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The break-up of East Gondwana along the northeast coast of Oman: evidence from the Batain basin

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Abstract – Recent detailed studies on the Batain nappes (northeast coast of Oman), which represent a special part of the so-called 'Oman Exotics', have led to a better understanding of the Neotethyan geodynamic evolution. The Batain Exotics bear witness to volcanic activity, sea-level changes, tectonic instability, rifting and oceanization along the Eastern Oman margin during Late Palaeozoic and Mesozoic times. They allow definition of the Batain basin as an aborted Permian branch of Neotethys. This marine basin was created in Early Permian times extending southward to the East African/Madagascar region and was linked to the Karoo rift system. The presented revised classification of the Batain nappes considers the Batain basin to be no longer a part of the Hawasina basin and the Neotethyan margin proper. We attribute the Batain basin to a Mozambique–Somali–Masirah rift system (Somoma). This system started in Early Permian, times, creating a marine basin between Arabia and India/Madagascar; rifting in the Late Triassic and oceanization during Late Jurassic times led to the separation of East Gondwana.

1. Introduction

The Batain plain area is located in northeast Oman, southeast of the town of Sur, bounded to the west by the Wahiba Sands, to the east by the Arabian Sea and to the north by the Gulf of Oman (Fig. 1). The Batain nappes are represented by allochthonous Permian to Maastrichtian marine sediments, as well as volcanic rocks and the Eastern Oman Ophiolite Nappes, obducted onto the Oman continental margin at the Cretaceous/Tertiary boundary (Immenhauser *et al.* 1998; Schreurs & Immenhauser, 1999). They are unconformably overlain by autochthonous Late Paleocene to Miocene continental siliciclastic and shallow-marine calcareous sediments. The Batain series consists of marine basin sediments of the Qarari and Aseelah units, the Sal, the Guwayza and the Wahrah formations, and further down the slope, deposits of the Ad Daffah Unit and the seamount relicts of the Ruwaydah Unit (Fig. 2). They represent a continuous stratigraphic sequence, with some similarities to the lithostratigraphy of the Hawasina nappes (Immenhauser *et al.* 1998; Schreurs & Immenhauser, 1999; Peters *et al.* 2001).

The 'Exotics' within the Batain nappes are characteristic pale grey, mostly isolated outcrops of megabreccia and conglomerates protruding from the

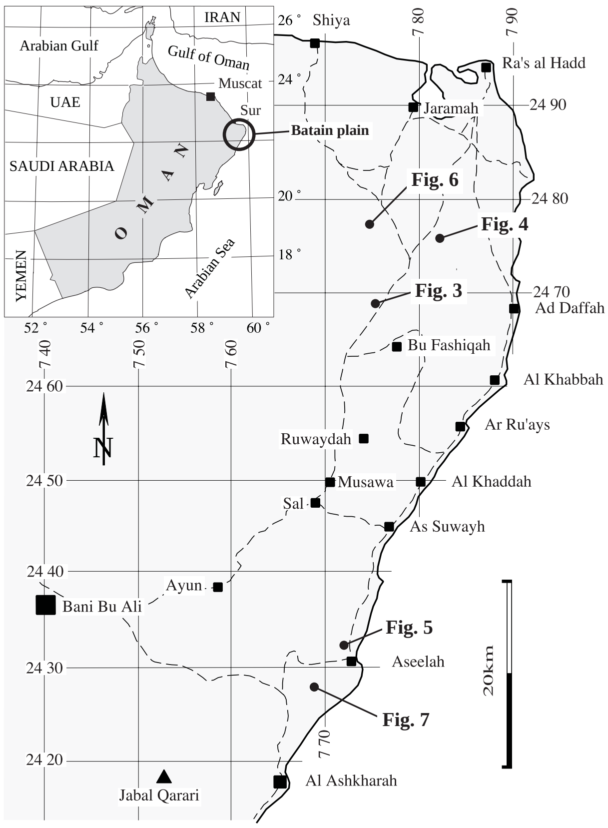

Figure 1. Simplified topographic map of the Batain plain with the locations of the measured lithological sections mentioned in the text (UTM coordinate map grid).

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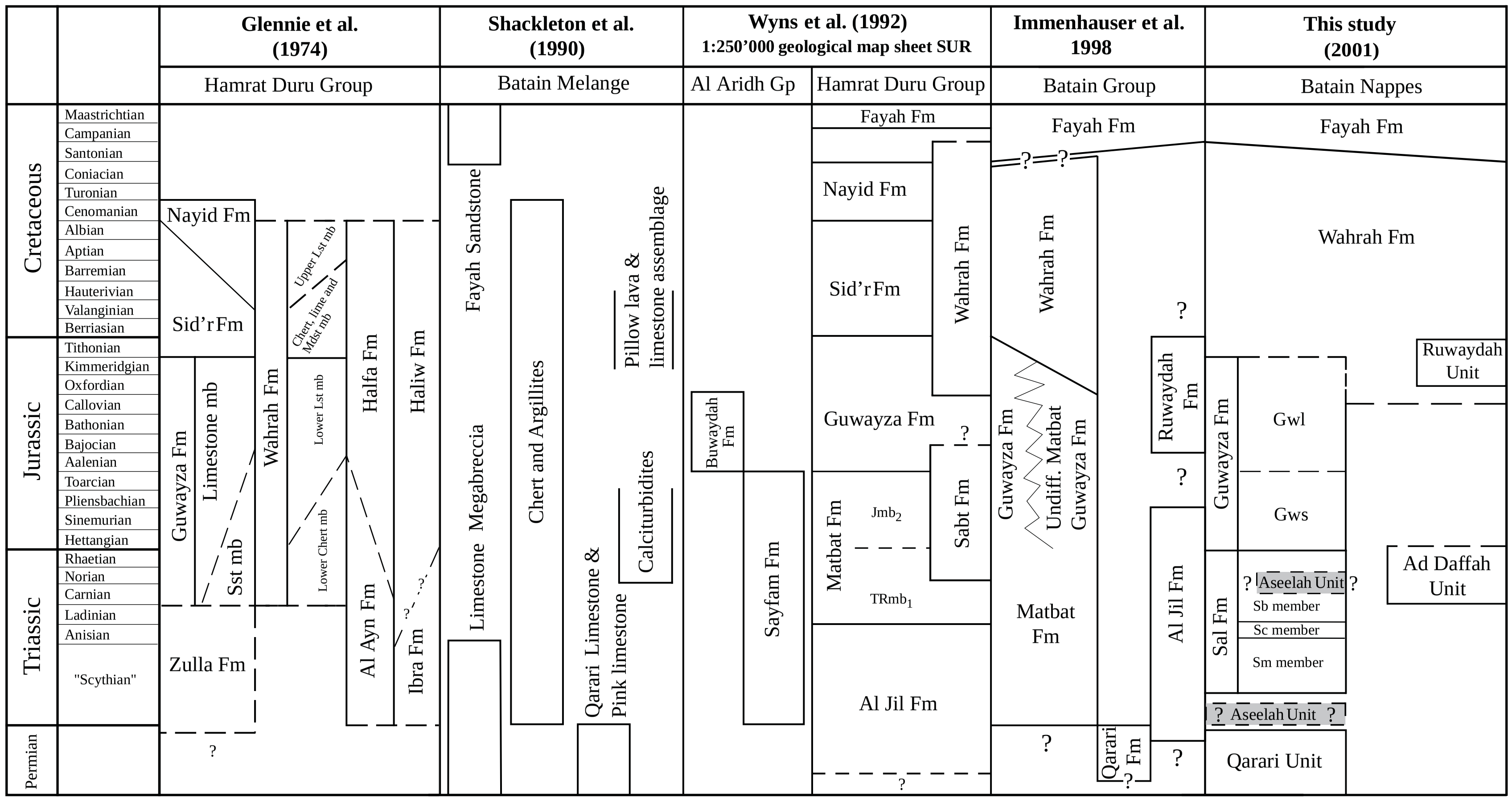

Figure 2. Overview of the stratigraphy in the Batain plain showing the different stratigraphic subdivisions of the Batain Melange, the Hamrat Duru Group and the Batain Group. Abbreviations: Fm – Formation; mb – member; Lst – Limestone; Jmb – Jurassic, matbat member; TRmb – Triassic matbat member; Sb – brown member of the Sal Formation; Sc – chert member of the Sal Formation; Sm – mudstone member of the Sal Formation; Gwl – limestone member of the Guwayza Formation; Gws – sandstone member of the Guwayza Formation; Sst – Sandstone; Mdst – Mudstone.

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generally flat yellow sandy plain. Their occurrence is restricted to a zone, about 20 km wide, which is parallel to the Batain coast. The megabreccia layers form numerous thrust sheets scattered along the Batain coast; small exposures, hills and ridges reach up to 200 m above the plain. These outcrops are composed of partly recrystallized limestone blocks several metres in size, polymict limestone breccia units and conglomerates, locally associated with Mesozoic radiolarian cherts, volcanic rocks and blocks of strongly tectonized ophicalcite. Because of different lithologies and their apparently chaotic depositional relationship, similar exposures were interpreted in the Oman Mountains as a series of carbonate build-ups, deposited in part on oceanic islands or seamounts (Searle & Graham, 1982) or as slope deposits of the Arabian platform margin (Blendinger, 1991). These lithologies were previously mapped in the Batain area as the Ibra and the Al Aridh formations by Glennie *et al.* (1974), or were considered as 'limestone megabreccia' in the 'Batain Mélange' by Shackleton *et al.* (1990) (Fig. 2). Roger *et al.* (1991), Béchennec *et al.* (1992) and to some extent Wyns *et al.* (1992) generally attributed the megabreccia and conglomerate units from the Batain plain to the Al Jil Formation (Fig. 2). The large occurrences of megabreccia and volcanic rocks from the northern Batain area were mapped by Wyns *et al.* (1992) as part of the Al Aridh Group (Fig. 2). Pillevuit (1993) and Pillevuit *et al.* (1997) extend the classification concept of Searle & Graham (1982) to classify the 'Oman Exotics' according to their depositional sequence and into different palaeogeographic units, and to integrate them into a modern scheme of the Neotethyan evolution. They present a revised division for the 'Oman Exotics' and introduce new stratigraphic groups, attributing the exotic blocks from the Batain plain to 'reworked Permian platform limestones in the Hawasina basin'.

2. Stratigraphic framework and sedimentology

2.a. Qarari Unit

The 'Qarari Limestone' (*sensu* Shackleton *et al.* 1990), known only from the Batain area, was assigned by Béchennec *et al.* (1992) and Wyns *et al.* (1992) to the Al Jil Formation. Immenhauser *et al.* (1998) separate the Qarari Formation from the Al Jil Formation within the newly introduced Batain Group (Fig. 2). Because of the absence of well-defined formational boundaries, Peters *et al.* (2001) replace the Qarari Formation with the informal Qarari Unit. The type locality is 12 km northwest of Al Ashkharah at Jabal Qarari (Fig. 1), where a large thrust sheet of the Qarari Unit is exposed with a maximum thickness of 170 m (Wyns *et al.* 1992). The Qarari Unit normally forms isolated outcrops without any stratigraphic contacts, the upper and lower boundaries being thrust planes or masked by scree; in the Bu Fashiqah section (Fig. 3) the typically nodular Qarari mudstone is bounded at its base and top by thrust planes. There, the Qarari Unit displays intraformational breccia and calcirudite horizons, yellowish interbeds of marly shales with a well-preserved assemblage of Permian ammonoids (Peters *et al.* 2001).

Light to dark grey nodular micritic limestones represent the most common lithofacies of the Qarari Unit. This unit is comprised of typically 10–30 cm thick nodular and platy beds, made up of mudstones with some single decimetre-sized coarse bioclastic turbidite layers. Sedimentary structures were rarely observed except for some slump-structures, centimetre-sized ripples and bioturbation. In contrast, coquina accumulations are common along the upper bedding planes, where they are formed by bivalves, productid brachiopod shells, fenestellid bryozoans, small solitary corals, crinoid stems and blastoids.

The dominant microfacies within the nodular bedded Qarari Unit is a non-cyclic, thin-bedded alternation of fine peloidal, partly silicified, homogeneous mudstones and wackestones with rare recrystallized radiolarians, conodonts and siliceous sponge spicules. The second microfacies is a millimetre-sized, faintly rippled microsparite with less than 5% small angular quartz grains, which is partly to completely dolomitized and occurs predominantly in the upper part of the Qarari Unit. A third microfacies represents calciturbidite, comprising reworked shallow-marine and lagoonal components, large fragments of echinoderms, bivalves, bryozoans and algae, including abundant foraminifers represented by the genus *Hemigordius*.

An Early to early Middle Permian age for the Qarari Unit was determined by Shackleton *et al.* (1990) and Lee (1990), who mentioned an extensive fauna of fusulinids, productid brachiopods, bryozoans, corals, blastoids, crinoids and trilobites from the Jabal Qarari area. The early Late Permian age determined by Wyns *et al.* (1992) is demonstrated by conodont assemblages with *Gondolella* cf. *orientalis* (Barskov & Koroleva) and *Hindeodus typicalis* Sweet, and by an assemblage of Early Murgabian (Roadian) ammonoids (Peters *et al.* 2001) found in yellowish shaly interbeds from the Bu Fashiqah section (Fig. 3).

2.a.1. *Interpretation*

The occurrence of slumping and subordinate ripple structures, as well as the microfacies and microfauna including the presence of pelagic and intra-shelf ammonoid species, indicate a hemipelagic depositional environment, located on an open sea shelf and shelf slope.

2.b. Aseelah Unit

The Aseelah Unit, 3 km southwest of Aseelah (Fig. 1), is defined by Peters *et al.* (2001) as a conglomerate

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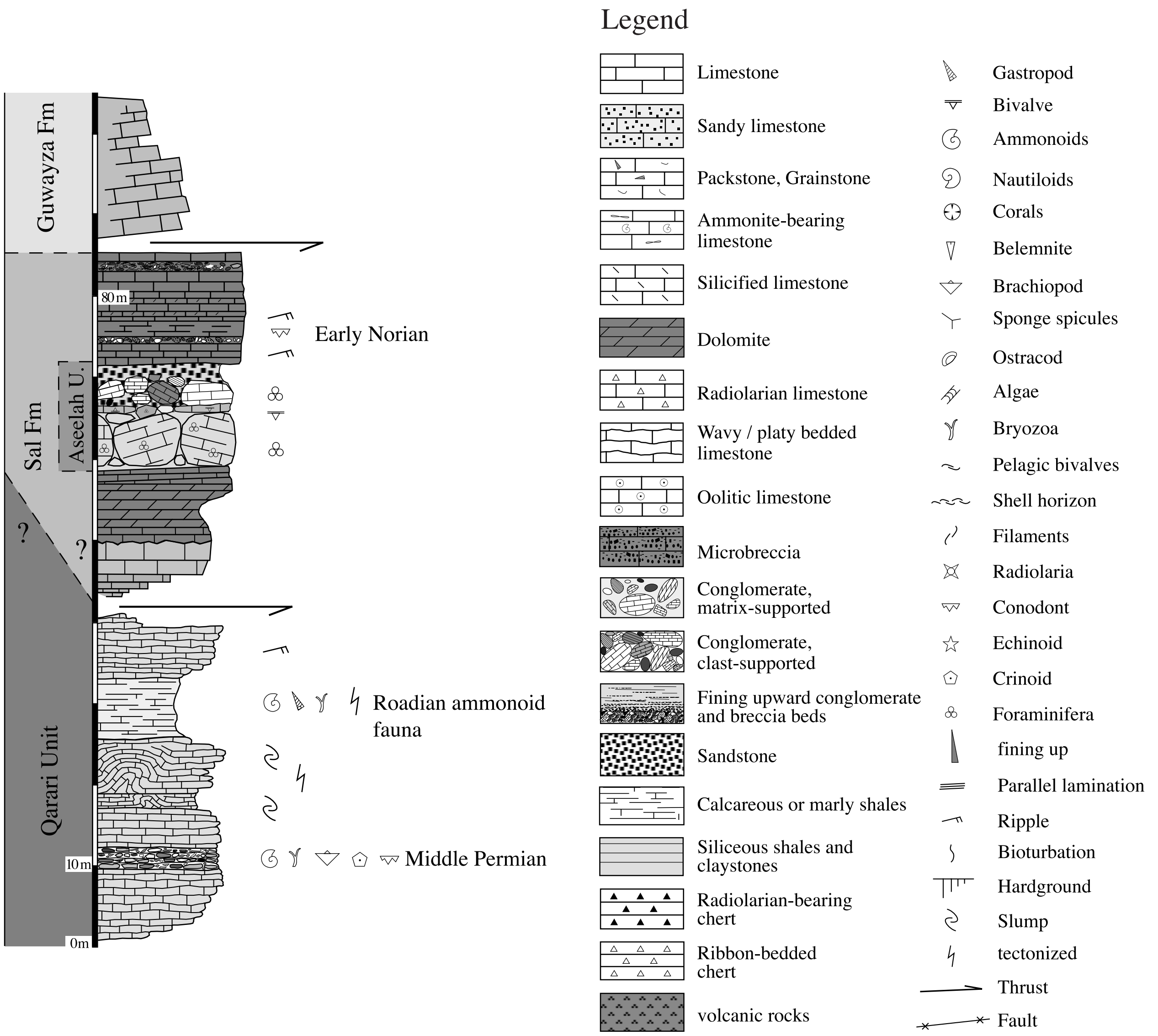

Figure 3. Overview of the overturned sequence and the measured section at the locality 6 km northwest of the village of Bu Fashiqah (UTM coord. 775769/2468896) (modified after Wyns *et al.* 1992).

which consists exclusively of boulders of Early Permian (Yakhtashian) to Late Permian (Dzhulfian) age (Hauser *et al.* 2000), normally in a sandy matrix, associated with a whitish coarse-grained sandstone or sandy calcarenite. On their 1 : 250 000 scale geological map, Wyns *et al.* (1992) and Béchennec *et al.* (1992) attributed these rocks to the Al Jil Formation.

The Aseelah Unit consists mainly of clast-supported, moderately to very poorly sorted, vari-coloured sandy limestone conglomerate. At the type locality the unit displays 5–10 m thick bedded channel-fills, composed of limestone conglomerates which pass upwards into a 20 m thick succession of 0.5–3 m thick large-scale cross-bedded white sandstone beds.

The centimetre- to metre-size rounded to sub-rounded boulders are made up of lagoonal and reef limestones and shelf sediments. Some of these boulders contain a Permian macrofauna with Rugosa corals of *Wentzelella*-type and brachiopods of *Richthofenia*-type. The partly reef-derived carbonate components of the conglomeratic Aseelah Unit are made up of bioclastic wackestones, packstones and grainstones. A rich microfauna of fusulinids (Hauser *et al.* 2000), smaller foraminifers, gastropods, bryozoans, sponges, echinoderms, dasyclads, red algae and new algal forms (Vachard *et al.* 2002a) was found in boulders of algal boundstone, rudstone and floatstone. The conglomerate matrix is made up of sandy calcarenites or very coarse-grained white sandstones. The calcarenitic matrix consists of skeletal packstone and crinoidal grainstone with large echinoderm fragments, algae and benthic foraminifers, the same as the reworked shallow-marine carbonate blocks (Peters *et al.* 2001). At the type locality, the well-sorted and sub-angular to rounded sandstone shows a dark brown hematite-rich duricrust in two horizons, probably indicating old weathering surfaces.

Because the Aseelah Unit is often bounded by thrust contacts the total thickness is difficult to estimate. The beds vary from cm up to several metres in thickness. At the locality Bu Fashiqah (Fig. 3), the unit measures approximately 15 m, intercalated between calcarenite of the Sal Formation dated as Early Norian (Peters *et al.* 2001), whereas at the locality 3 km southwest of Aseelah, the thickness reaches *c*. 35 m without any stratigraphic contact. The occurrences of the Aseelah Unit are commonly found in the northern area of Musawa (Fig. 1), interbedded within calcarenite and calcirudite of the upper part of the Triassic Sal Formation (Hauser *et al.* 2001; Peters *et al.* 2001).

When considering the age of the Aseelah Unit, no dating of the conglomerate matrix was possible, nevertheless, the Permian microfauna found in the allochthonous limestone components yield Yakhtashian, Bolorian, Kubergandian, Murgabian, Midian and Dzhulfian ages (Wyns *et al.* 1992; Béchennec *et al.* 1992; Hauser *et al.* 2000; Vachard *et al.* 2002*a*,*b*). Some sandstone occurrences which undoubtedly belong to the Aseelah Unit were dated as Late Permian by Shackleton *et al.* (1990), but attributed at that time to the 'sandstone bodies' of the Fayah Formation. Also, Glennie *et al.* (1974) mentioned the occurrence of exclusively Permian boulder beds of an 'Oman Exotic' facies, mapped as Ibra Formation in the Batain region.

2.b.1. Interpretation

The microfacies as well as the macro- and microfauna of the clasts indicate the existence of lagoonal, reef and open-marine shelf environments during the Permian (Hauser *et al.* 2000). Channel-fill material with a large grain-size distribution, containing subrounded blocks from different depositional environments, suggests a debris flow origin for the Aseelah Unit. These debris flow deposits resulted from the disintegration of a carbonate platform margin after the Dzhulfian. Emersion, erosion and possibly overstepping of some areas of the platform, resulted in the redeposition of periplatform conglomerates and breccia at the toe of the slope. Clasts of lithified lagoonal limestones, framestones, coral blocks and loose skeletal debris deposited on the 'fore-reef' slope were subject to downslope mass transport. The siliciclastic input, originating from emerged highs along the Eastern Oman margin, is demonstrated by the deposition of 20 m of calcareous sandstone at the top of the Aseelah Unit and by emersive weathering surfaces. The depositional event for the Aseelah Unit cannot be constrained. We suggest two possible sedimentary events: deposition during eustatic sea-level drops in the Late Permian/Early Triassic (Haq, Hardenbol & Vail, 1988; Baud, Atudorei & Sharp, 1996), or debris flow deposits shed during tectonic instability in the Late Triassic.

2.c. Ad Daffah Unit

The Ad Daffah Unit, defined by Peters *et al.* (2001), 10 km northwest of the village Ad Daffah, is used to describe in the Batain plain the typical occurrences of unsorted and unstratified megabreccia with basalt interlayers overlying reddish filamentous limestones and radiolarian cherts. Wyns *et al.* (1992) attributed these large occurrences of megabreccia units, extrusive rocks and pelagic filamentous limestones to the Sayfam Formation (Al Aridh Group), whereas the remaining outcrops of the 'Oman Exotic' facies were generally mapped as Al Jil Formation (Hamrat Duru Group) by Béchennec *et al.* (1992), Roger *et al.* (1991) and Wyns *et al.* (1992). The Ad Daffah Unit is similar in part to the Al Aridh Formation *sensu* Blendinger (1990) or to the Al Aridh Group defined by Béchennec (1987).

The Ad Daffah Unit normally crops out as large thrust sheets, overlying the surrounding sediments of the Batain series. At the type locality (Fig. 4) the Ad Daffah succession begins with 10 m of thin-bedded reddish limestones with lumachelle beds and shell horizons of *Halobia beyrichi* and calcareous shales dated as Carnian to Early Norian (Lacian) by radiolarians and conodonts. These are overlain by 15 m of radiolarian cherts and silicified *Halobia* limestones dated as Early to Middle Norian (Peters *et al.* 2001). They are overlain by a 20 m thick succession, starting with dolosiltite, followed by fining-upward graded calcarenite, microbreccia and conglomerate. The type-section ends with unstratified metre-size megablocks made up of unsorted breccia with andesite interlayers.

2.c.1. Cherts and pelagic limestones (Lower Ad Daffah Unit)

The lower part of the Ad Daffah Unit crops out in a section 3 km north–northwest of the village of Aseelah (Fig. 1). There, the succession starts with red-greenish radiolarian cherts of Late Ladinian age (Peters *et al.* 2001), overlain by brown-yellowish 1 to 10 cm thick bedded strongly silicified *Halobia* limestones. Stratigraphically above, the section continues with reddish-pale radiolarian cherts and isolated thin-bedded *Halobia* limestones interbedded with shaly partings. The section ends with yellowish pale radiolarian cherts of Late Carnian–Early Norian age (Peters *et al.* 2001), overlain by brown, platy decimetre thick bedded *Halobia* limestones and calcarenite.

2.c.2. Megabreccia (Upper Ad Daffah Unit)

The chaotic megabreccia consists of up to house-sized limestone blocks and calcirudites, predominantly in a coarse-grained carbonate matrix, or in red finely laminated calcarenite, occasionally containing crinoid ossicles. The white or pinkish, marble-like limestone megabreccia are often strongly recrystallized and

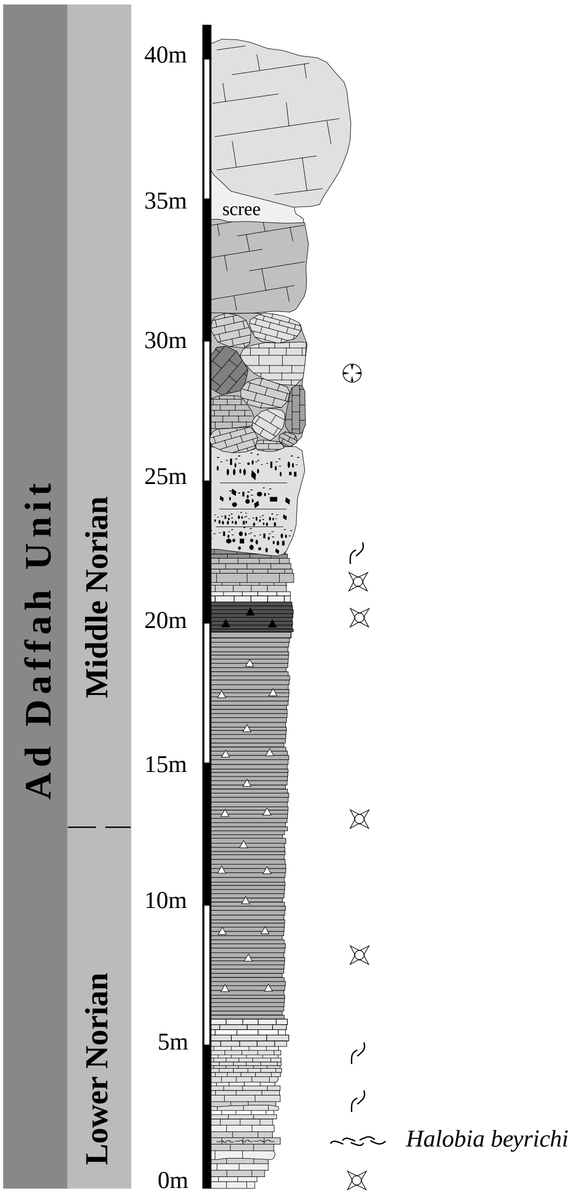

Figure 4. The type-section of the Ad Daffah Unit consisting of Late Carnian to Middle Norian radiolarian-bearing cherts overlain by calcirudites and megabreccia (UTM coord. 783547/2474428). For legend see Figure 3.

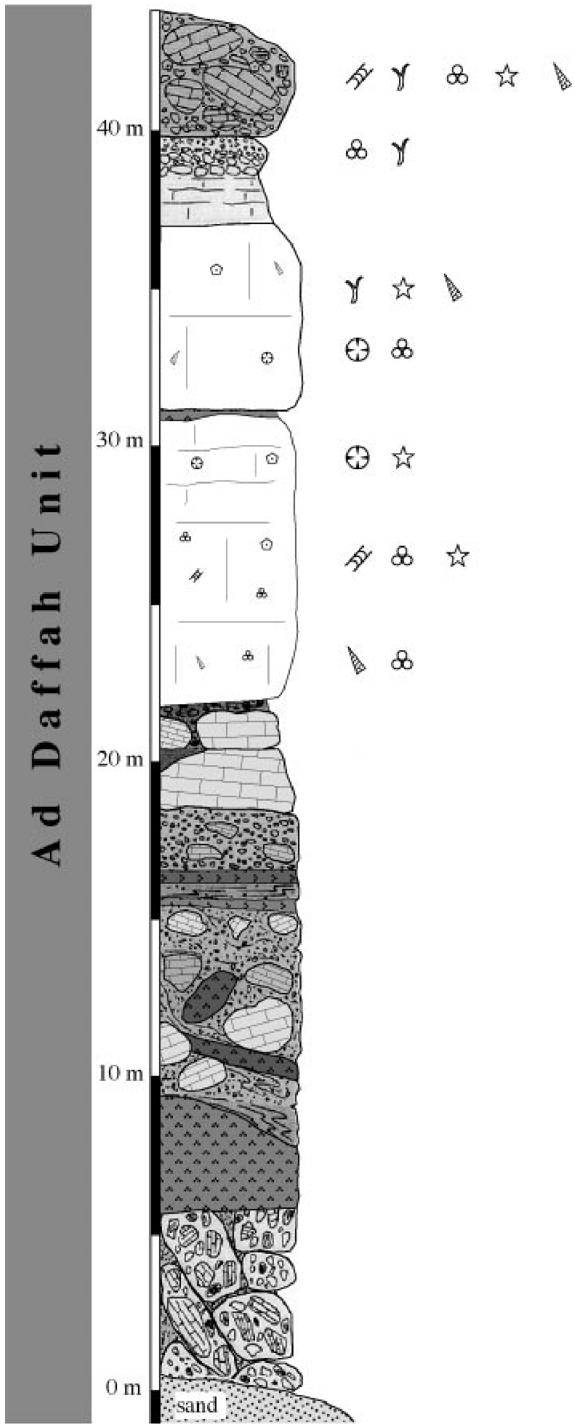

Figure 5. Varicoloured breccia of the southern facies of the Ad Daffah Unit (UTM coord. 772207/2432544). For legend see Figure 3.

consist of unsorted, polymict Triassic limestone clasts. Some megaboulders are well stratified and exhibit repetitive successions of fining-up graded microbreccia beds, such as those seen at a locality 6 km west–northwest of Aseelah (Fig. 1). The contacts between the megabreccia units and basalt flows are exposed 3 km north–northeast of Aseelah near the beach and 2 km north–northwest of Aseelah, west of the Ra's al Hadd road (Fig. 1). There, the limestone breccia comprises a variety of Triassic shallow-water carbonates, dark red to purple calcarenites, radiolarian cherts and abundant alkaline volcanite boulders, interlayered with basalt flows (Fig. 5). A strong tectonization is indicated by many fissures and fractures through the clasts, filled with calcite. A conglomerate facies of the Ad Daffah Unit crops out 4 km north of Al Ashkharah (Fig. 1), where a poorly sorted, clast-supported varicoloured conglomerate, with blocks from a centimetre up to several metres in diameter, overlies 25 m thick black pillow basalts. The conglomerate is made up of Triassic shallow-marine limestone boulders, containing decimetre-sized megalodonts, brachiopods and microfauna of Late Triassic age.

2.d. The Guwayza conglomerates

In contrast to the megabreccia of the Ad Daffah Unit, the well-rounded and mostly clast-supported conglomerate of the Guwayza Formation comprises channel-fills within the calcareous turbidite of the Guwayza Formation (Béchennec *et al.* 1992; Wyns *et al.* 1992; Immenhauser *et al.* 1998), but only in a few cases were true sedimentary intercalations identified.

At the locality 15 km south–southwest of Jaramah (Fig. 1) a stratified polymict conglomerate succession crops out within the Guwayza Formation (Fig. 6). The clast diameter of the unsorted conglomerate varies from millimetre-fine calcarenite to 4 m size boulders. The metre-thick beds are unsorted and show erosive basal contacts, whereas some thinner beds exhibit normal grading. The clast-supported conglomerates with a mainly oolitic matrix are made up of hemipelagic limestones of the Qarari Unit, shallow-marine and hemipelagic Triassic limestones with reworked cephalopods of Scythian to Norian age (Peters *et al.* 2001). Further, they contain reworked chert fragments and rare volcanic clasts. Some of the hemipelagic limestone boulders were dated as Scythian and Anisian using conodont evidence and belong to the Sal Formation (Hauser *et al.* 2001; Peters *et al.* 2001). The lithological section approximately 3 km southwest of Aseelah (Fig. 1) shows several conglomerate horizons with up to metre-sized blocks, embedded in the oolitic Guwayza Formation (Fig. 7). There, the oolitic calciturbidites overlie radiolarian-bearing cherts and mudstones dated as Late Bajocian on the basis of radiolarians (Peters *et al.* 2001).

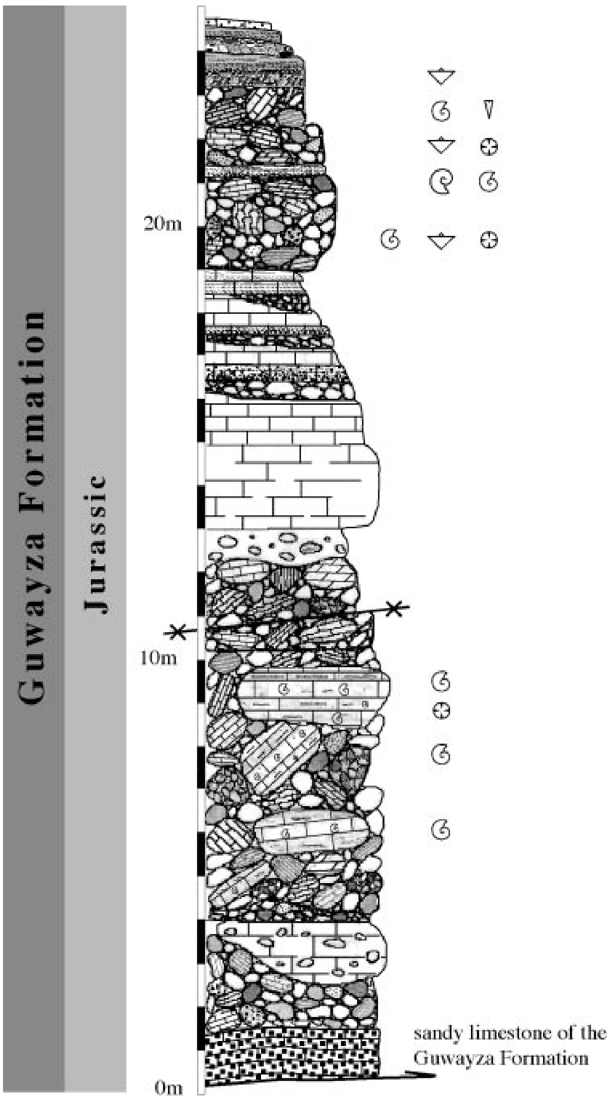

Figure 6. Lithological section from the Guwayza conglomerate with reworked ammonoids and macrofossils of Scythian to Norian age (UTM coord. 774166/2476570). For legend see Figure 3.

2.e. The Ruwaydah Unit

The Ruwaydah Unit 2 km northwest of the Bedouin village of Ruwaydah (Fig. 2) was defined by Peters *et al.* (2001) as a distinctive succession of volcanic and clastic carbonate rocks (Fig. 8). This succession was previously attributed to the Buwaydah Formation of the Al Aridh Group by Wyns *et al.* (1992) (Fig. 2). Based on the lack of well-defined lower and upper formation boundaries, Peters *et al.* (2001) replaced the Ruwaydah 'Formation' of Immenhauser *et al.* (1998) with the stratigraphically correct term 'Unit' for the Ruwaydah succession.

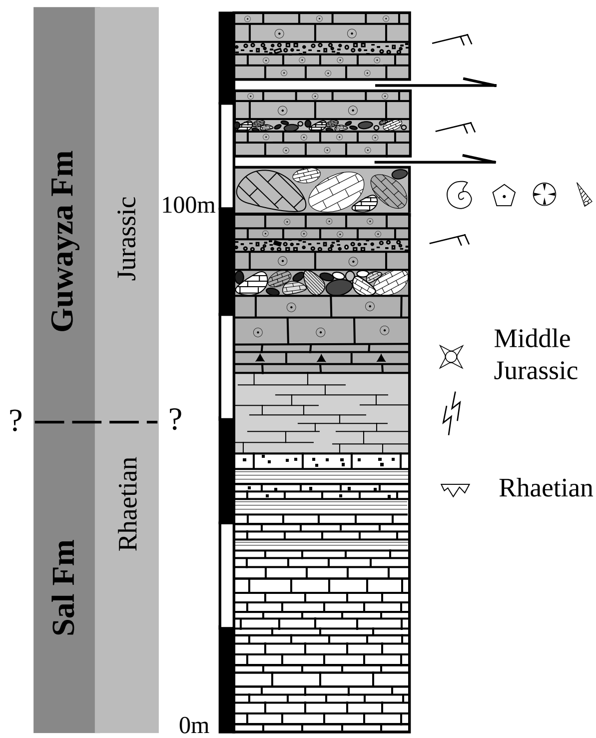

Figure 7. Lithological section showing the conglomerate horizons within the oolitic limestones of the lower Guwayza Formation (UTM coord. 769868/2428819). For legend see Figure 3.

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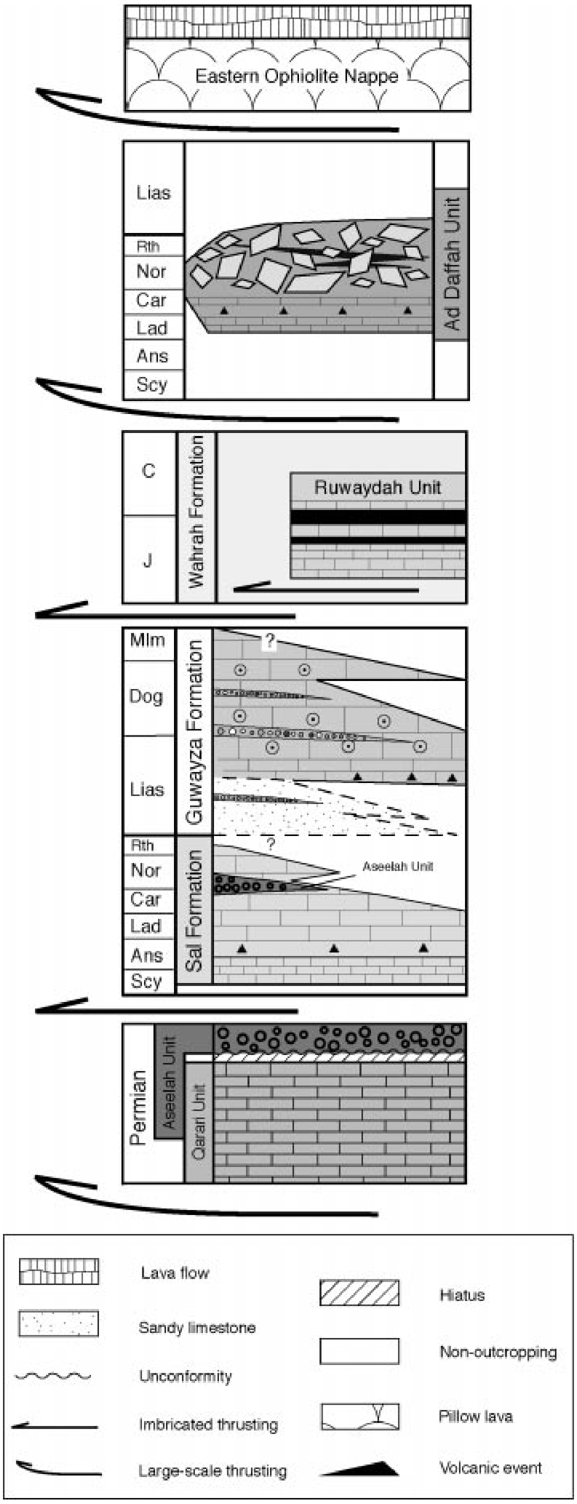

Figure 8. Litho- and tectonostratigraphic correlation chart of the Batain Group.

At the type locality the Ruwaydah Unit is exposed in an elliptically shaped WSW–ENE-elongated outcrop made up of a single fold which measures about 2000 m in length and 800 m in width. The outer rim of a calcareous facies mainly consists of conglomerate, calcirudite, cross-bedded calcarenite intercalated with tuffites and basalt-flows and pillows. The base of the outer rim has been dated by Wyns *et al.* (1992) as Late Callovian–Oxfordian by radiolarian-bearing micrite interbeds and the top as Late Malm/Early Cretaceous on the evidence of calpionellids (Peters *et al.* 2001). The central part begins with ammonite-bearing crinoidal limestones and black pillow basalts. The pillows are interbedded with ammonite-hosting limestones of the Ammonitico Rosso type, which yield a Middle Kimmeridgian ammonite fauna (Peters *et al.* 2001). The Ammonitico Rosso limestones are overlain by trachybasaltic flows and breccia and pillow basalts. The Ruwaydah succession ends with an imbricated limestone conglomerate in the western part of the outcrop made up of micrite and purple radiolarian cherts of Late Tithonian age (Peters *et al.* 2001). The volcanic rocks of the Ruwaydah Unit consist of basaltic, intermediate and acid alkaline extrusives. Chemically the volcanic rocks show a differentation trend from basanites over tephrites to trachyandesite.

3. The evolution of the Batain basin

3.a. Permian

Earliest Permian (Asselian and Sakmarian) deposits are not present among the described carbonate sediments in the Batain plain. This probably reflects cold water and cold climatic conditions during the Gondwana glaciation (Belushi, Glennie & Williams, 1996), preventing the deposition of carbonates. The marine deposition began in the late Early Permian (Late Sakmarian/Artinskian) (Angiolini *et al.* 1997) after a climatic warming during the Sakmarian (Immenhauser *et al.* 2000) and the opening of a marine basin towards Madagascar (northern Karoo rift system) because of the first extensional movements between Afro-Arabia and India (Fig. 9a) (Hankel, 1994; Stampfli, Marcoux & Baud, 1991; Pillevuit, 1993; Veevers & Tewari, 1995; Pillevuit *et al.* 1997; Stampfli, 2000; Immenhauser *et al.* 2000). This allowed the immigration of eastern shallow-marine microfaunas known from the eastern Tethyan provinces (Hauser *et al.* 2000). Roadian ammonoids from the Qarari Unit (Peters *et al.* 2001) document a Permian shelf and sea-way along the northeast coast of Oman (Fig. 9a) (Blendinger, Furnish & Glennister, 1992; Le Métour *et al.* 1995), connected with opening of the Neotethys up to Sicily where a similar Middle Permian fauna is known (Kozur, 1995). The Murgabian age of the Qarari Unit is contemporaneous with the Khuff and Saiq formations (Béchennec *et al.* 1993) which represent the onset of a carbonate shelf above the coastal-plain deposits of the Gharif Formation (Dubreuilh *et al.* 1992; Roger *et al.* 1992). New biostratigraphic data from the Khuff Formation (Angiolini *et al.* 1998) indicated a Guadalupian age for a transgressive event along the western flank of the Huqf-Haushi High, and the establishment of a shal-

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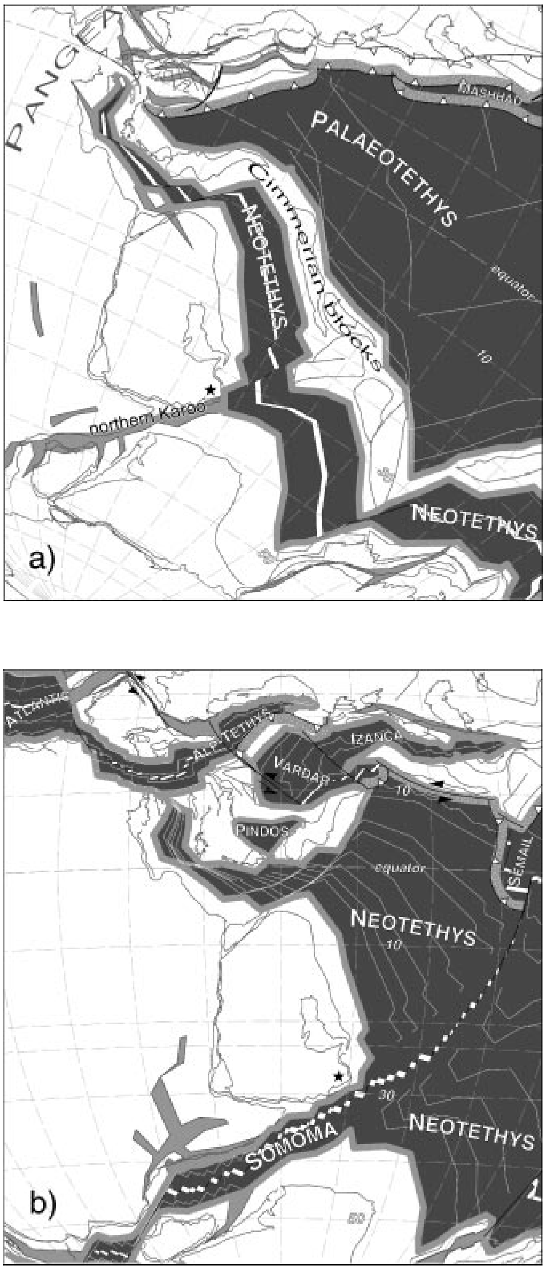

Figure 9. (a) Late Wordian reconstruction of the Tethyan realm (modified from Stampfli *et al.* 2001*a*,*b*). The north-oriented slab pull of Palaeotethys triggered the opening of Neotethys and the drifting of the Cimmerian blocks away from Gondwana. The northern Karoo rift represents an aborted branch of the Neotethys rift system. The star symbol shows the location of the Batain nappes. (b) Valanginian reconstruction of the Tethyan realm (modified from Stampfli *et al.* 2001*a*,*b*). The detachment of the Indian plate (East Gondwana) is constrained by magnetic anomalies in the Mozambique and Somalian basins. The sea-floor spreading of the Somoma ocean extends northward along a former Neotethys major transform. The slight rotation of the Indian plate in relation to Africa triggered an intra-oceanic subduction giving birth to the future Semail ocean. The star symbol represents the location of the Batain nappes.

low carbonate shelf on the Arabian Platform. These data are in agreement with the regional Permian transgression on the Arabian Platform, dated as 'Murgabian (= Guadalupian)' by Montenant *et al.* (1976), Le Métour (1988), Blendinger, Van Vliet & Hughes Clarke (1990) and Blendinger, Furnish & Glenister (1992), as well as the subsidence of the Arabian Platform during the 'Fusulinids Sea' transgression in the Late Murgabian (Le Métour *et al.* 1994, 1995).

In contrast to the Middle Permian volcanic activity in the Hawasina basin (Béchennec, 1987; De Wever, Bourdillon-de Grissac & Béchennec, 1988, 1990; Blendinger, 1990; Pillevuit, 1993; Le Métour *et al.* 1995; Pillevuit *et al.* 1997) no clear indication of any contemporaneous volcanism was found in the Batain basin (Peters *et al.* 2001). Furthermore, no evidence for extensional tectonics and 'oceanization' exists in the Batain basin, as was proposed for the Hawasina basin, for example by Blendinger (1988), Béchennec *et al.* (1990), Béchennec *et al.* (1991) and Le Métour *et al.* (1994, 1995). Pillevuit *et al.* (1997) mentioned the presence of tilted Permian platform blocks and submarine rockfalls incorporated in volcano-sedimentary sequences, deposited during 'oceanization' of the Hawasina basin that they placed in the late Early Permian (Stampfli *et al.* 2001a)

3.b. Permian/Triassic boundary

The first evidence of a relative sea-level drop is the increased quartz content in the strongly dolomitized limestones of the uppermost part of the Qarari Unit. Further possible demostrations of this drop are the platform-derived debris flow conglomerates composed of fossil-rich, exclusively Permian boulders and the coarse-grained calcareous sandstones from the Aseelah Unit. The high quartz content of this unit, and its dark brown hematitic duricrust, indicate a continental source, weathering surfaces and emersion, although the depositional event of the Aseelah Unit is not constrained (Fig. 8). The debris flows and sandstones from the Aseelah Unit probably represent the end of a major transgressive–regressive cycle around the Permian/Triassic boundary (Haq, Hardenbol & Vail, 1988; Vail *et al.* 1991; Hallam, 1996; Baud, Atudorei & Sharp, 1996) (Fig. 8). Additional evidence for a sea-level lowstand in the northern Karoo rift system is provided by the continental deposits of the lower Minjur Formation, overlying the Late Permian Khuff Formation in the Huqf area (Dubreuilh *et al.* 1992; Roger *et al.* 1992). Based on the biostratigraphic data, we believe that the sections from the Batain plain and from the Baid region (Blendinger, Van Vliet & Hughes Clarke, 1990, fig. 5; Blendinger & Flügel, 1990, fig. 3) display the same stratigraphic hiatus at the Permian /Triassic boundary (Fig. 8). Furthermore, the overlying platy lime mudstones from the Baid section are dated as Smithian (Scythian) by conodonts, contemporaneous with and similar to the Mudstone member of the Sal Formation (Hauser *et al.* 2001).

3.c. Triassic to Early Jurassic

The Upper Triassic shallow-marine limestones, reworked into the megabreccia and conglomerates of the Ad Daffah Unit, indicate carbonate build-ups and carbonate shoals in the Batain basin. The synsedimentary–tectonic occurrence of continental-type within-plate basalts interlayered in the megabreccia units (Wyns *et al.* 1992; Peters *et al.* 2001) reveals volcanic activity related to the onset of rifting, accompanied by the collapse of the Triassic carbonate platform. These large occurrences of slope deposits and volcanic rocks, developed by gravitational sliding, are clear evidence for rifting and tectonic instability during Late Triassic times in the Batain basin. Their deposition is contemporaneous with the debris flow deposits of the Aseelah Unit embedded in the upper Triassic Sal Formation (Hauser *et al.* 2001; Peters *et al.* 2001), reflecting erosion and tectonic activity (Fig. 8). They are time-equivalent to widespread synsedimentary tectonic activity along the northern Tethys margins, probably also reflecting the collision of the Cimmerian block with Eurasia and the plate tectonic reorganization at that time (Stampfli at al. 2001*b*). Magmatic and tectonic activities are also known from the Hawasina basin at the end of Triassic-Early Jurassic times (e.g. Murris, 1980; Cooper, 1990; Béchennec *et al.* 1990; Robertson & Searle, 1990; Béchennec *et al.* 1991; Stampfli, Marcoux & Baud, 1991; Le Métour *et al.* 1994; Pillevuit *et al.* 1997).

3.d. Jurassic

The conglomerate interbeds in the Guwayza Formation yield a reworked Hallstatt-type cephalopod fauna of Scythian to Norian age (Peters *et al.* 2001), emphasizing a biostratigraphic gap for the Rhaetian (Fig. 8). The section through the uppermost Sal Formation and the Guwayza Formation (Fig. 7) confirms the siliciclastic influx during the Rhaetian regression (Bernoulli & Weissert, 1987; Cooper, 1987, 1989, 1990; Murris, 1980; Blendinger, 1988; Bernoulli, Weissert & Blome, 1990; Béchennec *et al.* 1990) and reduced marine sedimentation during Early Liassic times (Fig. 8). The conglomerates also contain reworked limestones from the Sal Formation of Scythian and Anisian age, dated by conodonts (Peters *et al.* 2001); this is evidence for the partial destruction of the proximal Triassic Batain basin in Late Jurassic times. The conglomerates within the characteristic oolitic Guwayza Formation overlying radiolarian cherts of Late Liassic age (Fig. 8) demonstrate tectonic activity in the proximal and distal parts of the Batain basin, from where clasts of different facies and origin were shed into the basin during the Late Jurassic period. The tectonic activity can be attributed to thermal uplift and local compression, associated with sea level changes in the Somoma ocean system.

The volcanic rocks of the Ruwaydah Unit may reflect an active alkaline sea-floor magmatism that produced a seamount structure and many dispersed intrusives and extrusives in the Wahrah Formation (Peters *et al.* 2001). The Ruwaydah Unit reflects Late Jurassic to Early Cretaceous ocean spreading, connected with the break-up of Gondwana (Fig. 9b). Finally, thrust sheets of Late Jurassic/Cretaceous oceanic lithosphere from Masirah and the Eastern Ophiolite Belt (Peters *et al.* 1995; Gnos, Immenhauser & Peters, 1997) provide clear evidence of oceanization in the Somoma rift system, in which anomaly M 22 has been recognized in the West-Somali basin (Rabinowitz, Coffin & Falvey, 1983) and in the Mozambique basin (Bergh & Norton, 1976).

4. Geodynamic evolution and conclusions

(1) The Early Permian opening of the northern Karoo rift system is characterized by the immigration of microfaunas with eastern Tethys affinities, different from occurrences known from the Oman Mountains (Hauser *et al.* 2000; Vachard *et al.* 2002*a*,*b*). This implies the opening of the marine Batain basin between the eastern Oman margin and India, linked to the south with the Madagascar rift zone of Veevers & Tewari (1995) (Fig. 9a), and extending further south into the main Karoo rift system where the onset of rifting has been placed in latest Carboniferous times (Stollhofen *et al.* 2000)

(2) During Triassic times the development of a marine basin was characterized by the deposition of the Sal Formation (Hauser *et al.* 2001) and the Ad Daffah Unit. The Ad Daffah megabreccia layers bear witness to volcanic activity and rifting which led to the collapse of the Triassic carbonate platform. For the depositional origin we suggest an off-Arabian continental setting, possibly at the western margin of the Indian plate. With the onset of the southern drift of India and Madagascar (Hankel, 1994) the Ad Daffah deposits were separated from the Greater India shelf source and attached to the Batain Basin. This probably explains the exotic character of the Ad Daffah Unit within the Batain Group.

(3) The rare Permian and mainly Triassic boulders in the Middle Jurassic conglomerate indicate active rifting and shoulder uplift which led to a partial destruction of the Triassic Batain basin.

(4) The Ruwaydah seamount, volcanite and the manganese horizons and remnants of ocean floor are evidence of the break-up of East Gondwana and the oceanization of the Somoma rift system in Late Jurassic times around anomaly M 22.

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