzhulfian Saiq Fm., Montenat et al., 1976; Le Métour, 1987; Rabu et al., 1990; Baud et al., 2001; Weidlich and Bernecker, 2003). This Middle Permian transgression in central Oman has been regarded as the post breakup flooding of the newly formed Arabian margin rift shoulders (Blendinger et al., 1990; Pillevuit, 1993; Pillevuit et al., 1997; Baud et al., 2001; Angiolini et al., 2003a,b; Stampfli and Kozur, 2006). However, the finding of Late Carboniferous magmatic zircons in the As Sifah unit of Saih Hatat (Gray et al., 2005) may indicate that sedimentation started earlier.

Middle Permian volcanic rocks are commonly found in the Hawasina Nappes, as meter to decameter-thick sequences associated with pelagic sediments at the base of Permo-Triassic units (Murghabian radiolarians: De Wever et al., 1988; Béchennec, 1987; Wordian ammonoids and conodonts: Blendinger et al., 1992; Pillevuit, 1993; Baud et al., 2001; Kozur et al., 2001). In the Arabian Platform, coeval volcanics are only found in the Saih Hatat area.

In the northwestern part of the Saih Hatat, the Permian sediments of the Saiq Formation consist of a basal transgressive unit (Sq1V: conglomerate, tuffaceous mica schists and dolomites) overlain by approximately 500 m of dominantly carbonate series (Sq1L, Sq2 and Sq3). Within the latter occurs a hundred-meter thick volcanic member (Sq2V, Fig. 3; Glennie et al., 1974., Montenat et al., 1976; Le Métour, 1987) associated with dolomitic and siliciclastic interlayers (Sq2D). This volcanic member pinches out southwestwards (Rabu et al., 1990). Further east, the Hulw succession (Fig. 3) comprises a thick basal member of quartz–mica schists, sandstones and carbonate layers (Hw1), a massive unit of tuffs and volcanic flows (HwV), and an

uppermost succession of dolomitic (HwDMs) and siliceous mica schists (HwQMs). The latter are overlain either by calcschists and limestone (HwCs) or by alternations of beige dolomites and black limestones (HwLD).

This Hulw succession is regarded either as a volcano-detrital equivalent of the basal Saiq members (Sq1V-Sq1L, Fig. 3a, Le Métour et al., 1986; Le Métour, 1987; Rabu et al., 1990) or as part of the pre-Permian sedimentary basement (Fig. 3b, Glennie et al., 1974; Bailey, 1981; Hanna, 1990; Mann and Hanna, 1990; Gregory et al., 1998; Miller et al., 2002; Gray et al., 2005; Warren and Miller, 2007). The first hypothesis is based on lithologic similarities between the Hw1 and Sq1V stratigraphic members (Fig. 3a) and on Permian faunas found in carbonates of the eastern Hulw area (Le Métour, 1987; HwLD member and locality H in Fig. 3a). The second one (Fig. 3b) was proposed on the basis of Late Carboniferous (298 ± 3 Ma) U–Pb SHRIMP ages on zircons from a garnet-bearing felsic schist within an eclogitic megaboudin of the As Sifah unit (Gray et al., 2005). These volcanic rocks at the base of the As Sifah succession are tentatively correlated by these authors with a tuffaceous interlayer in the HwV volcanics of the Hulw unit (the white layer in HwV on Fig. 4a). The same authors also report negative $\delta^{13}C$ values from high-grade meta-carbonates or calcschists of the As Sifah succession. These values are regarded as supporting a pre-Late Permian age for the As Sifah rocks, which are further correlated with the calcschists of the Hulw succession (Gray et al., 2005). However, this correlation remains speculative. Moreover, some black limestones sampled in the top of the Hulw calcschists (so-called "Llm" unit by previous authors, Fig. 3b) and observed in the detrital basal succession (Hw1 or Lqms) yielded Late Permian $\delta^{13}C$ values (Gray et al., 2005).

Considering the correlation between the Saiq and Hulw successions, as proposed by Le Métour et al. (1986), Le Métour (1987) and Rabu et al. (1990), the lateral changes of facies and thickness are thought to be related to the morphology of the Permian platform, from the Jabal Tayin condensed horst succession (W Saih Hatat) to thick detrital sediments in the Hulw half-graben (Fig. 3a). The Middle Permian volcanic activity is represented by both the Sq2V basaltic flows and some mafic sills intruding the Sq1L limestones (SqDl in Fig. 3a). However, the interpretation of SqDl as a widespread laccolite (Fig. 3a, Le Métour et al., 1986; Le Métour, 1987; Rabu et al., 1990) is not consistent with the occurrence of pillow lavas and hyaloclastites observed by Miller et al. (2002).

Alternatively, if the Hulw and As Sifah successions are regarded as pre-Permian, they must be issued from distal parts of the Arabian platform or from an exotic continental block accreted to the Arabian plate during inversion of the margin (Gray et al., 2004, 2005; Warren and Miller, 2007). This postulated exotic origin requires the occurrence of a major thrust contact between the Saiq and Hulw units, so-called "lower and upper plates" (Fig. 3b) in Gregory et al. (1998), Miller et al. (2002) and subsequent papers.

Investigating the stratigraphic and structural relationships between the Saiq and Hulw successions is difficult because of increasing metamorphism and ductile deformation towards the northeast (Miller et al., 1999; Breton et al., 2004; Searle et al., 2004). However, the critical point of interpretation of the Permian platform paleogeographic pattern resides in the existing relationships between Middle Permian carbonates of the Saiq Fm. and the underlying metamorphic schists and metabasites, whose age is debated. Therefore, an understanding of the post-Permian deformation is essential to reconstruct the platform palaeogeography and the history of the Arabian margin.

The first-order regional structure is a northeast recumbent fold involving pre-Permian rocks and Permian to Cretaceous sediments of the Arabian Platform (Fig. 1c). This large-scale fold occurs between the overlying Hawasina and ophiolitic nappes and the underlying Hulw unit, on top of a stack of metamorphic slices (Michard et al., 1994; Jolivet et al., 1998, Miller et al., 2002). The reverse limb of this fold will

Saiq Fm. stratigraphy in the Ruwi-Quryat unit

Sq3	- Siltstone, black limestone, brownish mudstone
Sq2	- Thick bedded dolomite, limestone, cherty dolomite
Sq2V	- Basalts, andésite, tuffite and intercaled sediments (Sq2D : dolomitic and siliceous marls, brown dolomite)
SqDl	- Mafic intrusives
Sq1L	- Brown dolomite, black limestone, siliceous limestone
Sq1V / AmQms	- Conglomerate, tuffaceous micaschists, brown dolomite

Hulw succession stratigraphy

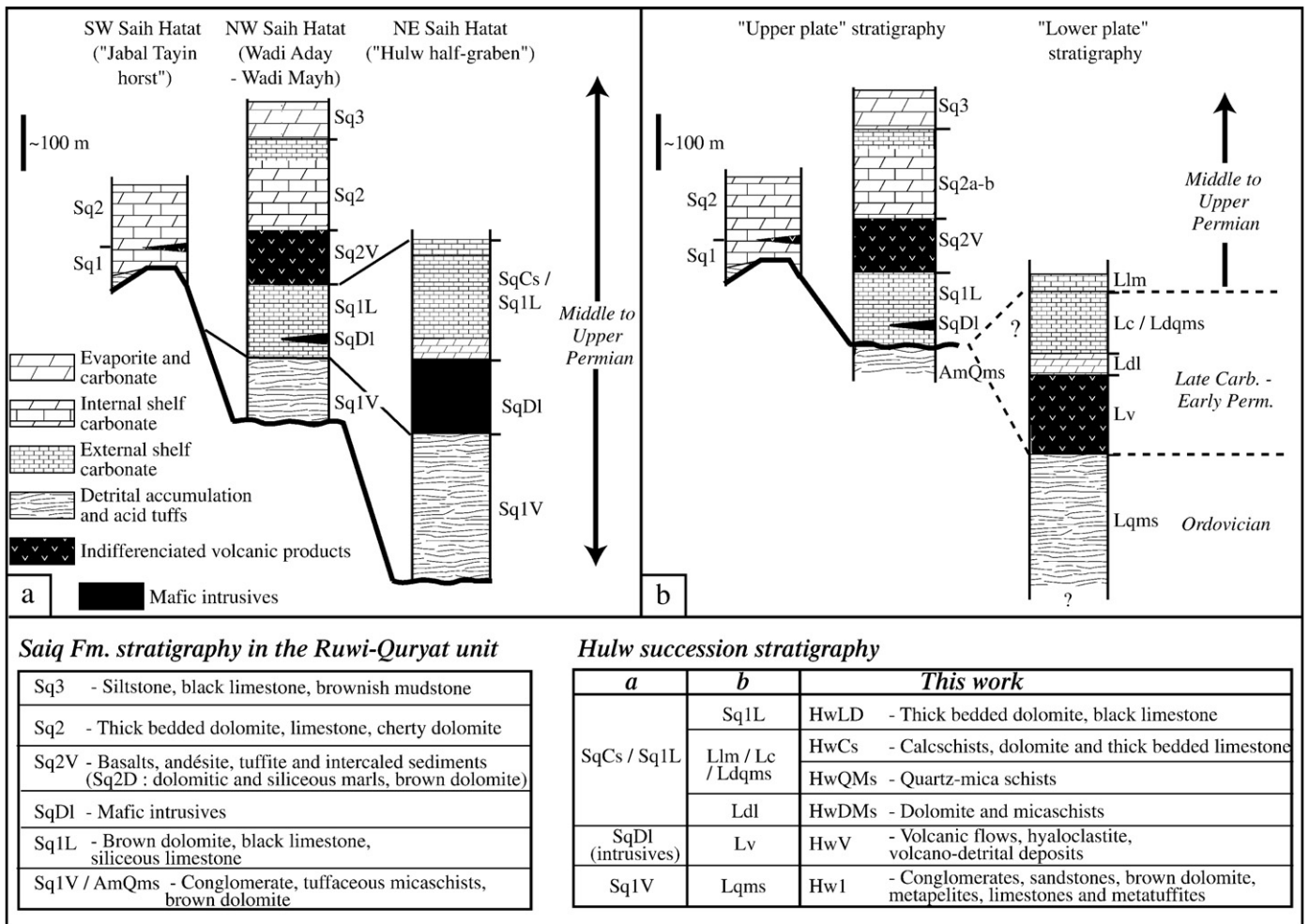| a	b		This work	
SqCs / Sq1L	Sq1L	HwLD	- Thick bedded dolomite, black limestone	
	Llm / Lc / Ldqms	HwCs	- Calcschists, dolomite and thick bedded limestone	
		HwQMs	- Quartz-mica schists	
	Ldl	HwDMs	- Dolomite and micaschists	
SqDl (intrusives)	Lv	HwV	- Volcanic flows, hyaloclastite, volcano-detrital deposits	
Sq1V	Lqms	Hw1	- Conglomerates, sandstones, brown dolomite, metapelites, limestones and metatuffites	

Fig. 3. Simplified stratigraphic successions of the northern Saih Hatat and controversial correlations between the upper and lower tectonic units: two different hypothesis after (a) Le Métour (1987); Le Métour et al. (1986) and Rabu et al. (1990); (b) Gregory et al. (1998), Miller et al. (2002) and Warren and Miller (2007). Contrary to a, the b hypothesis considers the Hulw succession as mainly made of Ordovician to early Permian sediments. Here, the Hulw and As Sifah units are named "lower plate" and are separated from the upper unit by a major tectonic contact ("the upper plate–lower plate discontinuity" Gregory et al., 1998). A correlation table is given (bottom).

be named the "Ruwi-Quryat upper unit" as opposed to the "Hulw lower unit" (Figs. 1c–4a). The whole tectonic pile was tilted and eroded during exhumation. The present outcrops show an eastward increasing metamorphic grade, from the least metamorphosed carpholite-bearing rocks of the structurally highest Ruwi-Quryat unit, to low-grade blueschists of the intermediate Hulw unit, and finally to garnet blueschists and eclogite-grade rocks of As Sifah, the lowermost and easternmost unit (Fig. 1b, Goffé et al., 1988; Michard et al., 1994; Searle et al., 1994, 2004; Jolivet et al., 1998; El-Shazly et al., 2001). This HP-LT metamorphism recorded subduction and exhumation of the edge of the Arabian platform (Goffé et al., 1988; Searle et al., 1994, 2004; Miller et al., 1999). The northeast recumbent folding postdates the subduction stage and overprints previous isoclinal hinges and sheath folds mainly developed within the lower units and at the base of the Ruwi-Quryat unit (Miller et al., 2002; Breton et al., 2004; Warren and Miller, 2007; Searle and Alsop, 2007). The NE-vergent structures are in turn affected by later E-vergent folds, producing interference features between the Hulw and As Sifah areas (Le Métour, 1987; Warren and Miller, 2007; Fig. 4a), and finally by late doming.

3. Field observations

The AA′ and BB′ cross-sections (Fig. 4) crosscut the main structures of the northern Saih Hatat. The less-deformed AA′ section illustrates the upper limb of the regional recumbent fold (Fig. 1c), whereas BB′ shows its lower limb, together with the underlying Hulw unit.

The AA′ section documents thickness variations within different stratigraphic members of the Saiq Fm., inherited from Permian extensional tectonics. The more complex BB′ section (NE–SW Wadi Mayh cross-section, Fig. 4a) outlines our interpretation of the main NE-directed folds developed in the Ruwi-Quryat and Hulw units, which are separated by a regional NE-vergent shear zone.

3.1. NW of Saih Hatat

In the Saih Hatat NW section (AA′, Fig. 4a–b), lateral thickness variations and erosion surfaces are observed in the conglomerates and volcano-sedimentary deposits of the Sq1V member, as well as in the overlying Sq1L limestones (Fig. 4a–b, logs A to D in Fig. 5).

In the southern part of the Jabal Muraywah, Permian sediments are overlying a continental erosion surface marked by a ~20 m-wide karst which crosscuts massive dolomites of the Hiyam Fm. which belong to the pre-Permian sedimentary basement. This 150-m-deep open fracture developed over a normal fault with a ~20–30 m offset (Fig. 6). The infill consists of reddish schists including many blocks derived from the pre-Permian host dolomites, as well as coral-bearing limestones eroded from a Permian wedge. The karst is capped by a ~10-m thick finely bedded yellowish dolomitic wedge (Fig. 4b, log A in Fig. 5), directly overlain by the Sq2V volcanic member of the Saiq Fm.
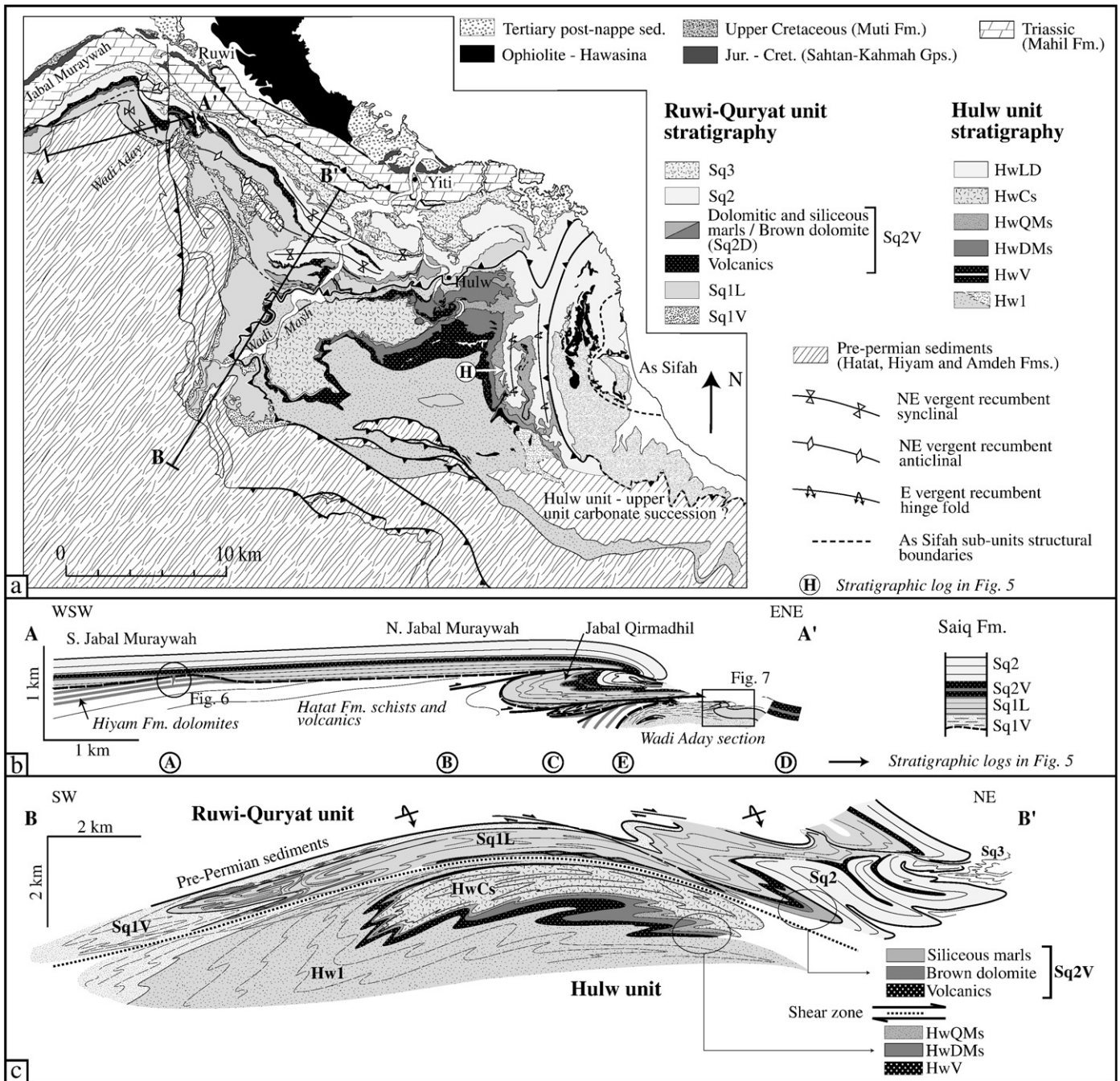
Fig. 4. a) Geological map of the northeastern Saih Hatat area (see Fig. 3 for lithological details). b–c) AA′ and BB′ cross-sections showing the main deformation structures which affected the Permian sediments in the northeastern part of the Saih Hatat.

The sidewalls of this karstified fracture are trending N160° and steeply dipping westwards (Fig. 6). The Sq1L member, which is absent or very condensed in this locality, thickens out toward the NE (Fig. 4a–b, logs A to D in Fig. 5). It remains unclear whether these Permian marine carbonates onlapped southwestwards over a basement high, or whether they had been previously deposited and removed by erosion and/or tilting in association with normal faulting. The second hypothesis is favored in view of the reworked coral-bearing limestones found in the karst.

An erosion surface that is possibly connected with the one described above is observed in the Wadi Aday, overlying the Sq1L member (Fig. 7, log D in Fig. 5). It is involved in a hectometric recumbent fold in the footwall of the Jabal Qirmadhil thrust (Fig. 4b). The erosion surface truncates the Sq1L strata southwestwards with an angular unconformity of at least 30°. The surface is dolomitized and overlain by green volcanoclastic schists of the Sq2V member. The fold hinge is cut by two low-angle apparent reverse faults (Fig. 7, middle). In our restoration (Fig. 7, bottom), it is proposed that they actually represent tilted and folded normal faults. The angular unconformity results from tilting and erosion during the emersion of the half-horst.

Our restoration is supported by the following observations: (i) the basal unit (Sq1), which is well developed and consists of platform limestones in the lower limb of the fold (or the hanging wall of the tilted block), disappears or grades laterally into thin dolomites in the upper limb (the footwall); (ii) the base of the volcanic unit (Sq2V) contains some reworked carbonate pebbles and discontinuous clastic layers that could derive from erosion of the half-horst; (iii) some reefal carbonates pebbles are ponded in the karst (Jabal Muraywah).
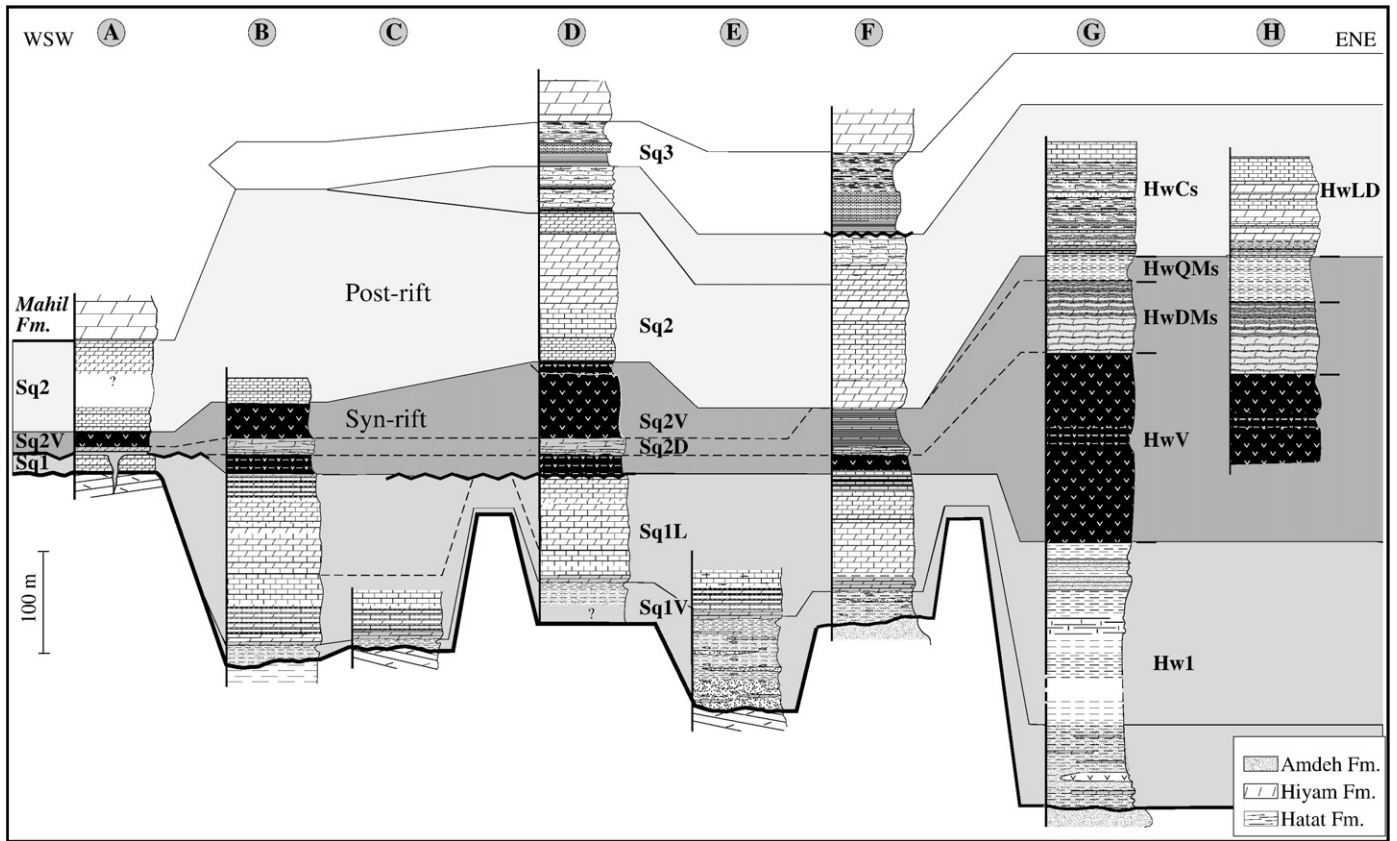
Fig. 5. Lithostratigraphic variations observed in the Middle to Upper Permian Saiq Fm. throughout the northern Saih Hatat. Letters A to H refer to localities of Fig. 4.

We assume that the Wadi Aday fault block and the Jabal Muraywah karstified fracture, located farther west, are coeval. Both document Permian ENE–WSW extension, block faulting and local tilting of the pre-Permian basement together with the earliest Permian (Sq1) deposits. A volcanic event (Sq2V) with minor syn-sedimentary faulting immediately followed this platform breakup (Pillevuit, 1993).
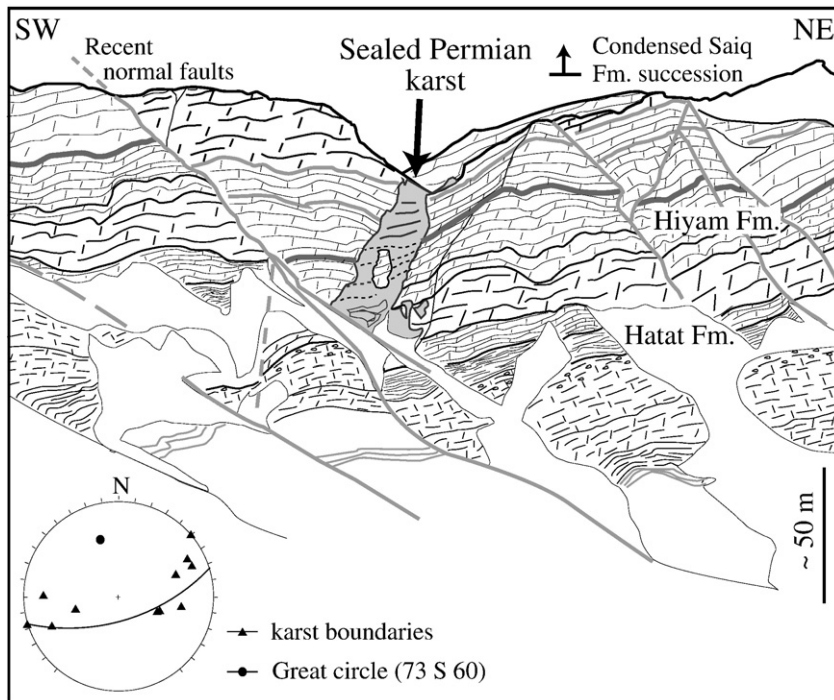

Fig. 6. Permian karst cutting the Hiyam dolomites. This NNW–SSE open fracture is filled by reddish clays with dolomitic and limestones pebbles (including reefal limestones issued from Sq1L), and it is overlain by the Sq2V volcanics (see Fig. 4b, log A in Fig. 5).
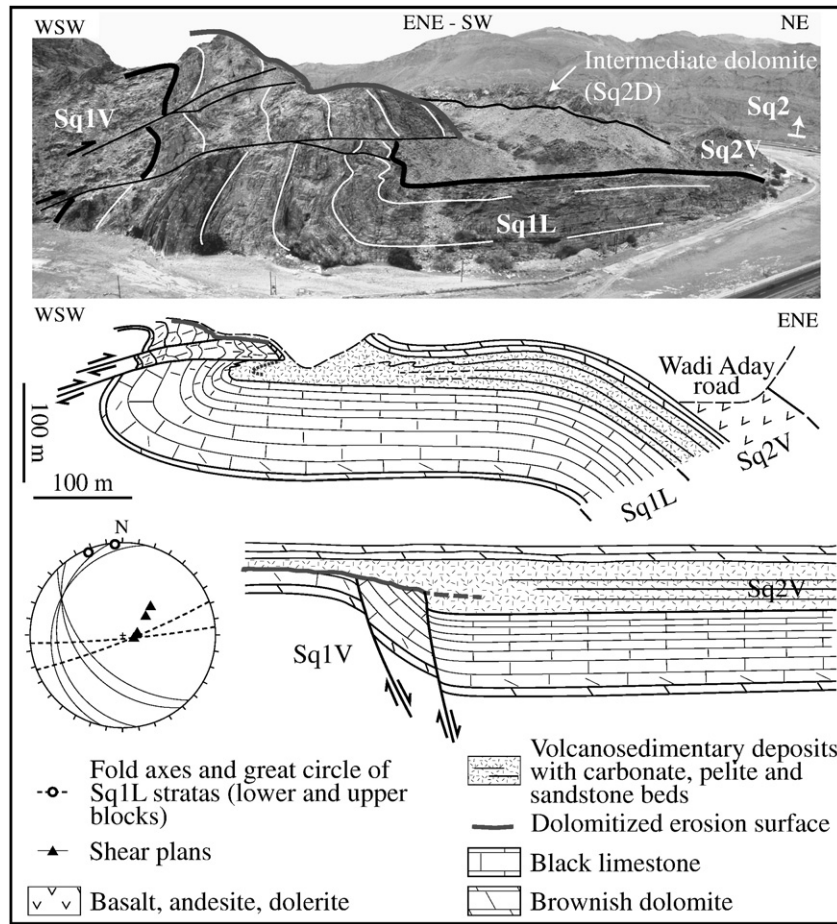
Fig. 7. Inverted syn-volcanic tilted block in the Wadi Aday (central part of section AA' Fig. 4, log B in Fig. 5).

3.2. Relations between the Ruwi-Quryat and Hulw units along the Wadi Mayh (W of Hulw unit)

The Sq2V basalts and associated volcanoclastic sediments can be traced continuously between Wadi Aday and Wadi Mayh (Fig. 4a), surrounded by the two Saiq Fm. carbonate sequences, Sq1L and Sq2 (Fig. 4c). In the Wadi Mayh, Sq2V volcanics, together with brownish-yellowish dolomites and marls and surrounding limestones, become involved in a set of kilometric recumbent folds. Map-scale interference features on the left bank of Wadi Mayh show that folding was polyphase, some kilometric hinges being deformed by top-NE low-angle thrusting (Fig. 4c, eastern part). The lowermost reversed limb involves Sq1L limestones and underlying Sq2V volcanic rocks (Fig. 4c) and can be followed for 4 to 5 km between the central and southern parts of the Wadi Mayh. It is highly stretched, as shown by sheath folding in the limestones and schists, and by boudinage in the dolomites. Underneath this structure is a large-scale, NE-directed recumbent syncline with a highly stretched upper limb, formed by the HwV member of the Hulw unit. Instead of a sharp thrust contact as postulated by some previous studies, the boundary between the stretched reversed limbs of the Ruwi-Quryat and Hulw units is marked by a 50-m thick, varicoloured (white, greenish or red) shear zone, composed of quartz–mica schists containing dolomitic boudins. Moreover, volcanic schists and boudins of the upper Hulw and lower Ruwi-Quryat units on both sides of this shear zone are lithologically very similar. The quartz–mica schists that mark the shear zone are found at the base of the stratigraphic series of both units (Sq1V, Fig. 4a and logs in Fig. 5; see also Le Métour et al., 1986; Le Métour, 1987).

3.3. E of Hulw unit

Miller et al. (2002) proposed that a major thrust contact separates the "upper plate Sq1L carbonates" from the Hulw detrital series in the eastern part of the Hulw unit (location H in Fig. 4a). In this area, however, we can observe a complete stratigraphic series (Logs G and H in Fig. 5), with strong polyphase folding but no evidence for any major tectonic unconformity. Grey quartz–mica schists of member HwQMs underlie the HwCs member in the northern part of the Hulw unit (Fig. 4a, log G in Fig. 5). Farther west, they continuously outline the major folds with a specific signature on satellite images, and they finally underlie the HwLD carbonate member. Therefore, as proposed by Searle et al. (2004), the HwLD member must be regarded as the top of the Hulw unit succession and as a lateral equivalent of the HwCs calcschists.

4. Discussion

4.1. Stratigraphic correlations between the Ruwi-Quryat and Hulw units

Very similar clastic, volcanic and sedimentary lithofacies are found in a similar sequence in both units. Our structural and lithostratigraphic observations are not fully consistent with the previously proposed stratigraphic patterns (Fig. 3). The new correlations we propose in Fig. 5 are supported by the following arguments:

a. Lower member: The same varicoloured quartz–mica schists interlayered with brownish dolomites (Sq1V) occur at the base of both
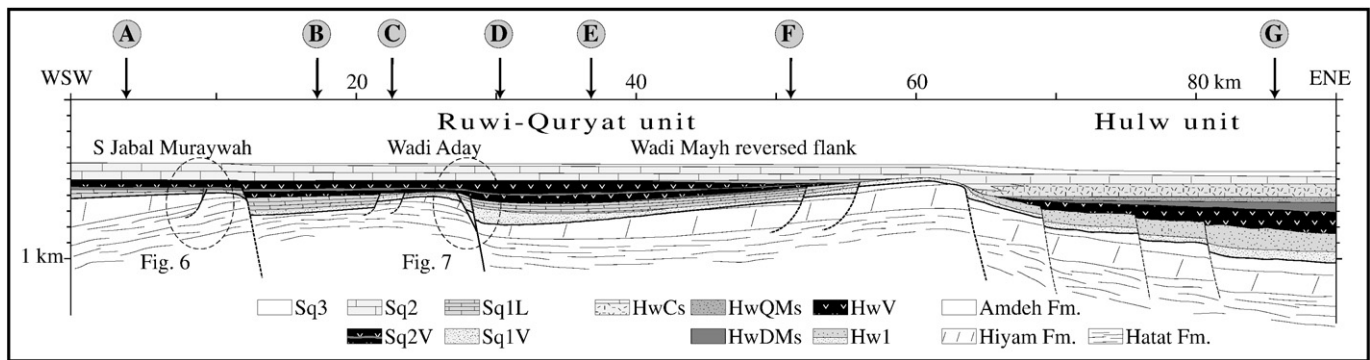
Fig. 8. Proposed Upper Permian reconstitution of the Arabian platform.

Ruwi-Quryat and Hulw units stratigraphic successions (Le Métour et al., 1986; Le Métour, 1987; Weidlich and Bernecker, 2003).

b. Volcanism: In the lower part of the Ruwi-Quryat unit, several volcanic occurrences crosscut by the central Wadi Mayh (Fig. 4a) were previously interpreted as magmatic bodies that intruded the base of the Saiq Fm. (SqDl member in Fig. 3, Le Métour et al., 1986; Miller et al., 2002). However, these volcanics show no intrusive structure. Except some local tectonic disturbances, they always lie in conformable stratigraphic contact between Sq1L and Sq2 limestones and dolomites and can be traced within the lowermost reversed part of the Ruwi-Quryat unit. We conclude that they represent a single basaltic member (Sq2V), affected by polyphase folding, stretching and boudinage together with the dolomites (Fig. 4c). In the upper part of the Hulw unit, a similarly boudinaged volcanic member (HwV) crops out on the right bank of the upper Wadi Mayh. This member occurs at the same level than Sq2V on the opposite bank of the valley, and both of them appear symmetrical with respect to the shear zone separating the Ruwi-Quryat and the Hulw units (along section B–B′, Fig. 4). Considering this, we infer that the HwV and Sq2V members are stratigraphically equivalent (Figs. 4c, 5 and 8). Furthermore, the sediments associated with both these volcanics (Sq2V and HwV) are correlatable (brownish dolomites and dolomitic marls of Sq2D and HwDMs; Fig. 4a–c; logs F and G in Fig. 5).

c. Upper carbonate-siliciclastic members: In the eastern Hulw area, we observe a lateral facies change from the HwCs mixed siliciclastic-carbonate member to the HwLD mostly dolomitic member. The striking similarities between the latter and the Sq2 carbonate member, which both overlie the volcanics, strongly suggest that HwLD, HwCs and Sq2 members can be considered as lateral equivalents (Figs. 4a and 5).

Thus, considering the lithological and sequential similarities, the symmetrical structure with respect to the boundary shear zone and the lack of evidence for a clear thrust contact, we propose to correlate the stratigraphic series of the Ruwi-Quryat and Hulw units, which both recorded Permian rifting of the Arabian platform. This stratigraphic correlation has consequences on the restoration of the Permian palaeogeography.

4.2. Palinspastic reconstruction and palaeogeography of the Permian platform

Considering the Hulw series as a lateral equivalent of the Saiq series makes possible a tentative paleogeographic restoration. The reconstructed palinspastic profile (Fig. 8) is based on lithostratigraphic correlations and on a regional-scale unfolding of the main E-vergent and NE-vergent structures along profiles AA′ and BB′ in the Saih Hatat. This provides an estimated minimal displacement of the

Ruwi-Quryat unit with respect to the Hulw unit, of 10 km eastwards and of 50 km northeastwards. Assuming that these tectonic units haven't undergone strong rotation during their tectonic displacements, the WSW–ENE azimuth of the unfolded section corresponds to the main paleogeographic gradient of the Permian Saih Hatat platform. The unfolded profile AA′ best illustrates the extensional features whereas the restoration of profile BB′ is more interpretative due to stronger deformation (Fig. 9).

The shear zone between the Ruwi-Quryat and Hulw units, marked by the Sq1V schists, is a critical feature of this interpretation: it undoubtedly represents a large northeastward displacement of the Ruwi-Quryat unit with respect to the Hulw unit, and in spite of this, the stretched volcanic layers in both units (Sq2V and HwV) are presently very close in the Wadi Mayh area (Figs. 4–9). Thus, it is necessary to have some space left between these two volcanic domains within the palinspastic section (Fig. 8). This space would consist of an intermediate area (Fig. 9) without any lava flows but covered with fine clastic sediments (presently the Sq1V varicoloured schists with dolomites) which localized the propagation of the detachment of the Ruwi-Quryat unit. This intermediate area can be interpreted either as a topographic high inherited from pre-Permian lithology and structures, or by Permian syn-rift uplift. The latter hypothesis is preferred considering the small-scale paleostructures described in the NW Saih Hatat (Figs. 6 and 7), and lateral thickness and drastic facies changes of Sq1L carbonates (between Jabal Muraywah, Jabal Qirmadhil and Hulw areas) which indicate
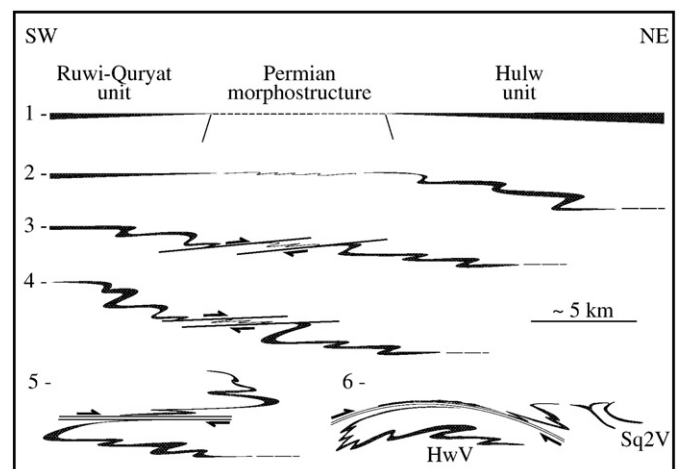

Fig. 9. Tentative unfolding and restoration of the main volcanic layer (HwV and Sq2V) in northern Saih Hatat: an incipient detachment propagated northeastwards along the Sq1V schists and ramped up on top of the intermediate uplifted area, causing the superposition of the two Saih Hatat tectonic units, which were later refolded together.

differential subsidence. Therefore, it may represent a decakilometric half-horst (Fig. 8) emplaced after the deposition of the lowermost Saiq Fm., and which separated the sedimentation areas of the Ruwi-Quryat unit and Hulw unit. The uplift would have been coeval with the development of karsts and tilted blocks in the inner platform (Jabal Muraywah and Wadi Aday, profile AA′). The postulated eastern boundary fault of this half-horst is consistent with the Wadi Aday features (Fig. 7).

The orientations of the restored sections remain speculative depending on the relative amount of EW and NE–SW shortening components. However, assuming that the paleogeographic gradient would have been roughly perpendicular to the extensional structures observed in Wadi Aday area, its orientation should have been close to WSW–ENE. At a larger scale, the WSW–ENE paleogeographic gradient is documented by the paleogeographic contrast between a weakly subsiding inner carbonate platform (the Jabal Akhdar and Saih Hatat Ruwi-Quryat unit) and a more external basin (Hulw unit). However, our reconstruction does not support the occurrence of a very large paleogeographic gap between these two domains. Consistently, it is shown that no significant gap in metamorphic grade occurs across the shear zone separating these two units, and that both display similar peak-pressure signatures (Yamato et al., 2007).

Thus the entire Saih Hatat domain, as the Jabal Akhdar area, was located during Permian times on a single continental shelf featured by shallow sedimentation constantly keeping up tectonic subsidence, with temporary exception of the Hulw basin. This shelf took place in a proximal domain of the Arabian margin and cannot be regarded as the transition between the platform and the Hawasina basin, or between the platform and an exotic terrane as proposed by Gray et al. (2004, 2005) and Warren and Miller (2007). The present structures of the northeastern Saih Hatat derive from tectonic inversion of this rifted shelf, but only small-scale extensional features have been partly preserved. The first-order paleogeographic boundaries evolved in shear zones during subduction and exhumation of the Arabian platform (Fig. 9).

4.3. Timing of the rifting

a. Saih Hatat platform: According to Le Métour (1987) and Rabu et al. (1990), the occurrence and distribution of volcanic rocks in Saih Hatat is connected to the subsidence of the platform during Murghabian times. The paleostructures and lateral variations shown by Sq1L and Sq2V members, together with the discrepancies between the lower Saiq and lower Hulw series (Sq1L and Hw1), indicate that platform breakup was initiated shortly after the deposition of Sq1V. The syn-rift volcanic activity corresponds to a short event, and occurred in subaerial setting as testified by dolomitic sedimentation interbedded within Sq2V and capping HwV (HwDMs). It is however widespread and marked by volcano-sedimentary deposits covering the whole western area of the Saih Hatat till Jabal Tayin (Fig. 1b, Le Métour, 1987). Later on, the paleogeographic contrast between a weakly subsiding inner carbonate platform (the Ruwi-Quryat unit in Jabal Akhdar and Saih Hatat) and a more external basin (Hulw unit) became less prominent as shown by the progradation of carbonate sedimentation in the upper Hulw succession (HwDL and top of HwCs). Consistently, no drastic thickness variations are observed in the Sq2 carbonate wedge of the Ruwi-Quryat succession. The deposition of these sediments may thus postdate the main Murghabian stretching episode marked by volcanism and formation of tilted blocks. According to the sparse biostratigraphic data available in the Ruwi-Quryat unit, the Sq2V volcanics are Middle to Upper Murghabian in age (Le Métour et al., 1986; Le Métour, 1987; Fig. 2). Thus the main rift activity occurred during a short time lapse (<5 My).

b. Arabian Margin: The Permian rifting in Oman is clearly related with the developments of both the Neotethyan s.s. rift between Gondwana and the Cimmerian continental blocks, and an Early Permian NE–SW-trending rift, located between the Arabian and Indian shields ("Arabia–India–Madagascar rift," Stampfli et al., 1991; Veevers and Tewari, 1995; Al-Belushi et al., 1996; Immenhauser et al., 2000; Stampfli and Borel, 2002; Angiolini et al., 2003a). This complex setting makes difficult to interpret the rift successions associated to the Neotethyan s.s. opening. Various scenarios have been proposed concerning the timing of the upper Paleozoic rifting in Oman:

- In the southeastern part of Oman, the onset of sea-floor spreading was regarded as Mid-Sakmarian in age by Angiolini et al. (2003a,b) and Al-Belushi et al. (1996). The latter authors consider ice-flow directions during the earliest Permian glaciation to be related to the mountains glaciers nucleation on the uplifted shoulders of the Neotethyan and Arabia–India–Madagascar rifts junction. Inversion of flow direction between the glacial and the post-glacial deposits is regarded as an indication of the collapse of the NE and SE sides of the Arabian margin. Moreover, Angiolini et al. (2003a) observe an unconformity separating the glacial to post-glacial early Permian Al Khlata Fm. from the fluviatile to shallow marine Upper Sakmarian deposits of the Saiwan Fm. (Fig. 2, Haushi-Huqf area, Angiolini et al., 2003a). They conclude that this unconformity represents the "breakup unconformity" sealing the earliest Permian syn-rift sequence of the Al Khlata Fm.

- Alternatively, many authors consider the occurrence of ammonias- and/or radiolarians-bearing pelagic sediments capping the Middle Permian basalts in the Hawasina Nappes as inferring contemporaneous accretion of the Neotethyan oceanic crust (Bernouilli and Weissert, 1987; Blendinger et al., 1990, 1992; Stampfli et al., 1991; Pillevuit, 1993; Pillevuit et al., 1997). Following the conceptual model of "flexural margin" (Stampfli et al., 1991), these authors propose that the Saiq Fm. basal unconformity in Jabal Akhdar and Saih Hatat would mark the Murghabian flooding of the deeply eroded rift shoulders. This event would be coeval with the onset of thermal subsidence of the newly formed southern Neotethyan margin (Blendinger et al., 1990; Pillevuit, 1993; Pillevuit et al., 1997; Angiolini et al., 2003a,b; Stampfli and Kozur, 2006). This interpretation involves a pre-Murghabian opening, regarded by Pillevuit (1993), Pillevuit et al. (1997) and Stampfli and Kozur (2006) as Artinskian-Kungurian.

Therefore, considering stratigraphic arguments together with traces of volcanoclastic occurrences, the Neotethyan rifting is regarded by many authors as having started during Late Carboniferous to Early Permian times (Pillevuit, 1993; Al-Belushi et al., 1996; Angiolini et al., 2003a,b; Gray et al., 2005), and then the opening of Neotethys would have predate the Murghabian deposition of the Saiq Fm. and the pelagic sedimentation in the Hawasina Basin. As no typical "breakup unconformities" are documented in Oman (with the exception of the assumed breakup unconformity of Angiolini et al., 2003a) the different ages proposed for the continental breakup coincide with different transgressions and associated unconformities observed on the Arabian platform (e.g. Sakmarian in SE Oman by Angiolini et al., 2003a; Artinskian in northern Oman by Pillevuit, 1993; Murghabian in central Oman by Blendinger et al., 1990; Baud et al., 2001).

Nevertheless, it is important to note that the stratigraphic sequences studied by Al-Belushi et al. (1996) and Angiolini et al. (2003a,b) are found in the southeastern part of Oman. The associated sedimentary structures and thickness variations are clearly linked with a NE–SW trending rift shoulder (bordering the present NE–SW Oman coastline) and thus with the Arabia–India–Madagascar rift trend (Lee, 1990; Pillevuit, 1993; Immenhauser et al., 2000; Angiolini et al., 2003a,b). These authors assume that these features also

document the coeval development of the Neotethyan rift trend further north, which is not demonstrated. Besides, extensional structures associated with the presumably syn-rift successions are lacking in the southeastern part of Oman.

Finally, whether Neotethys was largely opened during Murghabian times, what could be the significance of the widespread magmatic activity among remnants are observed both in the platform and basin environments of the south Neotethyan margin?

Alternatively, we propose to consider that extensional tectonics, together with magmatic activity which affected the Neotethyan platform during middle to upper Murghabian in central Oman, are the testimony of the last stage of continental distension just preceding the onset of Neotethyan oceanic accretion in this area. Consistently, Besse et al. (1998) palaeomagnetic data show that latitudinal translation of the Cimmerian blocks from the northern edge of Gondwana started at the end of the Middle Permian (~260 ± 10 Ma, see Fig. 9 in Besse et al., 1998), which implies that formation of Neotethyan oceanic floor must have started shortly after the Murghabian rift onset documented in the Saih Hatat.

4.4. A volcanic segment of the southern Neotethyan margin?

The newly described syn-rift extensional structures of Saih Hatat are coeval with intraplate volcanism which is also found in the Hawasina pelagic basin (Béchennec et al., 1988). The Hawasina Murghabian volcanic sequences were regarded as linked with the formation of Permian oceanic crust (Glennie et al., 1974; Pillevuit, 1993; Pillevuit et al., 1997) before their intraplate geochemical character was demonstrated (Maury et al., 2003; Lapierre et al., 2004). Their geochemical diversity, from depleted and enriched tholeiites to alkaline basalts, is interpreted by the latter authors as a result of mantle plume activity and continental lithospheric thinning. At the same time enriched continental tholeiites erupted in the Panjal Traps on the NW part of the adjacent Indian margin platform (Gaetani et al., 1990). The preserved remnants of these flood basalts are 2500-m thick in Kashmir and extend from N Pakistan to SE Ladakh areas (Pareek, 1976; Papritz and Rey, 1989; Vannay and Spring, 1993; Spencer et al., 1995). This widespread distribution of Permian within-plate volcanism in the adjacent margins strongly suggests a link with a thermal anomaly located north of Indian and Arabian plates during this period of Pangea breakup (Garzanti et al., 1999; Chauvet et al., 2008).

In spite of this, the southern margin in Oman is classically regarded as non-volcanic. However, recent mapping of flood basalts and seismic profiles show that volcanic rifted margins are much more frequent than previously thought. Menzies et al. (2002) compilation shows that they border the northern, central, and southern Atlantic Ocean, and parts of the Red Sea, Africa, Madagascar, India, Australia and Antarctica. Such volcanic margins develop in a very short time span, leading to ocean opening in less than 10 Ma (i.e. SE Greenland margin; Saunders et al., 1997). Considering this, together with (i) the observed correlation between rift onset and volcanism in the Saih Hatat, (ii) the short duration of rifting, and (iii) the coeval emplacement of Panjal traps, we propose that the studied area formed as a volcanic margin within the southern Neotethyan magmatic province centered north-west of the Indian plate (Fig. 10a). The Oman continental margin was at was at the periphery of this magmatic province, and the volume of magmatic effusions was probably considerably reduced when compared with more central areas as the Panjal Traps. However the Cretaceous obduction preserved only some remnants of the proximal parts of the margin, and one cannot exclude the occurrence of more significant volcanic bodies as Seaward Dipping Reflectors further ENE in the subducted distal parts of the margin.

4.5. Orientation and shape of the margin

Previous palinspastic models of the Arabian margin in Oman assume a cylindrical framework of the divergent margin (Searle and Graham, 1982; Béchennec et al., 1988; Stampfli et al., 1991; Pillevuit et al., 1997). The northward drift of the Cimmerian blocks documented by the palaeomagnetic record (Besse et al., 1998) was presumably preceded by N–S stretching during the Permian rifting. Our findings do not support this hypothesis because both the extensional paleostructures and the platform-basin gradient in the restored section suggest a more ENE–WSW to E–W orientation of extension.

In our viewpoint, contrasted stretching directions in the Saih Hatat platform along the edge of the Arabian plate can be related to the triple junction northeast of the Arabian margin. Following this, the Hawasina Nappes that outcrop on the western side of the Saih Hatat culmination (Fig. 1) are issued from a pelagic basin fringing the NW–SE segment of the south Neotethyan margin, whereas the Saih Hatat rifted platform represents the transition zone between the Arabia–India–Madagascar and the Neotethyan rifts. This setting would be analogue to the Afar area between the East African Rift, the Red Sea and the Arabian Sea, or to other large igneous province (Karoo, North Atlantic) located at a triple rift junction.

From a kinematic point of view, the Permian extensional setting observed in the Saih Hatat is consistent with the palaeogeographic models of Ricou (1994), in which the Tethyan oceanic floor opening occurred obliquely, leading to formation of a narrow oceanic domain along a transform-type southern Neotethyan margin (Fig. 10b). This is consistent with recent paleobotanical and paleontological data which indicate that the Neotethys ocean was much narrower than previously assumed (Broutin et al., 1995; Angiolini et al., 1997; Crasquin-Soleau et al., 2001; Berthelin et al., 2003). The simplified kinematic sketch (Fig. 10) illustrates this hypothesis in a regional-scale geodynamic
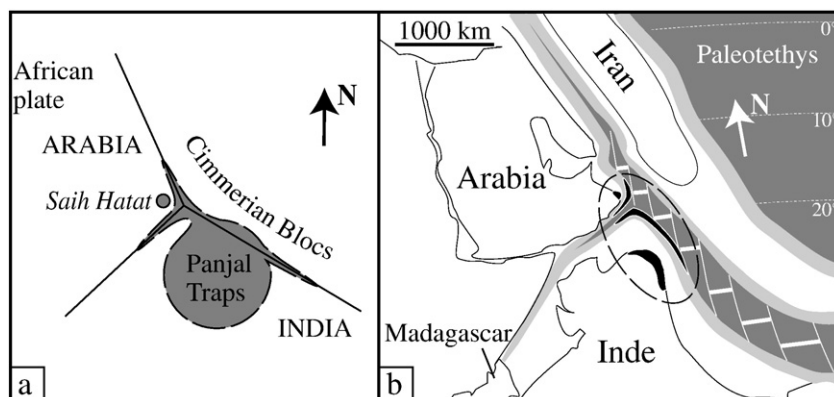

Fig. 10. a) Interpretative sketch of the Permian Tethyan rift system and of the associated magmatic province along the Indian and Arabian plates. b) Palaeogeography of the Neotethyan breakup during Middle Permian, modified after Ricou (1994). The main volcanic segments of the southern Neotethyan margins are indicated (black).

environment. We propose the development of volcanic-type margins along continental edges of the Arabian and Indian shields during emplacement of the Neotethyan plume (Lapierre et al., 2004) which gave birth to the Panjal Traps. The typical volcanic margin segments would have disappeared during the subduction of the Arabian margin.

5. Conclusions

Combined structural and lithostratigraphic analysis in the northern Saih Hatat tectonic window provides a reappraisal of the relationships between paleogeographic differentiation, extensional rift tectonics and volcanism on the Arabian platform during the Permian. Unlike some earlier interpretations, it is proposed that the main tectonic units of this area formed in a proximal part of the northern Arabian shelf. A tentative restoration obtained by unfolding the two main tectonic units reveals lateral changes that document coeval WSW–ENE extension. Extension is also documented by partly inherited, perpendicular paleostructures that underwent top-to-the-NE inversion. The corresponding rifting is coeval with intraplate volcanism in all parts of the Arabian margin, from the Saih Hatat platform to the pelagic basin exposed in the Hawasina Nappes. In the former area, there is no evidence of rifting after the volcanic event, and the overlying, post-Murghabian sediments show little facies and thickness variations. Thus the Arabian margin underwent a short rifting episode, probably shorter than 5 Ma, before the beginning of northward drift of Iran and the opening of the Neotethys Ocean. The Saih Hatat volcanics were coeval with voluminous magmas eruptions in many segments of the Arabian and Indian margins. A late Paleozoic mantle plume may have been responsible not only for rifting of the Iranian block but also for breakup of the Arabian and Indian plates. The proximity of the Arabia–India–Iran triple junction or a transform margin might explain the discrepancy between the WSW–ENE orientation of Murghabian extension recorded in the Saih Hatat and the northward drift of Cimmerian blocks documented by palaeomagnetic data (Besse et al., 1998).

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