Late Palaeozoic to Neogene geodynamic evolution of the northeastern Oman margin

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Abstract – When the highlands of Arabia were still covered with an ice shield in the latest Carboniferous/Early Permian period, separation of Gondwana started. This led to the creation of the Batain basin (part of the early Indian Ocean), off the northeastern margin of Oman. The rifting reactivated an Infra-Cambrian rift shoulder along the northeastern Oman margin and detritus from this high was shed into the interior Oman basin. Whereas carbonate platform deposits became widespread along the margin of the Neo-Tethys (northern rim of Oman), drifting and oceanization of the Batain basin started only in Late Jurassic/Early Cretaceous time. Extensional tectonics was followed in the Late Cretaceous by contraction caused by the northward drift of Greater India and Afro-Arabia. This resulted in the collision of Afro-Arabia with an intra-oceanic trench and obduction of the Semail ophiolite and the Hawasina nappes south to southwestward onto the northern Oman margin ~ 80 m.y. ago. During the middle Cretaceous, the oceanic lithosphere (including the future eastern ophiolites of Oman) drifted northwards as part of the Indian plate. At the Cretaceous–Palaeogene transition (~ 65 Ma), oblique convergence between Greater India and Afro-Arabia caused fragments of the early Indian Ocean to be thrust onto the Batain basin. Subsequently, the Lower Permian to uppermost Maastrichtian sediments and volcanic rocks of the Batain basin, along with fragments of Indian Ocean floor (eastern ophiolites), were obducted northwestward onto the northeastern margin of Oman. Palaeogene neo-autochtonous sedimentary rocks subsequently covered the nappe pile. Tertiary extensional tectonics related to Red Sea rifting in the Late Eocene was followed by Miocene shortening, associated with the collision of Arabia and Eurasia and the formation of the Oman Mountains.

1. Introduction

The northeastern part of Oman is a highly complex area of the Arabian Peninsula that bears key evidence for the geodynamic evolution of the early Indian Ocean and the Neo-Tethys. For the coastal region between Ra’s al Hadd in the north and Ra’s Madrekah in the south (Fig. 1), we use the term ‘northeastern Oman margin’. The geology of this area consists of five main tectono-stratigraphic units:

(1) A Proterozoic crystalline basement comprising metamorphic and igneous rocks (e.g. Lees, 1928; Glennie *et al.* 1974).

(2) An autochthonous Upper Proterozoic to Cenozoic sedimentary cover overlying the crystalline basement (e.g. Hughes Clarke, 1988; Droste, 1997).

(3) The Batain nappes, consisting of Lower Permian to uppermost Maastrichtian sedimentary and volcanic rocks (Batain Group) that were thrust on top of the autochthonous sedimentary cover of the northeast Oman margin (Immenhauser *et al.* 1998; Schreurs & Immenhauser, 1999).

(4) Thrust sheets of Jurassic/Lower Cretaceous oceanic lithosphere (eastern ophiolites; Gnos, Immenhauser & Peters, 1997).

(5) Palaeogene and Neogene shallow-marine to continental neo-autochthonous sediments (e.g. Peters *et al.* 1995; Le Métour *et al.* 1995 and references therein) that unconformably overlie units (1) to (4).

2. Tectono-stratigraphic setting of the northeastern Oman margin

2.a. Proterozoic basement of the Arabian craton

The oldest rocks along the east Oman margin are metamorphic, and igneous basement rocks exposed in the Huqf–Haushi area (Al Jobah), near Jebel Ja’alan, and near the village of Qalhat (Fig. 1; Lees, 1928; Glennie *et al.* 1974; Gass *et al.* 1990; Würsten *et al.* 1990; Le Métour *et al.* 1995; Loosveld, Bell & Terken, 1996). The basement consists of amphibolite-facies metasedimentary rocks (i.e. garnet–biotite gneisses, micaschists and migmatites), which are intruded by dioritic, granodioritic and granitic rocks and cut by a network of rhyolitic and doleritic dykes (Gass *et al.* 1990; Würsten *et al.* 1990; Wyns *et al.* 1992). Most

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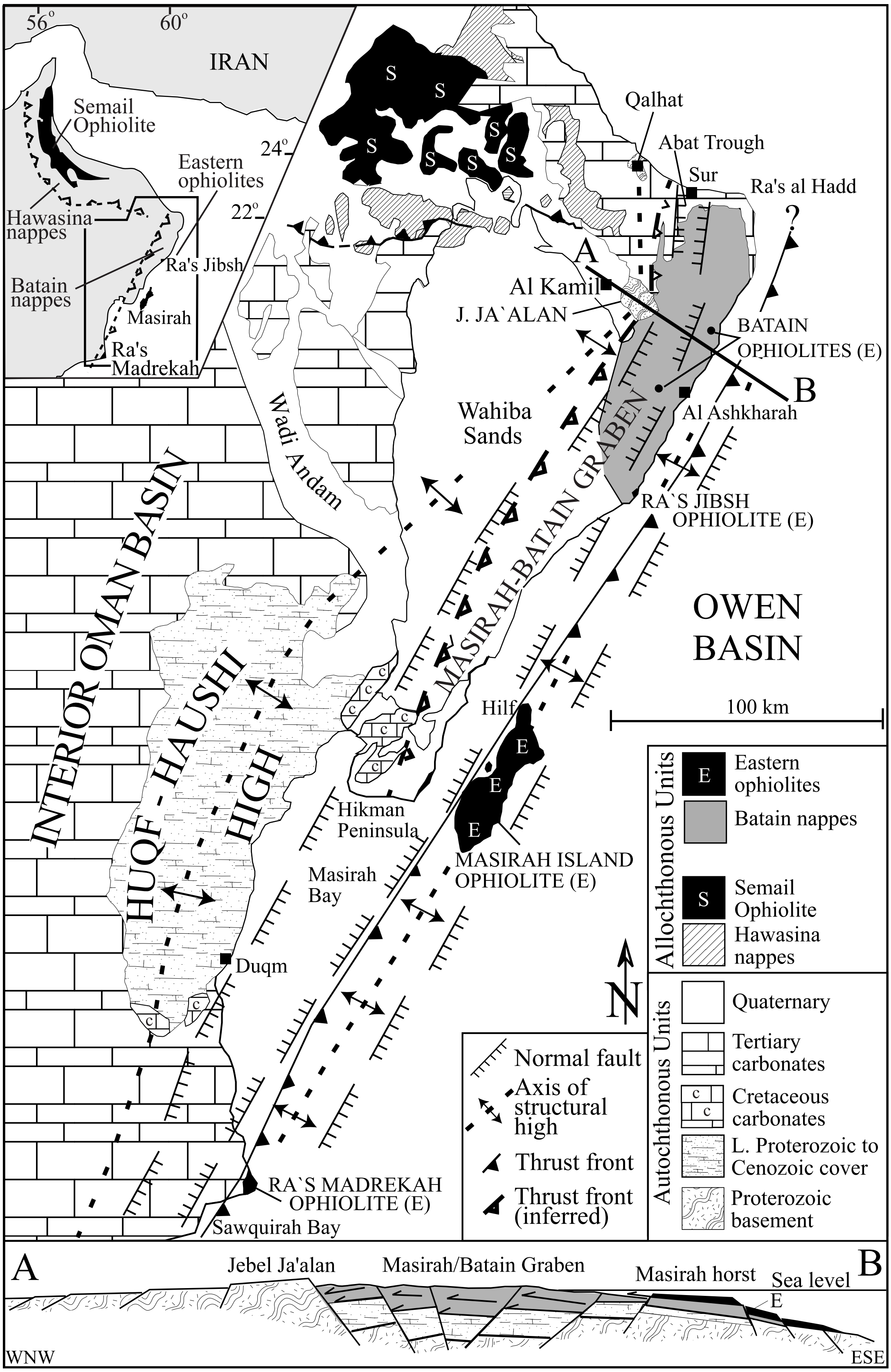

Figure 1. Geotectonic map of the northeastern Oman margin between the Sawquirah Bay in the south and Ra's al Hadd in the north. The map shows the distribution of allochthonous and autochthonous units, as well as the localities mentioned in this paper. Horst and graben structures are outlined and shown in a schematic profile (A–B). The inset in the upper left corner shows the regional context. Parts of this figure are based on Beauchamp *et al.* (1995), Le Métour *et al.* (1995) and Loosveld, Bell & Terken (1996).

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radiometric age determinations indicate that the intrusive rocks are late Proterozoic in age (830–750 Ma; Gass *et al.* 1990; Roger *et al.* 1991; Würsten *et al.* 1990), but also younger ages (~560 Ma) were determined (Le Métour *et al.* 1995). A Hercynian age of metamorphism of pre-Permian rocks was first postulated by Glennie *et al.* (1974), based on K–Ar data (327 ± 16 Ma). This age, however, was not confirmed by more recent radiometric dating.

2.b. Upper Proterozoic to Cenozoic autochthonous sedimentary cover

The autochthonous sedimentary cover of northeastern Oman is well exposed in the Huqf–Haushi area and in scattered exposures on the Hikman Peninsula (Fig. 1). The Huqf–Haushi area represents a north-northeast–south-southwest-trending regional high that separates the interior Oman basin from the Masirah–Batain graben system (Fig. 1; Ries & Shackleton, 1990). The high is bounded to the northeast by north-northeast-trending extensional faults (Gorin, Racz & Walter, 1982). The sequence ranges from Late Proterozoic to Cenozoic (Table 1).
Sedimentation gaps and facies changes allow a subdivision into six groups: (1) the Carboniferous to Permian Haushi Group, (2) the Permian to Rhaetian Akhdar Group, (3) the uppermost Triassic to Jurassic Sahtan Group, (4) the Lower Cretaceous Kahmah Group, (5) the middle Cretaceous Wasia Group and (6) the Upper Cretaceous Aruma Group (e.g. Hughes Clarke, 1988; Gorin, Racz & Walter, 1982; Loosveld, Bell & Terken, 1996).

The Late Proterozoic and Phanerozoic sedimentary rocks exposed in the Huqf–Haushi area show several unconformites recording intermittent uplift, with contemporaneous basin subsidence on either side (Ries & Shackleton, 1990). The deposits reach a maximum thickness of ~10 km in the interior Oman basin (Loosveld *et al.* 1996). Offshore, in Masirah Bay, the thickness of the basin deposits is up to 4 km (Gorin, Racz & Walter, 1982).

2.c. Lower Permian to uppermost Maastrichtian Batain Group

The Batain Group was recently established by Immenhauser *et al.* (1998), and comprises all Lower Permian to uppermost Maastrichtian sedimentary and volcanic rocks exposed in the Batain nappes of northeastern Oman (Table 2). These rocks form a tectono-stratigraphic unit that, for palaeogeographic, chronostratigraphic and kinematic reasons, must be differentiated from the Hawasina complex in the Oman Mountains (Schreurs & Immenhauser, 1999).

The Batain Group (Table 2) is built by the Lower to Upper Permian Qarari, the Upper Permian to Upper Liassic Al Jil (*sensu* Béchennec *et al.* 1992), the Scythian to Norian Matbat, the Lower Jurassic to Oxfordian Guwayza, the Mid-Jurassic to probably lowermost Cretaceous Ruwaydah, the Oxfordian to Coniacian/Santonian Wahrah, and the Santonian (Coniacian?) to uppermost Maastrichtian Fayah formations. A detailed description of these sedimentary and volcanic rocks was given by Roger *et al.* (1991), Béchennec *et al.* (1992), Wyns *et al.* (1992) and Immenhauser *et al.* (1998).

In the latest Maastrichtian/Early Palaeogene, thrusting of the eastern ophiolites and the Batain Group from southeast to northwest onto the northeastern Oman continental margin resulted in a thin-skinned fold-and-thrust belt (Schreurs & Immenhauser, 1999).

Table 1. Stratigraphy of the Huqf-Haushi area and interior Oman basin

Group	Formation	Age	Depositional environment	Thickness
n.d.	Atinah[1, 2]	Quaternary	Continental	n.d.
Fars	Taqa, Fars clastics and evaporites[3, 4, 5]	Oligocene to Pliocene	Continental to shallow marine	~1400 m
Dhofar	n.d.[5]	Late Eocene to earliest Miocene	Shelf, slope (south Oman)	n.d.
Hadramaut	Umm er Radhuma, Rus, Dammam, Andhur, Qitabit, Aydim[6, 7]	Palaeocene to Late Eocene	Shallow marine, sabhka, continental	~750 m
Aruma	Simsima, Fiqa[8, 9, 10]	Lower Senonian to Maastrichtian	Marine	~1550 m
Wasia	Nahr Umr, Natih[11, 12, 13, 14]	Late Aptian to earliest Turonian	Shallow marine to intertidal	~540 m
Kahmah	Shuaiba, Rayda, Salil, Habshan, Lekhwair, Kharaib, Hanifa, Jubaila[15, 16, 17]	Berriasian to Early Aptian	Marine	~1820 m
Sahtan	Mafraq, Dhruma, Tuwaiq[4, 18]	Rhaetian to Kimmeridgian	Continental to marine	~530 m
Akhdar	Khuff, Sudair, Jilh[19, 20, 21]	Late Permian to Rhaetian	Marginal marine	~1350 m
Haushi	Al Khlata, Gharif[23, 24, 25, 26]	Late Westphalian to Artinskian	Glaciogenic, continental, shallow marine	~1250 m

[1] Chevrel et al. (1992), [2] Burns & Matter (1995), [3] Kashfi (1980), [4] Hughes Clarke (1988), [5] Roger et al. (1991), [6] Platel & Berthiaux (1992), [7] Alsharhan & Nairn (1995), [8] Rabu et al. (1990), [9] Skelton, Nolan & Scott (1990), [10] Schumann (1995), [11] Harris et al. (1984), [12] Wagner (1990), [13] van Buchem et al. (1996), [14] Immenhauser et al. (1999), [15] Litsey et al. (1986), [16] Moshier et al. (1988), [17] Scott, Frost & Shafer (1988), [18] Pratt & Smewing (1990), [19] Kashfi (1980), [20] Abu-Risheh & Al-Hinai (1989), [21] Alsharhan & Nairn (1994), [22] Le Métour et al. (1995), [23] De la Grandville (1982), [24] Levell, Braakman & Rutten (1988), [25] Mercadier & Livera (1993), [26] Guit, Al-Lawati & Nederlof (1994). n.d. = no data.

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Table 2. The Batain Group

Formation	Stratigraphic age	Depositional environment and facies	Lithostratigraphic equivalent in Hawasina
Qarari	Lower to Upper Permian	Toe-of-slope/hemipelagic limestones	None?
Al Jil	Upper Permian to Upper Liassic	Periplatform slope/reworked platform deposits and olistostromes	Al Jil Fm of Hamrat Duru Grp and Sayfam Fm of Al Aridh Grp
Matbat	Scythian to Norian	Slope/turbidites and basinal sediments	Matbat Fm of Hamrat Duru Grp
Guwayza	Lower Jurassic to Lower Oxfordian	Slope/oolitic turbidites and quartz sandstones	Guwayza Fm of Hamrat Duru Grp
Ruwaydah	Mid-Jurassic to lowermost Cretaceous	Seamount/igneous rocks, arenitic limestones, radiolarites, coarse limestone breccias	Buwaydah Fm of Al Aridh Grp
Wahrah	Oxfordian to Santonian	Basinal setting/radiolarites	Wahrah Fm of the Hamrat Duru Grp
Fayah	Coniacian to Maastrichtian	Foreland basin/gravity flows	None (Aruma Grp)

After Immenhauser et al. (1998)

Table 3. The eastern ophiolites of Oman

Ophiolite	Formation age	Obduction age	Surface area above sea level (km^2)
Masirah Island ophiolites	Latest Jurassic to earliest Cretaceous	Maastrichtian-Palaeocene transition	~600
Ra's Madrekah ophiolite	Unknown, probably as Masirah	Maastrichtian-Palaeocene transition	~3–4
Ra's Jibsch ophiolite	Unknown, probably as Masirah	Probably as Masirah	~1–2
Batain ophiolites	Unknown	Probably as Batain Group	Several fragments from hundreds of m^2 to several km^2

After Gnos, Immenhauser & Peters (1997)

The basal thrust of the nappes is only exposed east of the Jebel Ja'alan, where allochthonous units of the Batain Group are thrust on top of autochthonous Maastrichtian sediments covering the Proterozoic basement. North of the Jebel Ja'alan, the basal thrust is hidden beneath Palaeogene and Neogene cover sediments, whereas south of the Jebel Ja'alan, it is covered by the Quaternary Wahiba Sands (Fig. 1).

2.d. Upper Jurassic/Lower Cretaceous eastern ophiolites

The eastern ophiolites of Oman (Gnos, Immenhauser & Peters, 1997) extend over 600 km in north–south extension from latitudes 17° to 22.5° (Fig. 1, Table 3). Most of the three (at least) major nappe sheets are covered by Palaeocene to Recent deposits, but were recognized in offshore seismic lines (Petroleum Development Oman, unpub. report, 1987). Nevertheless, two of the ophiolite nappes are well exposed on Masirah Island, and probably one nappe is present at Ra's Madrekah (Gnos, Immenhauser & Peters, 1997). The age and geo-tectonic relation of the small peridotite occurrences at Ra's Jibsch, and of those scattered across the Batain plain, are not sufficiently well understood (Table 3). Palaeomagnetic data suggest that the oceanic lithosphere of the lower Masirah nappe formed at latitudes 38° ± 12° S around 150 Ma (Tithonian; Harland *et al.* 1990; Gnos & Perrin, 1996) during the active break-up of Gondwana (Fig. 2b). Nevertheless, due to petrographic similarities, we assume that the other eastern ophiolites formed in the same setting. Detailed studies on the ophiolitic fragments along the northeastern Oman margin are given by Moseley & Abbotts (1979), Smewing *et al.* (1991), Marquer, Peters & Gnos (1995), Peters *et al.* (1995), Gnos & Perrin (1996), Immenhauser *et al.* (1996), Gnos, Immenhauser & Peters (1997), Meyer, Mercolli & Immenhauser (1997), Peters & Mercolli (1997, 1998), Marquer, Mercolli & Peters (1998) and others.

The stacking of ophiolite nappes resulted from intra-oceanic thrusting in the Maastrichtian, and was subsequently followed in latest Maastrichtian/Early Palaeogene time (Marquer, Peters & Gnos, 1995; Marquer, Mercolli & Peters, 1998) by the thrusting of the eastern ophiolites on top of the Batain nappes and the subsequent oblique obduction onto the northeastern Oman continental margin (Fig. 2d; Gnos, Immenhauser & Peters, 1997; Schreurs & Immenhauser, 1999).

2.e. Neo-autochtonous Palaeocene to Pliocene sediments

Upper Palaeocene to Pliocene sedimentary rocks unconformably overlie the Batain nappes and the eastern ophiolites along the northeastern Oman margin, and represent a neo-autochthonous sedimentary cover, the deposition of which post-dates ophiolite obduction. This Tertiary cover consists of three stratigraphic groups: the Palaeocene to Eocene Hadhramaut Group, the Upper Eocene to lowermost Mid-Miocene Dhofar Group, and the upper Lower Miocene to Pliocene Fars Group. A detailed description is given by Wyns *et al.* (1992). The Tertiary sedimentary rocks have only

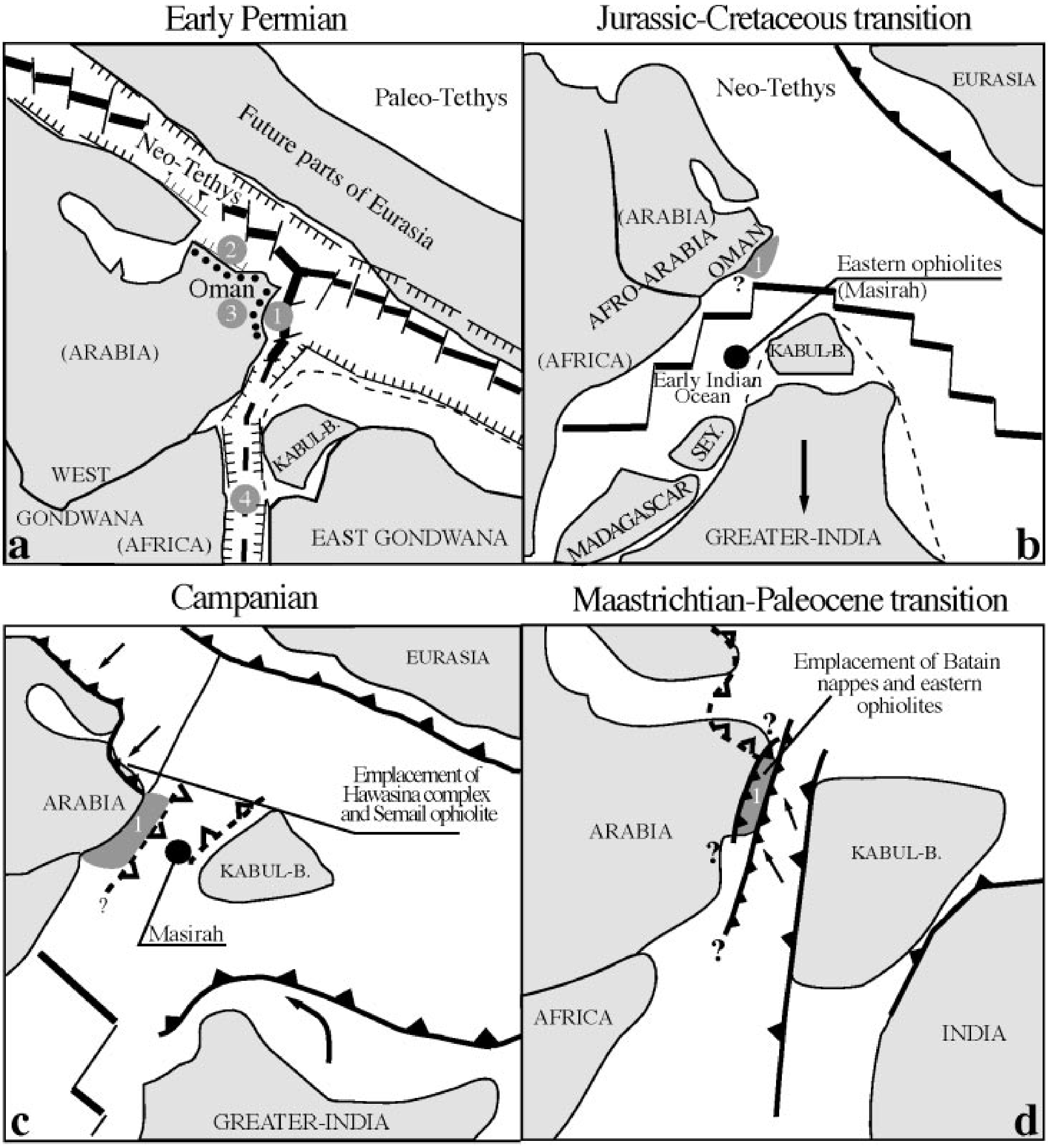

Figure 2. Schematic palaeogeographic reconstructions. (a) The Early Permian opening of the Batain basin (1) forming part of the early Indian Ocean, and of the Neo-Tethyan Hamrat Duru (Hawasina) basin (2); the interior Oman Basin (3); the Karoo rift (4). (b) The Late Jurassic break-up of east and west Gondwana and the formation of oceanic lithosphere (the future eastern ophiolites of northeastern Oman). (c) The Campanian shortening between Eurasia and Arabia, resulting in the obduction of the Hawasina complex and the Semail ophiolite. (d) The shortening at the Maastrichtian–Palaeocene transition between the Kabul Block, India–Arabia, resulting in the thrusting of the Batain nappes and the eastern ophiolites onto the northeastern Oman margin. The position and significance of the Kabul Block is poorly understood. Figure 2a is modified after Stampfli *et al.* (1991) and Baud *et al.* (1993).

undergone post-emplacement deformation, caused by the Red Sea–Gulf of Aden rifting, and the Late Miocene collision of Arabia with Eurasia (Fig. 3).

The Tertiary (possibly Neogene) extension produced north-northeast–south-southwest-striking normal faults in the eastern part of the Huqf–Haushi high (Beauchamp *et al.* 1995), and reactivated Mesozoic faults, causing further uplift and tilting of the Huqf–Haushi high and the Jebel Ja'alan block (Beauchamp *et al.* 1995). To the northeast of this high, the Abat trough formed during the Tertiary, and possibly represents the northerly extension of the Masirah–Batain graben system (Fig. 1).

Late Miocene shortening resulted in oblique inversion of faults that limit the Jebel Ja'alan/Huqf–Haushi tectonic high (Beauchamp *et al.* 1995; Le Métour *et al.* 1995; D. Carbon, unpub. Ph.D. thesis, Univ. Montpellier, 1996). This shortening event also

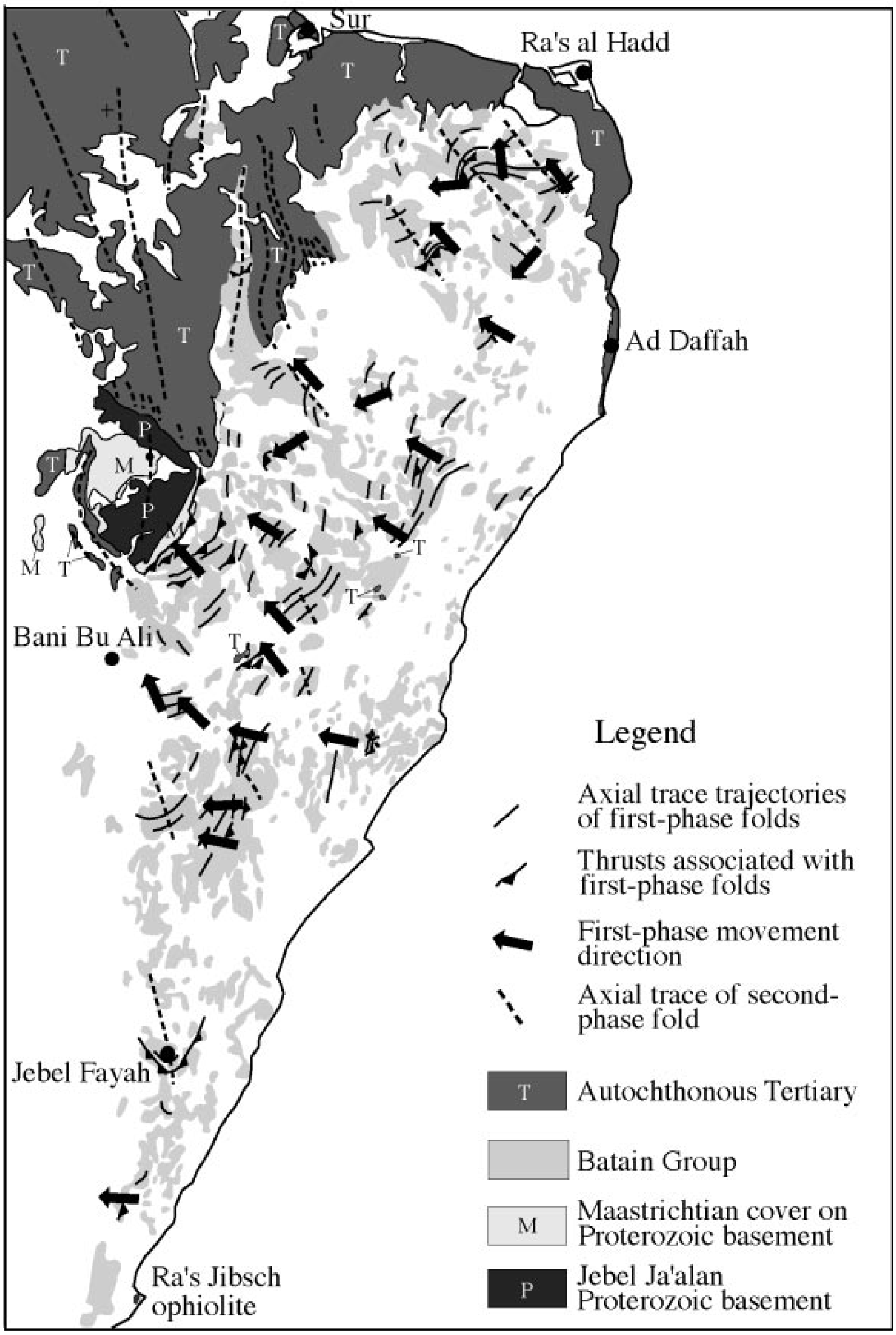

Figure 3. Schematic structural map showing axial trace trajectories of the obduction-related F^1 folds, associated thrusts and tectonic transport directions.

produced mostly open north-northwest–south-south-east to north–south-trending folds along the eastern Oman margin (Le Métour *et al.* 1995; Schreurs & Immenhauser, 1999).

3. Geodynamic evolution

3.a. Late Carboniferous to Late Cretaceous: rifting and drifting

At the end of the Palaeozoic, Oman was part of Gondwana, the southern half of the Pangea megacontinent (Figs 2, 4; e.g. Scotese & McKerrow, 1990; Dercourt, Ricou & Vrielmyck, 1993). Gondwana was bordered on the north and east by the Palaeo-Tethys and on the west by Panthalassa. A thick highland ice sheet (erosion valleys) covered eastern Oman in the Late Carboniferous to the Early Permian (Belushi, Glennie & Williams, 1996). Evidence for this glaciation is found in the tillites of the Al Khlata Formation (Haushi Group) of the Huqf–Haushi area (Table 1, Fig. 4; Braakman *et al.* 1982; De la Grandville, 1982; Levell, Braakman & Ruiten, 1988; Hughes Clarke, 1988).

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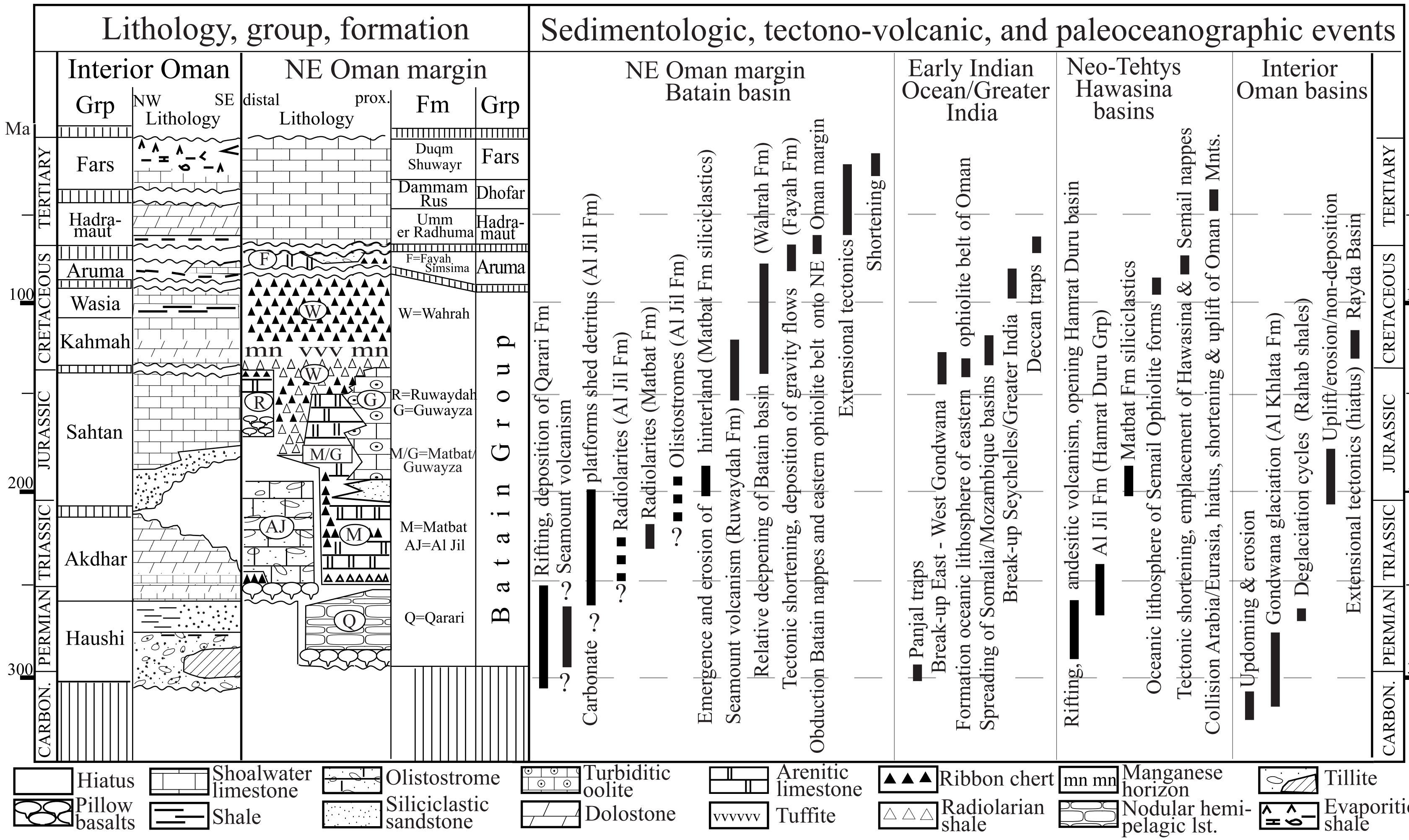

Figure 4. Lithostratigraphy of the interior Oman basin and the Batain Group. Major sedimentologic, tectono-volcanic and palaeoceanographic events in the Batain and Hawasina basins, the early Indian Ocean, Greater India and interior Oman basin. Q, Qarari Formation; AJ, Al Jil Formation; M, Matbat Formation; M/G, Matbat/Guwayza formations; R, Ruwaydah Formation; G, Guwayza Formation; W, Wahrah Formation; F, Fayah Simsima Formation.

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The Gondwana glaciation was followed by a climatic warming in the Sakmarian, resulting in deposition of lacustrine deposits in eastern Oman (Rahab shales). The first rift system developed between the northern domains of east Gondwana and eastern Oman (part of Afro-Arabia), and the second one separated Oman and future parts of Eurasia (Fig. 2a; Glennie *et al.* 1974, 1990; Béchennec, 1987; Baud *et al.* 1993). For reference purposes, we term the rift between Oman and east Gondwana as 'the early Indian Ocean' or 'the eastern Oman rift system', and the rift between Oman and Eurasia as 'the Neo-Tethys' or 'the northern Oman rift system'. These two rift branches possibly form part of a larger system related to a Permo-Carboniferous triple junction situated off northeast Oman, with the third rift branch separating Eurasia from Greater India (Fig. 2a). With time, the northern Oman rift system evolved in the Neo-Tethys, and the eastern Oman rift system in part of the early Indian Ocean (e.g. Stampfli, Marcoux & Baud, 1991; Le Métour *et al.* 1995; Pillevuit, 1993; Pillevuit *et al.* 1997; Belushi, Glennie & Williams, 1996).

Several lines of evidence for an eastern Oman rift system that separated Oman and India (part of east Gondwana) from Late Palaeozoic time onwards are found:

(1) Deeply incised Gondwana glacial valleys along the eastern Oman margin. These are indicative of rift shoulder uplift in this region (Belushi, Glennie & Williams, 1996).

(2) The shedding of coarse-grained siliciclastic rocks at the break between the middle and upper Gharif Formation in the Artinskian of interior Oman. This sudden change in facies is indicative of a pronounced change in topography, such as basement uplift (i.e. at a rift shoulder). The source area of the coarse-grained siliciclastic rocks, and therefore the rift shoulder itself, was most likely the present-day Huqf–Haushi axis. This area may have been a rift shoulder due to an Infra-Cambrian rift pulse (Najd rifting; Guit, Al-Lawati & Nederlof, 1994; Loosveld, Bell & Terken, 1996; B. Hartmann, unpub. Ph.D. thesis, Univ. Bern, 1996). The latest Carboniferous to Early Permian updoming in eastern Oman was most likely related to the eastern Oman rift system, and is difficult to reconcile with the almost perpendicular-trending northern Oman rift system (Fig. 4).

(3) The extrusion of the Panjal Traps of Northern India in Artinskian time. These trap basalts are normally viewed as related to a hotspot (Papritz & Rey, 1989). The hotspot may have initiated the eastern Oman rift system (Figs 4, 5).

(4) The Lower Permian to uppermost Cretaceous sedimentary and volcanic rocks of the Batain Group (Immenhauser *et al.* 1998), emplaced in a west-northwestward direction onto the Arabian continental margin at the Cretaceous–Palaeogene transition (Schreurs & Immenhauser, 1999), are firm evidence for a Permian to Late Cretaceous basin along the northeastern Oman margin. The Early to Late Permian age of the first marine deposits in the Batain basin (Qarari Formation, Table 2) overlaps in time with the Artinskian rift event.

Following rifting, interior Oman became an intracratonic rim basin (South Oman and Ghaba salt basin) *sensu* Veevers (1982).

Incursion of Late Permian sea over metamorphosed basement or Palaeozoic sediments is also known from northwest Pakistan–Afghanistan (part of east Gondwana; e.g. Kaever, 1967; Kazmi & Jan, 1997). In Oman, rift shoulder uplift and concomitant sea-level rise influenced the deposition of the Sakmarian to Artinskian shallow-marine and fluviatile Gharif sediments (Haushi Group) within this rim basin. Gharif sediments thin out towards the northeast, and are absent in the present-day Oman Mountain area that has been interpreted as an emerged land due to uplift related to the initial rift phase of the Hamrat Duru basin (Blendinger, Van Vliet & Hughes Clarke, 1990); i.e. rifting in the north (the northern Oman rift system) started later.

A widespread global rise in sea level in the Late Artinskian, combined with thermal subsidence of both of the rift shoulders, submerged first northern and then eastern Oman, and led to the deposition of the predominantly carbonatic Akhdar Group (Kungurian; Table 1; Alsharhan, 1993) in the interior Oman basin. Outcrops of the Khuff Formation (Table 1) document this transgressive event along the western flank of the Huqf–Haushi high.

By mid-Permian time, a large carbonate platform (Saiq and Khuff formations) was established over most of Oman, and bordered the seaways along northern Oman (Murris, 1980; Blendinger, Furnish & Glenister, 1992) and eastern Oman (Al Jil Formation of Immenhauser *et al*. 1998). The southern and western hinterland (parts of present-day Yemen and Saudi Arabia) were still emergent, and provided the source for clastic material (Khuff Red Beds; Murris, 1980). Along the northeastern Oman margin, both the Permian lower slope to basinal facies of the Qarari Formation and the detritus shed from now-buried Permo-Triassic platforms are found (Al Jil Formation, Immenhauser *et al.* 1998).

The nature of the original substratum of the now-allochthonous rocks of the Batain Group is not well known. Some pillow basalts are found at the base of the Al Jil Formation. In the proximal domains of the Batain basin, Al Jil platforms topped fault-block highs, while further seawards, coeval carbonate platforms probably grew on seamounts (Pillevuit, 1993; Immenhauser *et al.* 1998), similar to the 'exotics' in the eastern Hamrat Duru basin (Stampfli, Marcoux & Baud, 1991; Le Métour *et al.* 1995; Pillevuit *et al.* 1997). Exposures of the Al Jil Formation are commonly found in stratigraphic contact near or atop

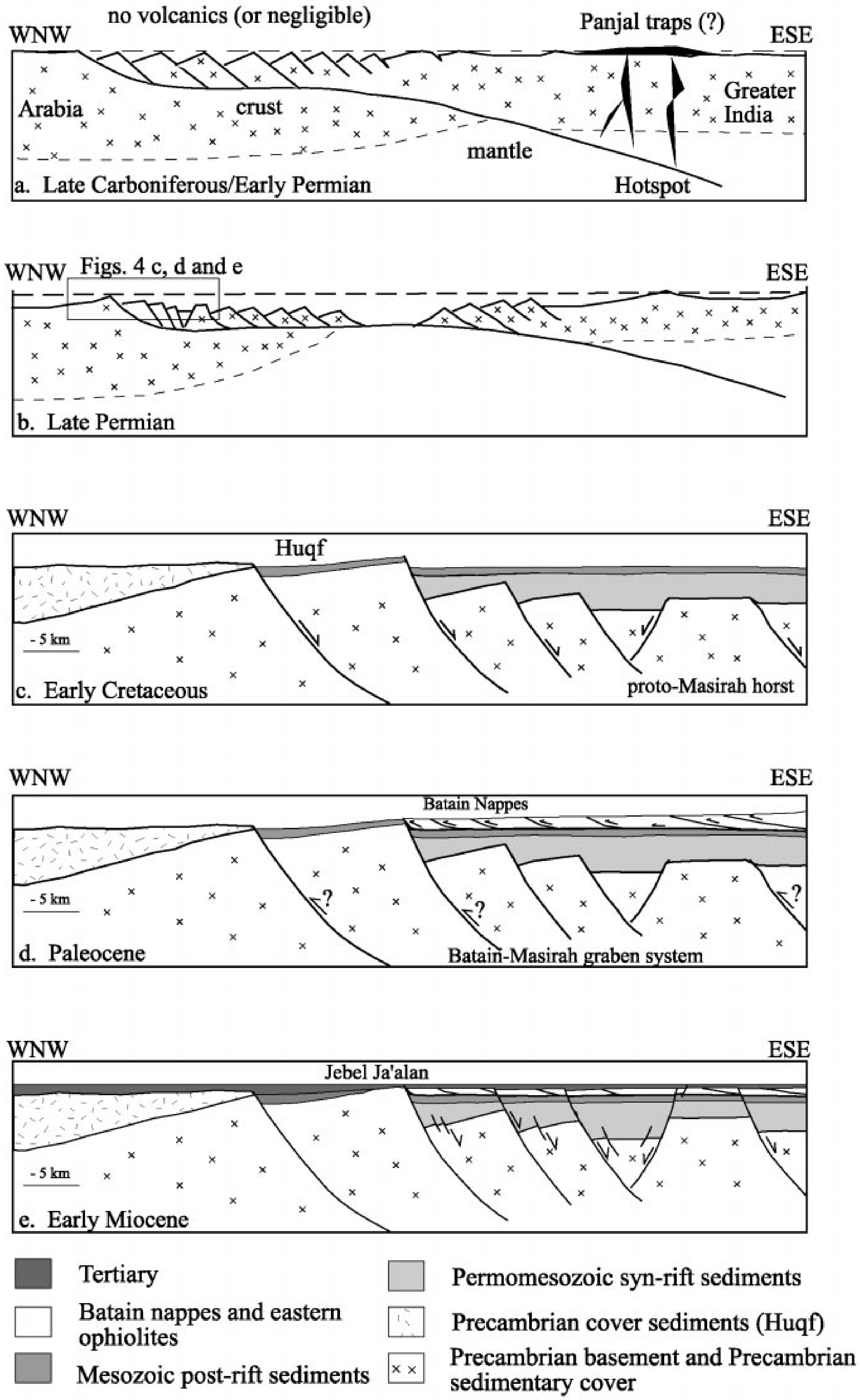

Figure 5. Schematic west-northwest–east-southeast cross-sections, showing the inferred evolution of the northeastern Oman margin. In part after Beauchamp *et al.* (1995).

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strongly tectonized, hydrothermally overprinted serpentinites and ophicalcites (i.e. brecciated and veined, silicified or serpentinized peridotites). The co-existence may be evidence of a Permo-Triassic exposure of subcontinental mantle at the base of the Batain basin (Fig. 4b).

Permian and Triassic carbonate detritus of the Al Jil Formation (Batain Group; Table 2) was shed from different shallow-marine sources (Shackleton *et al.* 1990; Pillevuit, 1993). All carbonate platforms that shed their detritus into the Batain basin (Al Jil Formation) declined in the Late Triassic to Early Jurassic (Immenhauser *et al.* 1998).

In the Triassic, hot and arid conditions favoured semi-evaporitic sedimentation on the Arabian Platform, and deposition in the basins along Oman's margins was reduced (Glennie *et al.* 1974; Murris, 1980; Béchennec, 1987).

Large-scale tectonic reorganization occurred at the end of the Triassic, as shown by reactivation of structural highs (Murris, 1980), and widespread formation of unconformites/disconformities in the interior Oman basin. Redeposition of large Permian to Triassic shoalwater carbonate blocks in early Carnian and locally Upper Liassic radiolarites express basement instabilities and shelf collapse.

On the east Gondwana side of the rift in Pakistan, shallow-marine sedimentation occurred as far south as the present central Indus basin (Jones, 1960).

Ladinian/Carnian radiolarites and siliceous shales from the base of the Matbat Formation in the Batain basin are coeval with radiolarite deposition in the Hawasina basin (Table 2; Bernoulli, Weissert & Blome, 1990). In the early to mid-Norian, siliceous sedimentation in the Matbat Formation gave way to a primarily carbonate facies in the Batain basin containing abundant pelagic bivalves. This facies change is also observed in the Matbat Formation of the Hawasina basin, and was explained with a sea-level highstand (Haq, Hardenbol & Vail, 1988). Bernoulli, Weissert & Blome (1990) interpreted this change in facies as a regional palaeoceanographic event in the Hawasina basin, and not due to fluctuations of the global calcite compensation depth.

Emergence and erosion of the Huqf–Haushi high and regression of the sea (Murris, 1980; Haq, Hardenbol & Vail, 1988) is reflected by deposition of latest Triassic to Early Jurassic continental detritus in the Matbat Formation of the Batain basin and clastic sedimentation in the interior Oman basin.

In the Bathonian, the northern and eastern Oman shelf were flooded once again and high-energy carbonate platforms with ooid shoals were established (Murris, 1980). These high-energy platforms provide the source for oolitic turbidites and conglomerates of the Guwayza Formation, found in the proximal domains of the Batain and Hawasina basins (Fig. 4; Immenhauser *et al.* 1998).

In the beginning of the Late Jurassic, the break-up of east and west Gondwana took place (Fig. 2b; ~157 Ma, Oxfordian, anomaly M25; Ricou, 1994; Salman & Abdula, 1995; Gnos, Immenhauser & Peters, 1997). The formation of the Masirah oceanic crust, dated as late Tithonian (Beurrier, 1987; Le Metour *et al.* 1992; Immenhauser, 1996), is related to this event (Fig. 3b). Palaeomagnetic evidence shows that parts of Masirah, and probably all of the oceanic lithosphere of the eastern ophiolites of Oman, formed at southern latitudes of 38° ± 12° S (Fig. 2b; Gnos & Perrin, 1996; Gnos, Immenhauser & Peters, 1997), whereas Arabia was situated near the equator (i.e. much further north).

Late Jurassic/Early Cretaceous sedimentation in the Batain and Hawasina basins also reflects the break-up between east and west Gondwana (Fig. 5). Extensional sagging is recorded in the Hawasina basin during late Tithonian/Berriasian time (Béchennec *et al.* 1990). The edge of the northern continental margin of Arabia was drowned, and the shoreline subsequently retreated about 250 km southwestwards (Rabu, 1987; Le Métour *et al.* 1995). A marked hiatus at the Jurassic–Cretaceous boundary of the Huqf–Haushi area and the interior Oman basin (Fig. 4) is considered to be the result of extensional tectonics (Loosveld, Bell & Terken, 1996). In northeastern Oman, an eastward onlap of Early Cretaceous shallow-marine carbonates of the Kahmah Group (Fig. 3, Table 1) is observed (although less pronounced than that of the Early Jurassic; Petroleum Development Oman, unpub. report, 1987).

East–west sedimentation differences due to shoulder uplift also became strongly accentuated on the east Gondwana side (Pakistan) in the Late Jurassic. This is marked by the erosion of Middle to Upper Jurassic strata along the western margin, covered with a Lower Cretaceous transgression conglomerate, and followed by shallow-marine carbonates (Jones, 1960).

The retreat of the shoreline and local uplift of the continental margin (Le Métour *et al.* 1995) shut down carbonate platform production, reduced the bicarbonate influx into the basin, and siliceous radiolarites of the Wahrah Formation became predominant both in the Batain basin (Immenhauser *et al.* 1998) and the Hawasina basin (e.g. Béchennec *et al.* 1990). The development of radiolarian cherts at the Jurassic–Cretaceous transition represents an important relative *rise* in calcite compensation depth, and a drowning of the distal Arabian carbonate platform in the Batain and Hawasina (Sidr Chert) basins (Fig. 4). This contrasts with a widespread *lowering* of calcite compensation depth and the shift from radiolarites to Maiolica-type coccolith limestones in the Alpine Tethys–central Atlantic domain. Radiolarites along the Oman margins reflect a deep basinal setting (± 300 m; Petroleum Development Oman, unpub. report, 1987) and a palaeoceanographic regime different from the central Atlantic or the western Tethys (Bernoulli & Jenkyns, 1974).

Seamount fragments of the Middle to Upper Jurassic Ruwaydah Formation, Oxfordian to Berriasian/Valanginian chert-hosted manganese deposits, and Upper Jurassic layers of volcanic ash in the Wahrah Formation document a renewed phase of volcanic activity in the Batain basin (Fig. 4; Immenhauser *et al.* 1998). Chert-hosted manganese horizons are also known from the Al Hammah Range in the eastern extremity of the Oman Mountains (Kickmaier & Peters, 1990). The Berriasian/Valanginian volcanism in the marginal basins of Oman is probably the local expression of volcanism associated with spreading in the Somalia and Mozambique basins (Sykes & Kidd, 1994).

By Hauterivian time, progradation of deep-water carbonates towards the north-northeast had progressed so far that the position of the Lower Jurassic platform margin was re-gained (Haan *et al.* 1990). From this time forward, until the advance of thrust sheets in the Late Turonian, shallow-platform carbonate deposition dominated.

3.b. Albian to Campanian: closure of the Hawasina basin and emplacement of the Hawasina nappes and the Semail ophiolite

With the separation of India–Seychelles from Madagascar at *c*. 100–84 Ma, the closure rate of the Neo-Tethys increased. Coeval northward drift of Afro-Arabia led to the obduction and emplacement of the Hawasina complex (also termed Hawasina nappes) and the Semail ophiolite forming today the Oman Mountains. The direction of the emplacement was to the south and southwest (Fig. 2c; Allemann & Peters, 1972; Glennie *et al.* 1974; Boudier *et al.* 1985; Glennie *et al.* 1990). A break in sedimentation and subaerial exposure marks the onset of closure of the Hawasina and Semail basins in northern Oman after the Early Turonian (Allemann & Peters, 1972; Glennie *et al.* 1974; Béchennec, 1987; van Buchem *et al.* 1996). The obduction caused the formation of a foreland basin (Boote, Mou & Waite, 1990). This is also suggested by the onset of diagenetic quartz cementation at *c*. 80 Ma in the Permo-Carboniferous Al Khlata Formation (Table 2), documented by burial and thermal history modelling and fluid inclusion studies (K. Juhász-Bodnár, unpub. Ph.D. thesis, Univ. Bern, 1999).

3.c. Senonian to Early Palaeocene: closure of the Batain basin and emplacement of the Batain nappes and the eastern ophiolites of Oman

Closure of the Batain basin occurred in the latest Maastrichtian–earliest Palaeocene. West-northwest-directed shortening along the northeastern Oman margin during the Senonian is conceivably related to the break-up between India and the Seychelles micro-continent and/or the collision of the Kabul block with the Indian Plate (Fig. 2d; Tapponnier *et al.* 1981; Gnos, Immenhauser & Peters, 1997). Associated doming of the Arabian Platform led to the emergence and the erosion of large parts of Oman (Le Métour *et al.* 1995). Autochthonous units, such as the Natih and the underlying Nahr Umr formations (Fig. 4, Table 1) were deeply eroded, cut by channels and locally removed along the axis of Jebel Ja'alan–Huqf (Le Métour *et al.* 1995). Subsurface data from the Lekhwair region of the interior Oman basin (Boote, Mou & Waite, 1990) indicate similarly deep-cutting erosion.

West-northwest-directed shortening led to the detachment of sedimentary and volcanic rocks in the Batain basin from a 'continental' sequence in the proximal domains and from an unknown substratum in the more distal domains (Petroleum Development Oman, unpub. data). These Batain nappes were subsequently thrust westwards onto the eastern Oman margin at the Cretaceous–Tertiary transition. In front of the advancing nappes, a submarine foreland basin, the Masirah–Batain graben system, formed that resulted from Mesozoic reactivation of a pre-existing tectonic feature (Fig. 5; Beauchamp *et al.* 1995). Radiolarites of Coniacian/Santonian age on Masirah Island (Dumitrica, Immenhauser & Dumitrica-Jud, 1997) and at the Jebel Qarari in the Batain area (Immenhauser *et al.* 1998) show that the Masirah–Batain graben remained underfilled until mid-Senonian time.

Emergence and erosion of the eastern Oman margin is documented by the onset of the siliciclastic sediments of the Fayah Formation shed into the Masirah–Batain graben (Fig. 6, Table 3). Senonian sedimentary rocks of the Fayah Formation form part of the Batain Group in the Batain area, and are present on Masirah Island and on the Ra's Madrekah ophiolite (Gnos, Immenhauser & Peters, 1997). Thick successions of Fayah sandstone and shale were drilled in offshore wells (Sawquirah Bay-1), in contrast to Masirah Bay (Masirah Bay-1), where only a thin sequence is present (Fig. 1; Petroleum Development Oman, unpub. report, 1987).

The first influx of Fayah Formation gravity flows in the Batain region and onto the Masirah ophiolite is dated as Coniacian (Turonian?), and spans the entire Senonian up to the latest Maastrichtian (Shackleton *et al.* 1990; A. Immenhauser, unpub. Ph.D. thesis, Univ. Bern, 1995). Palaeocurrent data (current marks and ripples) indicate two main directions of sediment transport (Fig. 6). Gravity flows with mainly continental siliciclastic debris exposed along the Batain coast were shed towards the east and northeast, into the foreland basin. There is no evidence along the northeast Oman margin for a southward sediment transport from northern bulges related to the emplacement of the Hawasina complex or the Semail ophiolite. Conversely, gravity flows of the Fayah Formation,

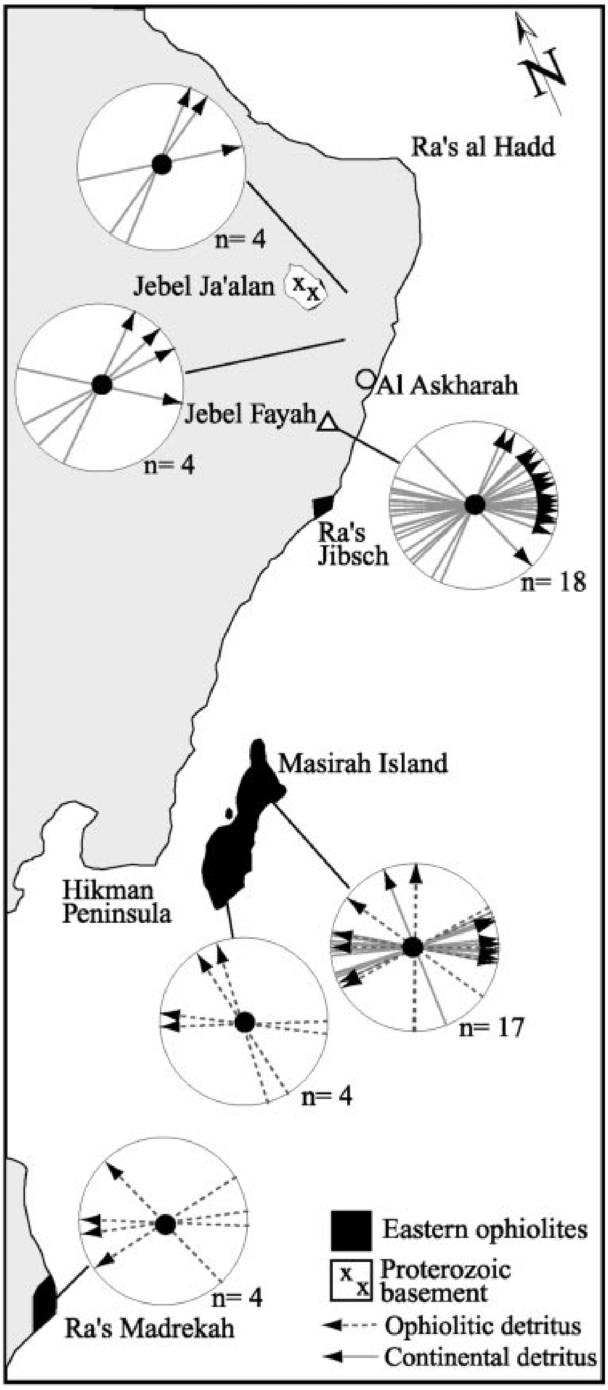

Figure 6. Overview map showing the transport directions of the Senonian Fayah Formation, as inferred from current marks and ripples.

with predominantly ophiolitic detritus, were shed from the advancing eastern ophiolites westwards and northwestwards. On Masirah Island, both continental and oceanic detritus and both transport directions are found (Fig. 6).

Metre-sized boulders of granites and gneisses derived from the continental basement of Oman glided downslope onto the lower Masirah ophiolite nappes (Peters *et al.* 1995). Pebbles of reworked granites and rhyolites in the Fayah Formation of the Batain plain, however, do not exceed a few decimetres in size. The scarcity and small size of reworked basement pebbles in the Fayah sandstone south to southeast of the Jebel Ja'alan high, suggest that during the Senonian, this region was not a major area of clastic provenance. A thick cover succession of Maastrichtian rudist limestones (Simsima Formation; Béchennec *et al.* 1992) exposed on the western slope of the Jebel Ja'alan (Fig. 1), indicates that this area remained submerged during the Late Cretaceous.

Tectonic activity related to nappe thrusting along Oman's northeast margin is diachronous. In the case of the Masirah ophiolites, final emplacement onto the continental margin occurred during or after the latest Maastrichtian, as all pre-Tertiary sedimentary rocks are affected by contractional, emplacement-related folding and thrusting. Post-nappe Palaeocene/Eocene deposits only record post-Early Oligocene extensional tectonics (Marquer, Peters & Gnos, 1995; Peters *et al.* 1995; Immenhauser, 1996) and in the Batain area also weak to moderate northeast–southwest to east–west oriented contractional deformation (Figs 3, 4).

In the Batain area, the Tertiary sequence unconformably overlies the thrust wedge southeast of Masirah Island (offshore). Eocene sediments are seen on seismic lines either to be involved in thrusting or to be overridden by the Batain nappes (Petroleum Development Oman, unpub. report, 1987). This late thrusting is possibly related to the obduction of ophiolites onto the Indian plate (Gnos *et al.* 1998), where the youngest sediments involved are also Lower to Middle Eocene.

Biostratigraphic and structural evidence from Ra's Madrekah (Fig. 1, Table 3; Gnos, Immenhauser & Peters, 1997) and the Batain region, bracket ophiolite emplacement between the Late Maastrichtian and the Early Palaeocene. The tight folding and associated thrusting during west-northwest-directed obduction-related deformation affected all allochthonous units, including Upper Maastrichtian Fayah sedimentary rocks (Schreurs & Immenhauser, 1999).

As the intensely deformed Fayah sedimentary rocks are unconformably overlain by neo-autochthonous Palaeogene–Miocene sedimentary rocks, timing of obduction must be at the Cretaceous–Palaeogene transition. Ophiolite obduction along the northeastern margin thus occurred ~15–20 m.y. after the obduction of the Semail ophiolite. Sedimentation was not continuous in northern Oman during that time. In the interior Oman basin, pore-fluid dilution by meteoric water during quartz cementation occurred on a regional scale at *c.* 68–58 Ma (K. Juhász-Bodnár, unpub. Ph.D. thesis, Univ. Bern, 1999), and was probably triggered by emplacement-related fault reactivation.

Evidence for a major southwest-directed 'eoalpine' deformation phase along the northeastern Oman margin, as postulated by Shackleton & Ries (1990) and Béchennec *et al.* (1992), is lacking. Although Shackleton *et al.* (1990) suggested the presence of struc-

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tures preceding emplacement-related thrusting and folding, Schreurs & Immenhauser (1999) showed that these structures can be explained as the result of the Tertiary folding of emplacement-related deformation.

The superposition of two contractional and an intervening extensional event on an already-complex palaeotectonic situation in the Batain area resulted locally in apparently irregular, disjointed and chaotic structures, especially in areas where continuous outcrop is lacking. Nevertheless, detailed mapping showed that there is far more structural coherence in the Batain area than previously believed (Fig. 3), and we consider the term 'Batain Melange', such as introduced by Shackleton *et al.* (1990) no more appropriate.

Late Maastrichtian sedimentation of the Fayah Formation is represented by the deposition of large blocks of Triassic, Jurassic and Cretaceous sedimentary rocks on Masirah Island (Immenhauser, 1996), and by olistostrome deposits in the Batain area (Wyns *et al.* 1992). Both on Masirah Island and along the Batain plain, these blocks are in stratigraphic contact with deep-water red clays, with few radiolarian tests, and locally with marls with calcareous nannoplankton. On Masirah Island, some of the marls have been dated as Late Maastrichtian on the basis of coccolith assemblages (Immenhauser, 1996; von Salis & Immenhauser, 1997). Olistostromes in the Batain area are embedded in coarse-grained siliciclastic sandstones with a calcareous matrix. Nevertheless, this facies association (olistostromes and red deep-water clays) is found exclusively in the Late Maastrichtian Fayah Formation, and cannot be compared with the sedimentary setting of the other Batain Group formations.

Slope deposits of the Masirah–Batain graben systems have been identified in the Duqm area (Platel *et al.* 1992) and on the eastern flank of the Huqf–Haushi uplift (Dubreuilh *et al.* 1992). Upper Danian basinal marls and mudstones of the Mahdi Formation grade vertically and laterally into the Mid-Thanetian to Lower Ypressian Sirab Formation. The Sirab Formation comprises slope deposits characterized by mixed turbiditic and debris flow deposits with olistoliths of shelf limestone (Le Métour *et al.* 1995). These might be the youngest known sediments deposited during the final stage of nappe emplacement.

3.d. Palaeogene/Neogene: post-nappe emplacement structural evolution

The Tertiary evolution of the northeastern Oman margin is complex. Major tectonic events, post-dating nappe thrusting, contributed to the present-day geological setting.

Extensional intraplate deformation reflects the Red Sea/Gulf of Aden opening (Fig. 4; Hempton, 1987; Platel & Roger, 1989). East–west-running seismic lines off northeast Oman document uplift and tilting in an extensional regime during Early Neogene time. This is indicated by tilted turbidite strata of Oligocene (and younger) age, unconformably overlain by downlapping post-Lower Miocene pelagic units with numerous slumps off northeast Oman (Shipbord Scientific Party, 1989).

Shortening related to the collision of Arabia with Eurasia (Hempton, 1987; Mann, Hanna & Nolan, 1990; Le Métour *et al.* 1995) is reflected in the overprinting of emplacement-related structures (Fig. 4). This Tertiary shortening is pronounced in the north of the Batain area, and its intensity seems to decrease towards its southern parts.

Tertiary contractional tectonism reactivated and overprinted pre-existing north-northeast–south-southwest-oriented structures in northeastern Oman (underlying the allochthonous units). These structures might have a Late Precambrian origin (Fig. 1; Beauchamp *et al.* 1995).

Rifting and progressive opening of the Gulf of Aden constitutes the major plate tectonic event during the Late Eocene–Early Miocene period of the eastern Oman margin (Beydoun, 1982; Platel & Roger, 1989; Le Métour *et al.* 1995). The intrusion of Upper Eocene tholeiitic olivine basalt dykes in the south of the Batain area (37–44 Ma; A. C. Ries, unpub. data) is considered to be the result of a phase of reactivation of older structures in eastern Oman. This is also documented by syntectonic deposition of basinal sediments in north-northeast–south-southwest-trending graben structures since the Palaeocene, and locally by erosion, non-deposition or sedimentation of shallow-marine to continental successions on the associated horsts.

Masirah Island and Ra's Madrekah (Fig. 1) are presently situated on a horst (Beauchamp *et al.* 1995; Loosveld, Bell & Terken, 1996). The earliest post-emplacement deposits on the Masirah ophiolites are uppermost Maastrichtian to Lower Eocene laterites (A. Briner, unpub. Diploma thesis, Univ. Bern, 1994; D. Stucki, unpub. Diploma thesis, Univ. Bern, 1994; Peters *et al.* 1995). The overlying Eocene/Oligocene deposits reflect a shallow-marine setting (Peters *et al.* 1995). Two phases of post-Early Oligocene directed extension are documented in the Tertiary cover of Masirah Island (Marquer, Peters & Gnos, 1995; A. Immenhauser, unpub. Ph.D. thesis, Univ. Bern, 1995). The first one is north–south and the second one is east–west oriented. Rocks older than Upper Eocene to Lower Miocene (Platel *et al.* 1992) are absent on the Ra's Madrekah ophiolite, suggesting an uplifted position comparable to that of Masirah Island.

A graben structure is recognized beneath the Sawquirah and the Masirah bays to the southwest of Masirah Island (Fig. 1; Beauchamp *et al.* 1995). Thick sequences of ophiolite detritus and deep-water gravity flows (Fayah Formation; Figs 4, 6) form the basin fill documenting a period of continued subsidence associated with the emplacement and uplift of the ophiolites

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(Petroleum Development Oman, unpub. report, 1987). The northeastern continuation of this structure is visible on seismic lines and on depth maps of the magnetic basement (Loosveld, Bell & Terken, 1996) in the Batain coast area. We suggest that the Abat trough of Wyns *et al.* (1992) in the Sur area is linked to this graben (Fig. 1).

The Masirah–Batain graben is filled in the north with about 1.5 km of Late Cretaceous emplacement-related sediments and stacked imbricates forming part of the Batain fold-and-thrust belt. These thrust units cover a thick sequence of autochthonous units (Fig. 1; Beauchamp *et al.* 1995). Towards the west, the allochthonous units pinch out against the fault-bounded Huqf–Haushi/Jebel Ja'alan horst (Fig. 1; Beauchamp *et al.* 1995).

Post-emplacement extensional structures were also observed on outcrop scale in the Batain area. Here, normal faults cut across folds and thrusts of the Batain nappes, and affect the overlying Tertiary cover. The extensional structures are refolded by large-scale folds that also deform Lower Miocene sediments. Retrodeformation of Miocene folding gives a north-northeast–south-southwest trend for a dominant set of conjugate normal faults.

The Huqf–Haushi/Jebel Ja'alan/Qalhat axis forms a structural high (Ries & Shackleton, 1990; Filbrandt, Nolan & Ries, 1990; Loosveld, Bell & Terken, 1996) that is probably the foreland bulge caused by the obduction of the eastern ophiolites. The relative uplift of the Jebel Ja'alan is dated post-Middle Eocene (Filbrandt, Nolan & Ries, 1990). Uplift of this domain during the Tertiary is complementary to the subsidence of the Ghaba Salt basin (interior Oman basin; cf. Loosveld, Bell & Terken, 1996) to the west, and the Masirah–Batain graben to the east (Ries & Shackleton, 1990), and is probably related to extension.

Since the Early Miocene (Burdigalian), shortening in northern and eastern Oman is generally considered to be a result of the collision of Arabia with the Eurasian Plate (Hempton, 1987; Glennie *et al.* 1990; Wyns *et al.* 1992; Le Métour *et al.* 1995; D. Carbon, unpub. Ph.D. thesis, Univ. Montpellier, 1996). This event created the present-day Oman Mountain chain (Le Métour *et al.* 1995) and the Zagros fold belt in Iran.

The Palaeocene to Mid-Miocene sedimentary cover of the Batain nappes displays north–south and northwest–southeast-trending open folds, reflecting Miocene northeast–southwest-oriented shortening (Wyns *et al.* 1992). The lateral changes in the orientation of the Miocene folds in the Batain area are possibly controlled by major pre-existing structural trends such as the Masirah graben (Fig. 1).

4. Summary

The latest Carboniferous to Early Permian break-up of Gondwana affected the northern and eastern margins of Oman, and led to the opening of two basins: first, the early Indian Ocean–Batain basin to the east, separating eastern Oman from northern east Gondwana; and second, the Neo-Tethyan Hawasina basin separating northern Arabia and future parts of Eurasia.

The latest Carboniferous/Early Permian Oman rift shoulder of the Batain basin was located in the present-day Huqf–Haushi area, and its detritus is found in the interior Oman basin. Remnants of the Batain basin, the Lower Permian to uppermost Maastrichtian sedimentary and volcanic rocks, are exposed in the Batain area (Batain Group). During the middle Cretaceous, sea floor drifted northwards as part of the Indian Plate. Fragments of this oceanic lithosphere (eastern ophiolites) and the sedimentary rocks of the Batain basin (Batain Group) were juxtaposed during Maastrichtian time, and were subsequently thrust onto the eastern edge of Arabia (eastern ophiolites and Batain nappes).

Emplacement along Oman's northeast margin occurred about 15–20 m.y. later than the obduction of the Semail ophiolite and the Hawasina complex in northern Oman.

Early Tertiary extensional tectonism, conceivably related to rift and drift of the Gulf of Aden, was followed by Late Miocene shortening, associated with the collision of Arabia and Eurasia. Both events affected the allochthonous units along the northeastern Oman margin and their neo-autochthonous Tertiary cover.

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