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Structure and sequence of thrusting in deep-water sediments during ophiolite emplacement in the south-central Oman Mountains

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Abstract—Sedimentological and stratigraphical investigations of the deep-water passive margin sediments of the Oman Neo-Tethys (the 'Hawasina Ocean'), when allied with structural relationships between duplexes of these units emplaced on to the Oman margin during late Cretaceous ophiolite obduction, allow the reconstruction of sediment distribution in the Hawasina Ocean. From this starting point, and the observed stacking order of duplexes, the sequence of thrusting of the oceanic sediments can be deduced. Imbrication proceeded through foreland-propagating thrusts, whilst the assembled thrust stack was modified at a late stage of emplacement by out-of-sequence thrusting related to sequential locking of thrust planes towards the hinterland, and gravity sliding off the flanks of a major anticline that developed in the underlying autochthonous shelf and basement. Two main factors governed duplex and imbricate fan formation and distribution. Firstly, two contrasting sedimentary basins were present along the central Oman margin, the 'Duru basin' distal to the 'Al Ayn basin'. Secondly, competent sedimentary successions were bulldozed ahead of the Semail Ophiolite, whilst less competent shale and chert units were overridden by the ophiolite or imbricated along its leading edge.

INTRODUCTION

AREAS that preserve large volumes of deep-water passive margin sediments emplaced on to a continental margin during ophiolite obduction are rare and usually suffered complete ocean closure following emplacement. The attendant dismembering and structural restacking rarely allows detailed reconstruction of the initial sequence of thrusting in the sub-ophiolitic oceanic sediments. Thus, for example, in the Zagros of Iran (Stocklin 1974) and the Ladakh Himalaya, NW India (Fuchs 1979, Thakur 1981, Searle 1983), Neo-Tethyan passive margin sediments are confined to narrow, 10–20 km wide, highly complex suture zones with the apparent elimination of large volumes of sediment. This is illustrated, for example, by the absence of coarse-grained slope material from the Lamayuru Complex of Ladakh, which displays more distal characteristics (Fuchs 1979, author's observations). Whilst the dismembered eastern Mediterranean passive margin remnants of Othris, Greece (Price 1977, Johns 1978), Mamonia, Cyprus (Robertson & Woodcock 1979, Swarbrick 1979), and Antalya, Turkey (Robertson & Woodcock 1981), can be related to adjacent platform successions and schematic palinspastic reconstructions attempted, it has not yet been possible to determine the precise sequence of early thrusting within the deep-water sedimentary units.

The Oman Mountains (Fig. 1), almost uniquely, preserve a wide (50–180 km) belt of Neo-Tethyan (Hawasina Ocean) deep-water sediments that were emplaced during the late Cretaceous, with the vast Semail Ophiolite, on to a southern Neo-Tethyan carbonate margin (Glennie *et al.* 1973, 1974). Final ocean closure, however, has yet to occur and a remnant of Neo-Tethyan oceanic crust is being subducted at the present day beneath the Makran of Pakistan and SE Iran (White & Ross 1979). The structural complexities of the Oman Mountains thus largely reflect sequential thrust patterns related solely to sediment and ophiolite obduction. By integrating the sedimentology and stratigraphy of the superbly exposed passive margin successions with their present-day structural positions within the thrust

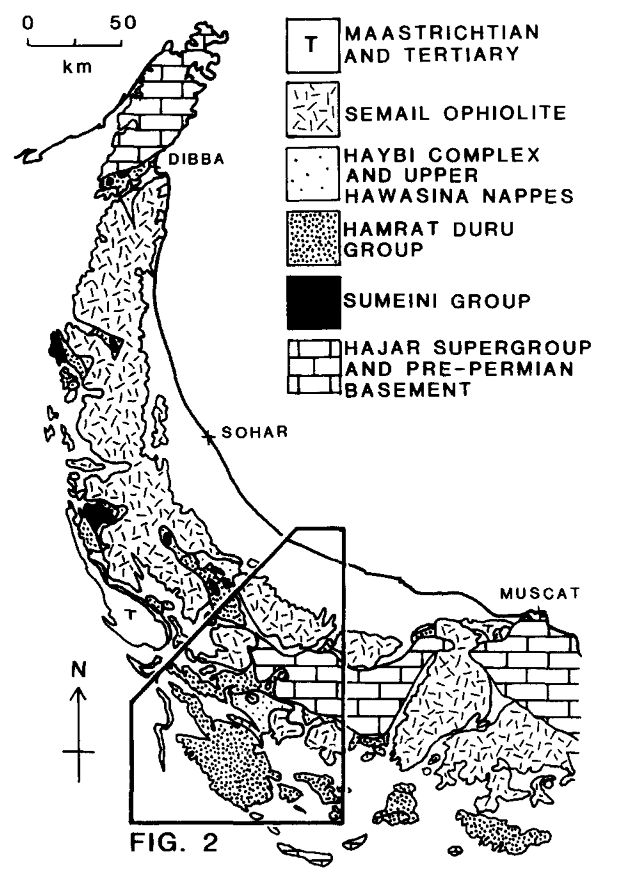

Fig. 1. Geological map of the Oman Mountains, modified slightly from Glennie *et al.* (1974).

stack, a pre-thrusting palaeogeography can be reconstructed (Cooper in press) from which detailed thrust sequences can be established. The thrust sequences are illustrated using a transect across the central Oman Mountains, where the most complex palaeogeography is developed.

STRATIGRAPHY OF THE OMAN MOUNTAINS

Following the major investigation of Glennie *et al.* (1973, 1974), with later modifications, the Oman Mountains have been subdivided into nine main components, namely a metamorphic basement unconformably overlain by a Permian to mid-Cretaceous shelf sequence which is itself overlain unconformably (and locally conformably) by the syn-tectonic sediments of the Aruma Group. The major allochthonous components are the Sumeini Group continental slope deposits, the Hawasina Complex continental rise and abyssal plain sediments, the Haybi Complex (Searle 1980) sedimentary and tectonic melanges, exotic limestones and volcanics, the Semail Ophiolite and its sedimentary cover, and the Batinah Complex (Robertson & Woodcock 1983). Maastrichtian and Tertiary shallow-water carbonates onlap these units and represent the cessation of the ophiolite emplacement event.

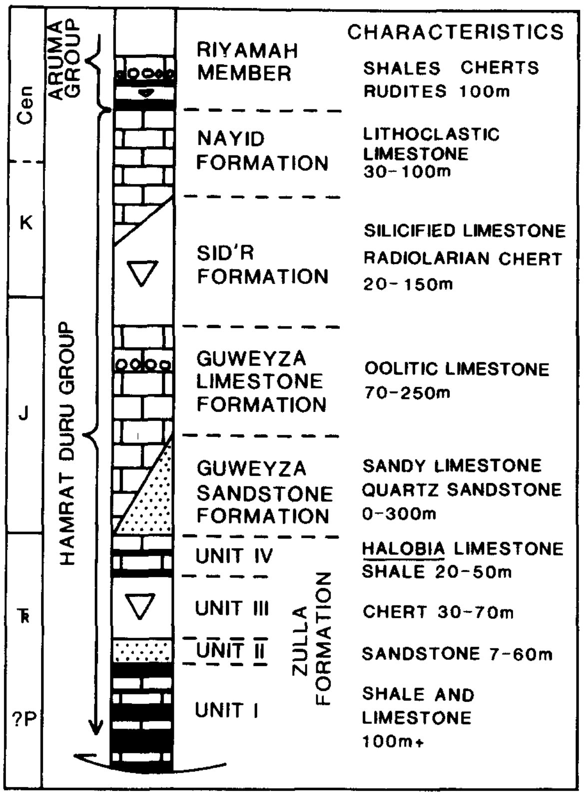

Fig. 2. Generalized stratigraphy of the Hamrat Duru Group.

Stratigraphy of the Hawasina Complex

The deep-water passive margin sediments of the Hawasina Complex crop out as a series of duplexes and imbricate fans ahead of, and in windows through, the Semail Ophiolite. The original tectono-stratigraphical nomenclature, erected by Glennie *et al.* (1974) has been rationalized by litho-stratigraphical correlation between duplexes (Cooper 1987). Coarse-grained units, rich in redeposited carbonates and clastics, are all placed within the Hamrat Duru Group (Fig. 2). The Halfa and Haliw Formations (chert-rich successions) and the Al Aridh and Ibra Formations (exotic limestone-rich successions) are retained, although exclusively Triassic components of the Halfa Formation represent, in part, the substrate of distal Hamrat Duru Group duplexes (Bernoulli & Weissert 1987).

Two distinct sedimentary sequences are noted within the south-central Oman Mountains transect. Sections rich in both coarse- and fine-grained clastic carbonate occur in the foreland imbricate fans of the Hamrat ad Duru and J. Wahrah, whilst in the Hawasina window and the W. Al Ayn area, sections contain considerably more shale and coarse-grained terrigenous material, most notably in the Zulla and Guweyza Sandstone Formations (Fig. 3).

STRUCTURE OF THE CENTRAL OMAN MOUNTAINS

The central Oman Mountains transect (Fig. 3) crosses all major structural units. Three units of the Hamrat Duru Group lie structurally above Aruma Group sediments in the SW foreland. These are named the Hamrat ad Duru imbricate fan (HDIF), the Wahrah imbricate fan (WIF) and the Al Ayn duplex (AAD), respectively, and are structurally overlain by imbricates of the Upper Hawasina nappes (Halfa and Al Aridh Formations), the Haybi Complex (melanges and 'Oman exotic' limestones) and the Semail Ophiolite. The autochthonous platform carbonates of the Hajar Supergroup are exposed in a window through the allochthon as a NW–SE-trending anticline. Discussion of the main structural features is based on a SW–NE transect of the mountains.

Hamrat ad Duru imbricate fan

Two cross-sections (HD1 and HD2) have been constructed parallel to the transport direction (NE–SW) through the Hamrat ad Duru (Fig. 4). Both structural sections can be broken into three distinct units. From the leading (SW) edge of the Hamrat ad Duru to the main watershed lying at the head of W. Zibra (HD1) and W. Futayhah (HD2), thrusting is subordinate to SW-facing asymmetrical folding. Widely-spaced thrusts cut fold forelimbs with displacements that rarely exceed 100 m and pass laterally into thrust-cored antiforms that plunge away from the exposed fault surfaces. Minor out-of-syncline thrusting is developed in the relatively incompetent Nayid Formation. The intensity of thrusting decreases towards the leading edge of the imbricate fan, where gently folded silicified limestones of the Sid'r Formation lie tectonically over dismembered siliceous lime-mudstones, marls and rudist-bearing patch-reef

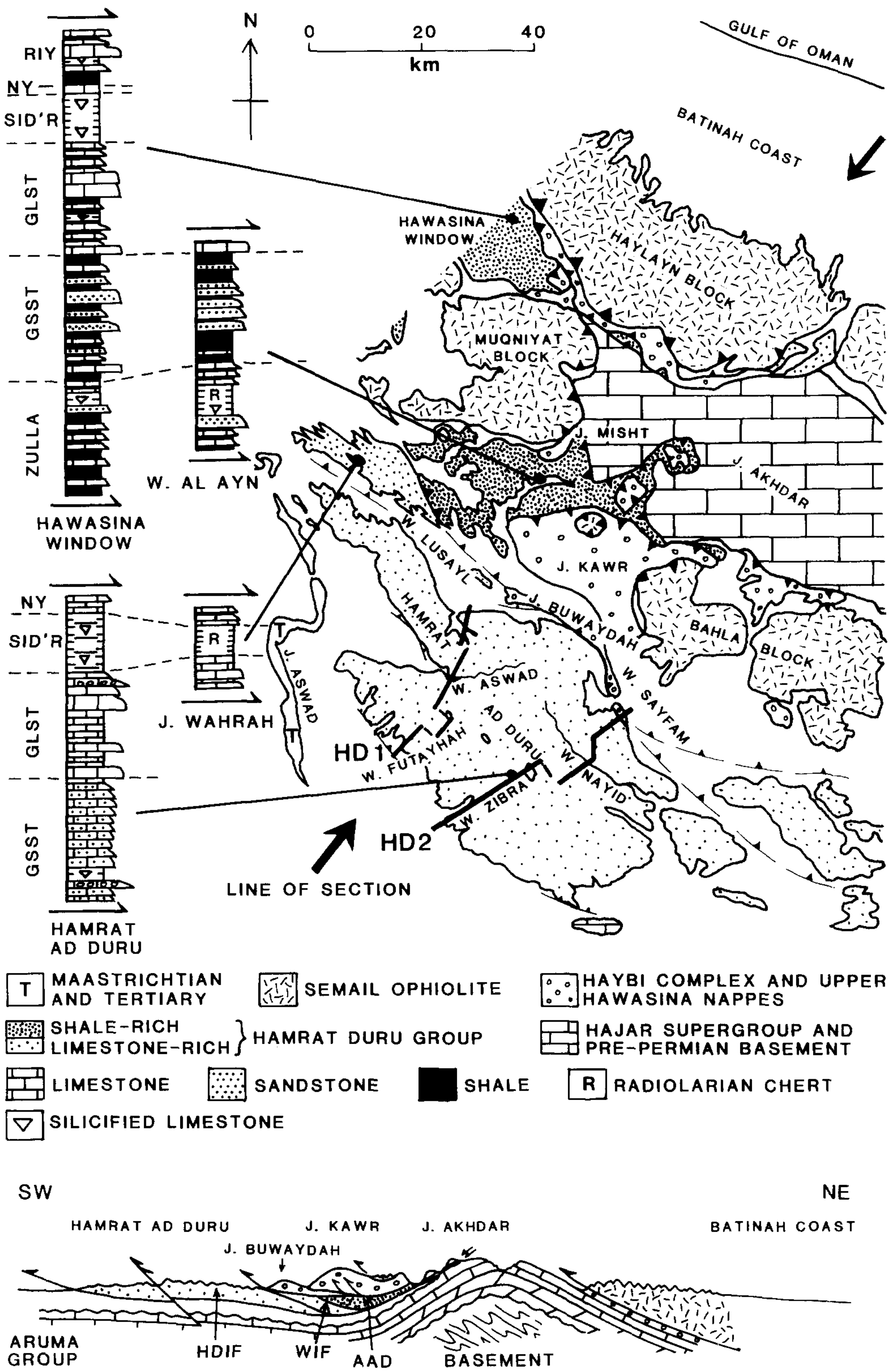

Fig. 3. Geological map of the southern central Oman Mountains, modified slightly from Glennie *et al.* (1974), and cross-section (3× vertical exaggeration), modified from Glennie *et al.* (1974) and Searle (1985). Stratigraphical logs illustrate the distribution of the two main sequences of the Hamrat Duru Group, with greater terrigenous input in the Hawasina window and W. Al Ayn areas, and predominantly clastic carbonate input in the Hamrat ad Duru and J. Wahrah areas. GSST—Guweyza Sandstone Formation; GLST—Guweyza Limestone Formation; NY—Nayid Formation; RIY—Riyamah Member, Muti Formation.

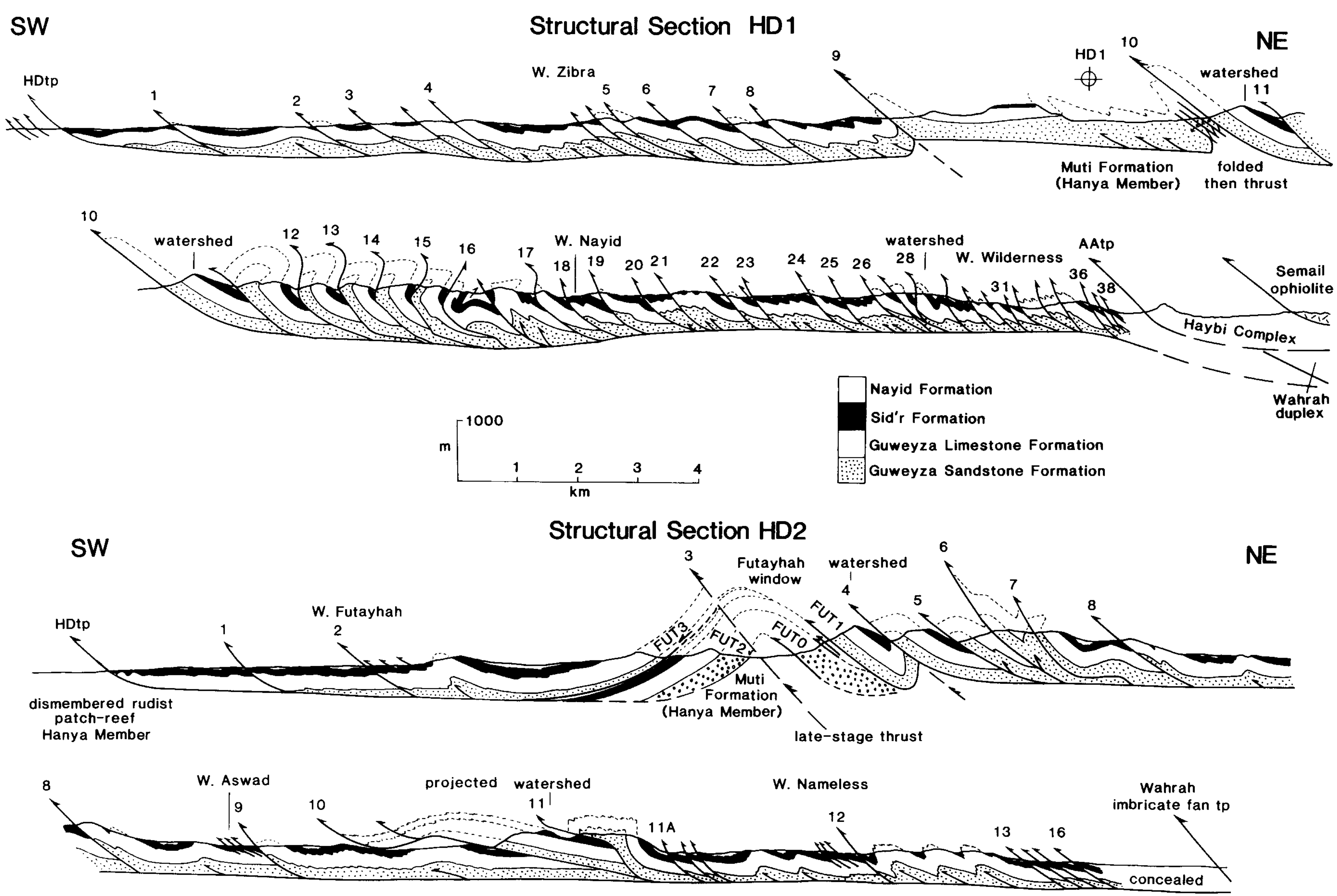

Fig. 4. Structural sections through the Hamrat ad Duru imbricate fan (HDIF) (see Fig. 3 for their location); surface geology is constrained by almost 100% exposure. The position of the Hamrat Duru sole thrust (HDtp) is constrained by exposures along the leading (SW) margin of the imbricate fan, at the head of W. Zibra (well HD1) along section HD1, and by outcrop of the Aruma Group in the Futayhah window along section HD2. Elsewhere its position has been estimated by balancing of the cross-sections.

limestones of the Aruma Group (Cooper 1986, Robertson 1987a).

The northern terminations of both W. Zibra (HD1) and W. Futayhah (HD2) are wide valleys, bounded on their NE sides by a major watershed-forming ridge. In W. Zibra, this valley is floored by folded quartz-bearing grainstones assigned to the Guweyza Sandstone Formation. Green marls assigned to the Aruma Group have been locally intercalated along thrust planes. Incorporation of footwall rock along Hamrat ad Duru thrust planes is also well-developed along the SW margin of the arm of the Hamrat ad Duru to the north of W. Aswad. Along the NE side of this valley, closely-spaced imbricated lozenges of limestone conglomerates and siliceous lime-mudstones are all inverted, representing the multiply imbricated upper limb of an overturned synform in the footwall of a major thrust surface (thrust 10, Fig. 4a).

The head of W. Futayhah contains a tectonic window (the Futayhah window, Fig. 4b) through the Hamrat ad Duru imbricate fan into the underlying marls, silicified marls and limestone conglomerates of the Aruma Group. The syn-orogenic sediments are cut by a steeply NE-dipping thrust that also penetrates the Hamrat Duru Group and is, therefore, a late-stage feature, postdating emplacement of the HDIF. The displacement along this thrust is small—only a few 10s of metres—increasing to about 300 m 3 km to the NW.

A consequence of thrust-related folding is that two imbricates on the SW side of the Futayhah window dip towards the SW. Structural interpretation of this area hinges on stratigraphical comparisons between imbricates, most notably within the Guweyza Sandstone Formation. In the lower imbricates (FUT 0 and FUT 2, Fig. 4b), this formation contains coarse-grained quartz sandstones and limestone conglomerates, quite unlike the equivalent sections in the upper imbricates (FUT 1 and FUT 3, Fig. 4b) in which quartz silts are overlain by lime-mudstones. This suggests that the lower sequences must form part of a duplex of unknown dimensions that lies beneath the main HDIF. If the HDIF sole thrust is assumed to be approximately even, then the dimensions of this underlying duplex cannot be much greater than its exposed size. This is further supported by the apparent exposure of the trailing edge of the lower duplex on the NE side of the window, where only the lower stratigraphical units, up to the base of the Guweyza Limestone Formation, are seen. The differences in stratigraphy suggest that NE-directed back-thrusting was not responsible for this structure which is interpreted as a small imbricate of the Hamrat Duru Group that was detached from the leading edge of the HDIF and subsequently overridden.

The second structural zone lies between the main watershed at the top of W. Zibra and W. Futayhah and two wadis that cross the Hamrat ad Duru, W. Nayid and W. Aswad (Fig. 3). Between W. Zibra and W. Nayid (thrusts 10–18, Fig. 4a), imbricates are more closely spaced (600–1000 m) and form a series of hinterland NE-facing antiforms that are related to the back-steepening, folding and overturning of thrust surfaces resulting from successive footwall collapse and ramp development. Gravity-driven back-thrusting is occasionally seen in the inverted lower limbs, although displacements do not exceed 100 m.

Northeast-facing antiforms are also seen in the equivalent area along strike in HD2 (thrusts 4–8, Fig. 4b), although they are comparatively rare. Close-spaced thrusting is, however, well-developed, with displacements an order of magnitude greater than on the SW side of the Futayhah window.

The third zone along HD1 (W. Nayid to W. Sayfam, thrusts 19–38, Fig. 4a) shows increasingly close-spaced thrusting. Only the Guweyza Limestone, Sid'r and Nayid Formations are seen, although the Guweyza Sandstone Formation is presumed to be present and involved in thrusting at depth. The trailing edge of the HDIF is structurally overlain by imbricates of the Al Aridh Formation, although the contact is obscured by wadi gravel.

Along HD2, shortening between W. Aswad and W. Lusayl (thrusts 8–16, Fig. 4b) is accommodated by asymmetrical folding and large-scale overthrusting by suprajacent imbricates. Relative displacements may exceed 3 km (thrust 10, Fig. 4b). Major thrust surfaces have minor footwall splays (e.g. thrusts 9 and 12, Fig. 4b). Close-spaced thrusts, analogous to those developed in a similar position along HD1, are only seen close to the NE margin of the HDIF, near to where it is overthrust by the WIF, although again, this contact is obscured by wadi gravel.

Both structural sections have widths of 35 km and restore to a minimum of 52 km, implying a minimum average shortening of 33%. Shortening is not, however, evenly distributed and in the gently folded and thrust sequences along W. Zibra and W. Futayhah it is just 8–15%, climbing to 50% along the trailing edge of the HDIF. More local zones of higher shortening are superimposed on this general NE-directed increase in shortening, e.g. between thrusts 10 and 17 of section HD1 (55% shortening) and thrusts 9 and 11A of section HD2 (50% shortening).

Wahrah imbricate fan and Al Ayn duplex

The Wahrah imbricate fan (WIF) lies structurally above the trailing edge of the HDIF. Imbricates are composed of the Guweyza Limestone to Nayid Formation of the Hamrat Duru Group. Older lithologies are not exposed. There are close sedimentological and stratigraphical affinities with the HDIF, although the deep-water sequence is finer-grained and more distal in character. The stratigraphical succession is about 150 m thick, although thrust slices show some tectonic thickening due to minor internal thrusting and SW-facing asymmetrical folding.

Surface outcrop dips vary between 50° and vertical towards the NE with rare oversteepening producing steeply SW-dipping inverted beds. Imbricates are laterally continuous over distances that can exceed 10 km, producing parallel razor-backed ridges. These strike

035° at the SE end of the WIF near J. Buwaydah and curve gently towards 020° at the NW end, near Ibri.

The suprajacent Al Ayn duplex (AAD) lies along the trailing edge of the WIF and strikes obliquely to WIF trends, particularly towards the SE end, where imbricates of the WIF trend 035° and those of the AAD strike 060°. The dip of imbricates reflects their position in a SW-facing asymmetrical syncline resulting from the folding of the J. Akhdar Anticline in the Hajar Supergroup to the NE (Fig. 3). Thus, imbricates along the SW, leading edge of the AAD dip up to 70° towards the NE, whilst along the trailing edge of the AAD to the NE of J. Kawr, imbricates dip gently (up to about 30°) towards the SW. The sole thrust to the AAD lies on the WIF on the SW side, but on the NE side of the imbricate fan the AAD lies directly on autochthonous limestones of the Aruma Group and the Hajar Supergroup carbonate platform. No intervening thrust slices of HDIF or WIF lithologies are seen.

The AAD is quartz-sandstone and shale-rich, with only the Triassic to Mid-Jurassic (Zulla to lowest Guweyza Limestone Formation) sequence preserved. The sedimentary succession is, however, identical to that of the equivalent formations in the Hawasina window, where a complete succession of the Hamrat Duru Group extends up to the Cenomanian. The absence of upper stratigraphical levels implies that they have been tectonically removed along a mid-Jurassic detachment prior to imbrication of the AAD along a sole thrust in early Triassic sediments.

Upper Hawasina nappes and Haybi Complex

The Upper Hawasina nappes of the Halfa Formation (radiolarian cherts) and the Al Aridh Formation (cherts and exotic limestone conglomerates) crop out along the SW edge of the mountain-sized J. Kawr Oman exotic limestone, forming J. Buwaydah (Fig. 3). They are absent from the northern side, thus the trailing edges of these duplexes lie beneath J. Kawr. Elsewhere, around W. Al Ayn, isolated outcrops above the AAD are exclusively of smaller exotic limestone blocks and the Haybi Complex. The J. Kawr exotic itself is folded into a major SW-facing anticline–syncline pair with subordinate internal thrusting (Glennie *et al.* 1974) and a small klippe of the Semail Ophiolite is perched on top in the Sint Syncline. Again, the SW dip of the trailing edge of the exotic reflects the folding of the J. Akhdar Anticline.

Other blocks of the Semail Ophiolite lie to the east of J. Kawr (Bahla block), where its topographically depressed position reflects the lateral discontinuity of the exotic limestone, and to the NW of the W. Al Ayn exposures of the AAD (Muqniyat block), where again it is in a topographically low position against the J. Misht exotic. The Semail Ophiolite is absent in the intervening W. Al Ayn area (Fig. 3).

Hajar Supergroup and NE transect structure

The central Oman Mountains are dominated by the giant (2980 m) J. Akhdar Anticline, rooted in the autochthonous platform and pre-Permian basement units. This fold is slightly asymmetrical towards the SW, notably at the northern end of the J. Akhdar range where shelf carbonates plunge beneath the Hawasina Complex of the Hawasina window.

The sedimentary units of the Hawasina window are essentially identical to those of the AAD (Fig. 3), being shale and quartz-sand-rich. Both truncated Zulla and Guweyza Sandstone Formation, and complete Hamrat Duru Group successions are seen (Graham 1980, Searle & Cooper 1986).

The NE side of the anticline dips towards the NE at 20–40° and is separated from the Haylayn block of the Semail Ophiolite by a narrow belt of shales and Triassic cherts (D. Bernoulli personal communication 1983), then a melange zone of chert, shale, exotic limestone blocks and volcanics comprising the Habyi Complex. The Semail Ophiolite dips towards the NE and successively higher stratigraphical levels are encountered, from mantle peridotites to pillow lavas, before it becomes buried by Tertiary and recent sediments along the Batinah coast.

PRE-EMPLACEMENT CRETACEOUS CONFIGURATION

The palaeogeography of the Lower Cretaceous Arabian platform and Hawasina Ocean (Fig. 5) has been discussed elsewhere (Cooper in press). This section, therefore, summarizes the main lines of evidence that have been used to restore the Oman margin to its pre-ophiolite emplacement configuration.

In the southern Oman Mountains (Fig. 1), two main imbricate fans of Hamrat Duru Group lithologies are identified; the structurally lower, coarser-grained Hamrat ad Duru imbricate fan and a structurally higher, finer-grained Wahrah imbricate fan. Apart from the local restacking of these structural components (Cooper 1986, Barrette & Calon 1987), simple palinspastic restoration suggests that the structurally higher WIF lay distal to the HDIF. This arrangement is supported by palaeocurrent data (dominantly NW–NE directed), grain-size fining trends and increasingly distal sedimentary facies, from thick-bedded conglomerates and high density turbidite current deposits to thinner-bedded low-density distal turbidites in the structurally higher imbricates.

Shale-rich sections in the W. Al Ayn area can be matched with the stratigraphically identical, yet structurally low imbricates of the Hamrat Duru Group in the Hawasina window, 20 km to the NW (Fig. 3). Here, the succession rests directly on slope facies of the Sumeini Group and contains matrix-supported conglomerates of demonstrably proximal derivation; these debris flow deposits would have evolved into clast-supported sediments with continued transport (Naylor 1978). Palaeocurrent data from the Hawasina window and W. Al Ayn show NE-directed currents and a marked mar-

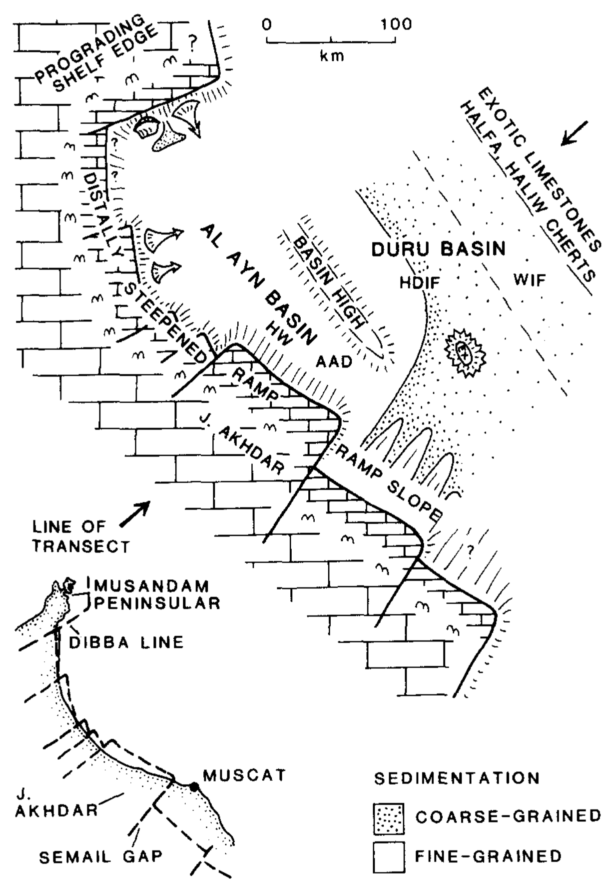

Fig. 5. Palaeogeographical reconstruction of the Hawasina Ocean for the Lower Cretaceous (Nayid Formation) showing the pre-ophiolite obduction location of the sediments of the Hawasina window (HW), W. Al Ayn duplex (AAD), Hamrat ad Duru imbricate fan (HDIF) and the Wahrah imbricate fan (WIF) (modified from Cooper in press). Inset shows the inferred relationship between the present day coast line and the Mesozoic Oman margin.

gin-parallel component, with both NW and SE palaeocurrents seen in individual localities. Rarely, SW-directed currents indicative of flow towards the margin are seen and interpreted as a product of the rebounding of turbidity currents from an intraoceanic submarine high. This high ponded sediment from the margin of the central Oman Mountains area, whose hinterland also acted as a source for the abundant terrigenous clastic material.

The predominantly carbonate successions of the HDIF and WIF were deposited in a basin area that lay towards the centre of Neo-Tethys relative to the AAD and Hawasina window units. Palaeocurrent directions and lateral facies variations both suggest that sediment for these imbricate fan areas was derived exclusively from the south with no source from the directly adjacent margin (i.e. across the presumed depocentre of the Hawasina window and W. Al Ayn units). The occurrence of rare, isolated cobbles of recrystallized shallow-water limestone, similar to the Oman exotics, within the Guweyza Sandstone Formation, and more abundant conglomeratic units in the Nayid Formation of the leading edge (SW) of the Hamrat ad Duru suggests that the Hawasina window–W. Al Ayn (Al Ayn) basin was separated from the Hamrat ad Duru–Wahrah (Duru) basin by a ridge that was capped by an intraoceanic carbonate platform. The later dismembering of this ridge during ophiolite obduction may have been the source of a component of the Oman exotics.

This intraoceanic ridge only appears to influence sedimentation in the central Oman Mountains and to the north all sedimentation reflects shale-rich Al Ayn basin patterns, whilst in the southeastern Oman Mountains, Duru basin sedimentation is observed.

Width of the Hawasina Ocean

The minimum widths of the main structural components of the Oman Mountains can be estimated by restoring cross-sections and applying approximate shortening values to structural units. Estimates produced by Glennie *et al.* (1974), Graham (1980) and Cooper (1986) are compared in Table 1. The considerable variation observed largely reflects differing interpretations of the extent of duplexes concealed beneath the Semail Ophiolite and, since the precise locations of the restored cross-sections of Glennie *et al.* (1974) and Graham (1980) are unknown, the measurements do not necessarily compare like with like.

It is, however, apparent that the *minimum* width of the Al Ayn basin was at least 100 km (Sumeini Group + AAD) and the Duru basin was at least 110 km

Table 1. Restored widths of the main units of the Hawasina Ocean, comparing data from Glennie *et al.* (1974), Graham (1980) and Cooper (1986). SH%—shortening. W_{min}—minimum restored width. W_{res}—minimum width including extrapolation of structural units. W_{max} maximum width

Unit		This study			Glennie *et al.* (1974, table 7.2)			Graham (1980, p. 220)	
		SH%	W_{min} (km)	W_{res} (km)	SH%	W_{min} (km)	W_{max} (km)	SH%	Original extent (km)
Sumeini Group	J. Rais–J. Mawq	50	30	40	50	20	80	33	21
	Hawasina window								
Hamrat Duru	HDIF–Hamrat ad Duru	33	50	80	66	150	315	24	55
Group	WIF–J. Wahrah	70	50	70	66	75	270	54	50
	AAD–W. Al Ayn	66	70	?80	66	135	195	50	53
Upper Hawasina	Halfa Formation*				66	60	210	60	69
nappes	Haliw Formation*				66	75	235	66	57
	Al Aridh Formation				50	40	160	50	14
	Ibra Formation				50	40	140	50	18
	Oman exotics				0	30	30	9	30

*May include substrate to the WIF.

wide (HDIF + WIF), with a further 245 km of more distal sediments in the Upper Hawasina nappes and the Haybi Complex (although it will be shown that a component of the Halfa Formation formed the substrate to the WIF). These values are absolute minima, and the true width of the Hawasina Ocean, including the Al Ayn–Duru basin ridge and sediment subducted or concealed beneath the Semail Ophiolite must have been considerably greater than the total 455 km estimated here.

SEQUENCE OF THRUSTING IN THE HAWASINA OCEAN

The initial closure of the Hawasina Ocean segment of Neo-Tethys was synchronous with a shift in the relative plate motion of Africa–Arabia with respect to Eurasia, from eastwards to northeastwards (Livermore & Smith 1984). This occurred 90–100 Ma ago and was probably coeval with a major opening phase in the South Atlantic. A product of this change in relative plate motion was the widespread generation of Cenomanian–Turonian ophiolites in the eastern Mediterranean (overview by Whitechurch *et al.* 1984, Troodos, Cyprus, Blome & Irwin 1985, the Zagros of Iran, Stocklin 1974, and the Semail Ophiolite in Oman, Glennie *et al.* 1974).

Robertson (1987a,b) concluded that the end of Mesozoic passive margin development and the onset of ophiolite obduction occurred in two phases. The first phase (Cenomanian–Turonian) consisted of uplift and erosion of the shelf edge as a result of initial crustal compression, producing massive debris flow deposits and glide blocks around the northern side of J. Akhdar (Robertson 1987a), the Ausaq conglomerate in the Dibba Zone (Searle *et al.* 1983) and megabreccias in the Sumeini Group (Watts & Garrison 1986). Flexure of the ocean crust may also have resulted in the creation of Cretaceous volcanic edifices, now preserved in the Haybi Complex (A. Robertson & A. Kemp, personal communication 1984).

The decrease in carbonate production during this emergent period, allied with the up-bowed shelf edge acting as a barrier to the off-margin transport of carbonate, resulted in the deposition of the cherts and shales of the Riyamah Member of the Muti formation (Fig. 2). Such sedimentation is restricted to the proximal parts of the Al Ayn and Duru basins. Their absence from more distal Duru basin localities may reflect the coeval initiation of imbrication in these latter units ahead of the Semail Ophiolite.

Thrusting in the Duru basin

Aside from the model of Allemann & Peters (1972), recent models of the emplacement of the Semail Ophiolite have all assumed NE-directed subduction of oceanic crust (e.g. Gealey 1977, Welland & Mitchell 1977, Graham 1980, Coleman 1981, Andrews-Speed & Brookfield 1983, Pearce *et al.* 1983, Lippard *et al.* 1986). Indeed, there is no evidence for major SW-directed subduction beneath the Oman margin.

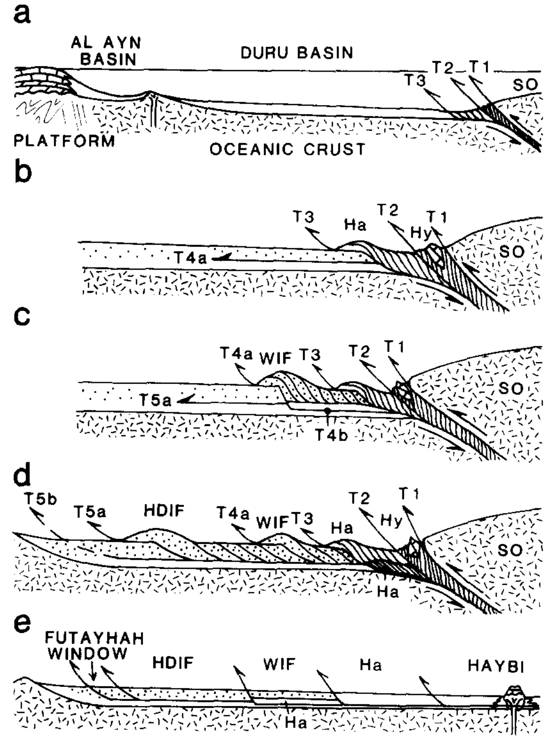

Fig. 6. Proposed sequence of thrusting of the Neo-Tethyan sediments of the Duru basin segment of the Hawasina Ocean. (a) Initial detachment of the Semail Ophiolite (thrust T1), imbrication of the Haybi Complex (Hy) as an accretionary wedge along the leading edge of the ophiolite (thrust T2) and imbrication of the Halfa and Haliw Formations (Ha) along thrust T3. (b) Detachment of the Wahrah imbricate fan along thrust T4a by ramping of the HDtp from Triassic to Mid-Jurassic levels. (c) Imbrication of the HDIF along thrust T5a, following detachment of the WIF substrate along thrust T4b to form a component of the Halfa Formation. (d) Detachment of the HDIF along an uppermost Triassic–lowermost Jurassic flat (T5a). Footwall collapse gives rise to the lower duplex of the HDIF of the Futayhah window (thrust T5b). The Halfa Formation substrate to the WIF is imbricated at the base of the Haybi Complex wedge. (e) Restored transect across the Duru basin showing the positions of the main structural units.

The destruction of the Hawasina Ocean started with the initiation of intraoceanic subduction. The subduction zone thrust, with the Semail Ophiolite in its hangingwall, is represented by T1 in Fig. 6. The most distal oceanic sediments were either subducted or partially accreted to the base of the ophiolite, along with detached and dismembered mountain-sized limestone-capped volcanic seamounts—the 'Oman exotics'. Debris flows in the trench ahead of the ophiolite generated sedimentary melanges (Graham 1980, Robertson 1987b). These components make up the Haybi Complex, bounded at its base by thrust T2 (Fig. 6a). Cherts and limestone conglomerates derived from the Oman exotics were either incorporated into the Haybi Complex or formed coherent thrust sheets that are preserved as the Al Aridh and Ibra Formations.

Décollement of the Upper Hawasina nappes of the Hawasina Complex (Halfa and Haliw Formations) proceeded along an approximately bedding-parallel sole thrust (T3, Fig. 6a) within pre-Carnian Triassic sediments. The basement to these distal sediments, probably oceanic crust, was subducted beneath the Semail Ophiolite.

The WIF was imbricated ahead of the Semail Ophiolite, following the ramping of the sole thrust of the Hamrat Duru Group (HDtp) into higher stratigraphical levels (thrust T4a, Fig. 6b). However, the HDtp must then apparently cut down-section between the WIF and the HDIF (to thrust T5a, Fig. 6c). It is located in the Middle Jurassic Guweyza Limestone Formation (Bathonian–Portlandian, Glennie *et al.* 1974) in the WIF (thrust T4a, Fig. 6), whilst, in the HDIF, it lies within Upper Triassic–Liassic Guweyza Sandstone lithologies (Glennie *et al.* 1974).

Whilst it is theoretically possible to account for such stratigraphical down-cutting, for example along the trailing edge of a surge zone (Fig. 7a & b), the regional palaeoslope must dip towards the subduction zone beneath the Semail Ophiolite, precluding the development of a thin-skinned surge zone in the sedimentary units directly ahead of the ophiolite.

Two possible alternative mechanisms exist to account for this phenomenon (Fig. 7c & d). Firstly, structural lowering of the WIF by normal faults could place the sole thrust at the required level to propagate into lower stratigraphical units. With this subsidence, up-section thrust propagation is thus possible into the structurally higher, yet stratigraphically older lithologies of the HDIF. The fault could also act as a line of weakness differentiating the two imbricate fans. However, it has

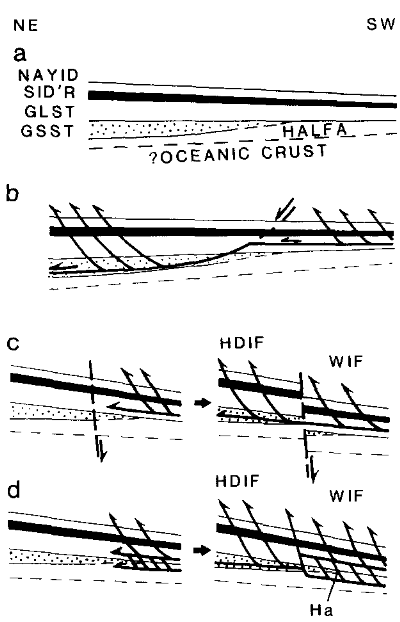

Fig. 7. Alternative models to account for the stratigraphical down-cutting of the HDtp between the WIF and the HDIF. (a) Pre-thrusting sedimentary configuration. (b) Surge zone model. A normal fault at the trailing edge of the surge zone brings the HDtp into stratigraphically lower sediments of the HDIF. Imbrication continues at the leading edge of the surge zone. (c) Normal fault model. Structural lowering of the WIF allows the propagation of the HDtp across a normal fault into stratigraphically lower sediments, with continued imbrication forming the HDIF. (d) Preferred model. The sole thrust of the WIF lies in the Guweyza Limestone Formation. The Halfa duplex (Ha) is imbricated along a stratigraphically lower thrust in Triassic sediments which cuts up-section to become the sole thrust of the HDIF.

earlier been suggested that the basement of the WIF was oceanic in character, and whilst it is still possible that major faults could have developed in this crust, this mechanism is not favoured.

The preferred mechanism is illustrated in Figs. 6(c) and 7(d). The HDtp is modelled as an extension of the Halfa sole thrust (T4b), which implies that exclusively Triassic to Lower Jurassic imbricates of the Halfa Formation must have been the substrate to the Wahrah imbricate fan, as originally suggested by D. Bernoulli (personal communication 1983). Initially, the sole thrust climbed a ramp and progressive footwall collapse along a Middle Jurassic flat (thrust T4a) created the WIF ahead of the Semail Ophiolite. An independent phase of footwall collapse in the Triassic–Lower Jurassic sequence along sole thrust T4b then created the Triassic–Lower Jurassic Halfa Formation successions. Finally this lower sole thrust climbed up section to the uppermost Triassic–Liassic base of the Guweyza Sandstone Formation to become the sole thrust to the HDIF. In this model, therefore, the HDIF and WIF have sole thrusts (HDtp) that represent two different thrust planes.

The HDIF developed along a plane within the Guweyza Sandstone Formation that shows notable uniformity of stratigraphical level along the length of the Hamrat ad Duru, although it demonstrably cuts up-section along the leading edge of the imbricate fan. This reflects two controls. Firstly, it may have been a response to the thinning of the stratigraphical section towards the intra-oceanic high that separated the Duru and Al Ayn basins. Secondly, the thick leading edge of the imbricate fan shows clear resistance to internal deformation and once a thrust penetrated to the surface (T5a, Fig. 6d) continued motion was accommodated along this plane rather than through renewed footwall collapse. Local footwall collapse and imbrication (thrust T5b, Fig. 6d) produced the structurally lower imbricate of the Futayhah window in the central Hamrat ad Duru. A sequence of limestone conglomerates, grainstones and partly silicified marls and lime-mudstones in the SW Hamrat ad Duru that appears, in part, to be a lateral equivalent of the Nayid Formation, has been interpreted by Warburton *et al.* (in press) as sediment generated by the cannibalization of Hamrat Duru Group sediments during the imbrication and translation of the HDIF.

The assembled stack of Hamrat ad Duru, Wahrah, Upper Hawasina and Haybi structural units was then emplaced over the subsided ridge that divided the Al Ayn and Duru basins. Permian or Triassic exotic limestones and Haybi volcanic blocks may also have originated from the tectonic erosion of this high, although direct evidence remains inconclusive.

Thrusting in the Al Ayn basin

The sediments of the Al Ayn basin (Fig. 5) are represented by the Al Ayn duplex (AAD) that lies structurally above the Wahrah imbricate fan and below the Upper Hawasina nappes (Al Aridh Formation) and

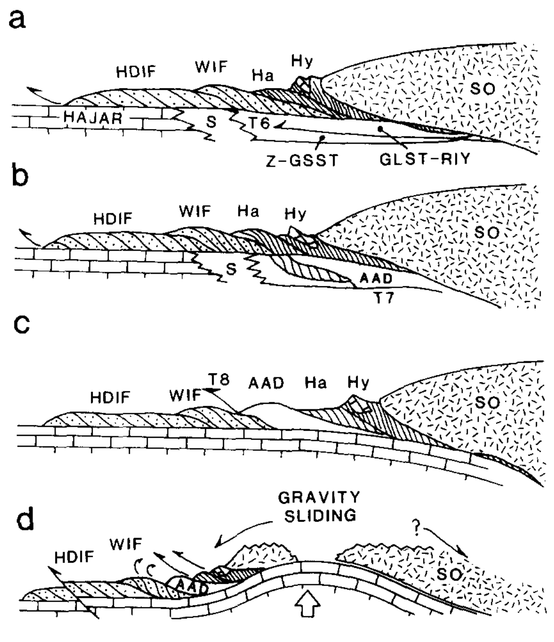

Fig. 8. Proposed sequence of thrusting in the Al Ayn basin area of the Hawasina Ocean. (a) Imbrication of the Guweyza Limestone Formation to Riyamah Member succession (GLST–RIY) of the Al Ayn basin along thrust T6 during overthrusting of the Semail Ophiolite. The Zulla and Guweyza Sandstone Formations (Z–GSST) are not affected. The HDIF and WIF are emplaced over the Sumeini Group slope deposits (S) on to the deeply-submerged platform and its syn-emplacement sedimentary cover (HAJAR). (b) Imbrication of the Zulla and Guweyza Sandstone Formation along thrust T7 to form the AAD. (c) Emplacement of the AAD over the trailing edge of the WIF by out-of-sequence thrusting along thrust T8. (d) Growth of the J. Akhdar anticline and associated gravity sliding of Hawasina sediments and blocks of the Semail Ophiolite down its flanks.

Haybi Complex (Fig. 3). Any model proposed to account for the sequence of thrusting in the Hawasina Ocean must not only consider this elevated structural position, but also the tectonic removal of the Middle Jurassic–Cretaceous successions of the Guweyza Limestone, Sid'r and Nayid Formations, all of which are present in the Hawasina window, 20 km to the NW (Fig. 3) (Graham 1980, Searle & Cooper 1986). The proposed sequence is illustrated in Fig. 8.

Initially, the upper stratigraphical levels of the Al Ayn basin were imbricated and transported towards the continental margin along a bedding-parallel décollement zone at the base of the Guweyza Limestone Formation (thrust T6, Fig. 8a). None of these units is exposed although, to the north in the Hawasina window, a duplex of Triassic–Lower Jurassic lithologies comparable to the Al Ayn duplex of W. Al Ayn is seen thrust over a complete Hamrat Duru stratigraphy (Searle & Cooper 1986), suggesting that the missing units were thrust over at least part of the unimbricated Al Ayn basin sedimentary succession. These units may form the Guweyza Limestone to Nayid Formation successions of the Hamrat Duru Group at W. Fatah, due west of the northern Hawasina window on the western edge of the Oman Mountains.

As emplacement of the Semail Ophiolite proceeded, progressive footwall collapse resulted in the imbrication of the underlying Zulla and Guweyza Sandstone Formations of the Al Ayn basin along a deeper sole thrust T7 (Fig. 8b). In the W. Al Ayn area, this thrust cut up-section behind the imbricated Jurassic–Cretaceous lithologies that originally formed their sedimentary cover, thus these units are not observed.

Final emplacement

Emplacement of the HDIF and WIF ahead of the Semail Ophiolite was followed by the emplacement of the AAD over the trailing edge of the WIF. This must have resulted from out-of-sequence thrusting since the palaeogeographical reconstruction places the AAD in a margin-proximal position with respect to the HDIF and WIF. It is suggested that, as the driving force for ophiolite obduction waned, the lowest thrust planes of the foreland imbricate fans became locked and motion of the thrust wedge was translated to successively higher thrusts. Late-stage overstep motion produced the truncation of structures within the Haybi Complex by the Semail Ophiolite sole thrust (Searle 1985) and may also account for the emplacement of the AAD obliquely over the WIF. There is, however, little evidence of overstep thrusting within individual imbricate fans and, for example, the truncation of thrusts and folds by later thrusts has not been observed.

The Upper Hawasina and Haybi thrusts of the J. Kawr area must post-date this out-of-sequence thrusting event as the sole thrust to the composite J. Buwaydah–J. Kawr Nappe is not displaced by the AAD sole thrust which passes beneath it at the western end of J. Buwaydah.

Late-stage motion on the J. Buwaydah–J. Kawr sole thrust may also reflect gravity sliding from the flanks of the J. Akhdar anticline (Fig. 8d), as originally proposed by Glennie *et al.* (1974). Sliding of ophiolitic blocks also occurred, with the rotation of the Wuqbah block, on the SW side of the Hawasina window away from the Hawasina window culmination—the NW extension of the NW-plunging J. Akhdar Anticline (Graham 1980, Rothery 1982). Compressional thrust faults along the foreland side and extensional normal faults along the trailing edge of this ophiolite block have been interpreted by Rothery (1982) as representative of gravity sliding away from the uplifted Hawasina window axis. Break-back thrusting in the Futayhah window, affecting both the Hamrat ad Duru and the Aruma Group may have resulted from a similar process. The timing of this event is unknown.

Normal faults around the edge of the J. Akhdar Anticline have eliminated sections of the Hawasina and Haybi Complexes. Thus along the SW margin of the Hawasina window, Searle & Cooper (1986) have noted that the Semail Ophiolite cuts progressively into the Hamrat Duru Group, abutting successively lower stratigraphical levels, until it ultimately eliminates the Hamrat Duru Group and rests directly on a duplex of the Sumeini Group. Similarly, the greatly thinned Hawasina Complex units of the northern rim of J. Akhdar may result from normal faulting and the elimination of section.

This phase clearly post-dates the late-stage gravitational emplacement of the Semail Ophiolite in the central Oman Mountains, along a low-angle normal fault that cuts up-section towards the trailing edge of the ophiolite NE of the Hawasina window area. This places progressively higher levels of ophiolite stratigraphy over Haybi and Hawasina Complex units towards the NE (Glennie *et al.* 1974, Graham 1980).

The timing of folding of the J. Akhdar Anticline is poorly constrained and, indeed controversy exists as to whether it is a thrust-cored anticline, as initially suggested by D. Bernoulli (personal communication 1982), in which case the normal faults are technically hangingwall drop faults (S. Hanna personal communication 1983, Searle 1985) related to late-stage late Cretaceous events, or whether it is a Tertiary feature, related to whale-back folding in the Oman foreland. A component of uplift of the Oman shelf sequence occurred in the latest Cretaceous since P. Cawood (personal communication 1987) has documented re-imbrication structures in the Hawasina Complex to the south of Saih Hatat that were related to gravitational sliding southwards from an uplifted Saih Hatat. These structures pre-date the unconformable deposition of lower Tertiary shallow-water carbonates. However, a major regressive Oligo-Miocene carbonate, evaporite, clastic sequence is also folded around the J. Akhdar structures, indicating a late Tertiary deformation phase (J. Warburton, personal communication 1987).

Aside from the culmination of J. Akhdar, Tertiary modification of the late Cretaceous structures is, in the south-central area, restricted to gentle open folding of the HDIF and Tertiary limestones of J. Aswad, and tight box-folding at the NW end of the HDIF around Ibri.

DISCUSSION

The structure and distribution of the Hawasina sediments yields circumstantial evidence about the wider processes involved in ophiolite obduction. Previous models for the generation of the Semail Ophiolite fall into two groups: by back-arc spreading above a subduction zone (Pearce *et al.* 1983, Lippard *et al.* 1986) or by detachment in a mid-ocean ridge setting (Coleman 1981, Boudier *et al.* 1985), whilst Michard *et al.* (1985) suggested intra-oceanic thrusting along the 800°C isotherm close (3–400 km) to the Arabian margin, controlled either by thermal gradients or by a lithospheric bulge linked to the approach of a subduction zone.

The geometrical constraints posed by the Hawasina sediments argue against a back-arc spreading model, since a fragment of older oceanic crust, perhaps 100 km wide (Lippard *et al.* 1986) must remain in the hangingwall of the subduction zone. This is nowhere preserved along the leading edge of the Semail Ophiolite and a second phase of intra-oceanic thrusting is required to account for its removal. A consequence of this is that the sole thrust to the Semail Ophiolite must cut down into the main subduction zone trench to remove the Haybi Complex and Hawasina Complex imbricates ahead of the trench. Whilst Lippard *et al.* (1986, p. 155) have addressed this problem, it remains unclear why the sole thrust should cut down section in this manner.

A model in which the Haybi and Hawasina Complexes developed directly ahead of the Cenomanian–Turonian Semail Ophiolite is therefore preferred, probably as the result of asymmetrical ridge collapse. This is the structurally weakest zone along which detachment might occur and the area of youngest oceanic crust, accounting for the almost coeval age of ophiolite generation and initial detachment (Coleman 1981). High temperature (850–1000°C) shearing of the basal peridotite layer, microstructure fabrics and the availability of slowly cooling magmas to yield gabbros, all suggest detachment on the distal side of a ridge (Boudier *et al.* 1985), although a 'roll-back' model, generating ocean crust directly above a subduction zone as suggested by Smith & Spray (1984) for some eastern Mediterranean ophiolites, cannot be discounted. The apparently 'back-arc' geochemistry of the Semail Ophiolite (Pearce *et al.* 1983) remains unexplained.

The primary emplacement mechanism of the external (foreland) units of the Hamrat Duru Group is clearer, and four lines of evidence suggest that they were bulldozed ahead of, and never covered by, the Semail Ophiolite. Firstly, the relative structural simplicity of the Hamrat ad Duru and Wahrah imbricate fans when compared with internal exposures of the Hamrat Duru Group (e.g. the Hawasina window, Graham 1980, Searle & Cooper 1986) precludes the overthrusting of a thick ophiolitic slab. Secondly, illite crystallinity is markedly greater in internal areas when compared to external areas (Cooper 1986). Thirdly, there is a notable absence of ophiolitic detritus in the incised wadi gravels on the foreland side of the Hamrat ad Duru. Finally, vitrinite reflectance data from the top of the Hajar Supergroup are immature over much of the foreland area, indicating that the ophiolite never extended much farther to the SW than its present day limit (J. Warburton personal communication 1987). It must, therefore, be inferred that the HDIF and WIF were emplaced by a push from the rear, since the thickness of the HDIF and WIF (*ca* 1500 m , Fig. 4) is insufficient to allow gravity spreading processes to operate (Elliott 1976), whilst the regional palaeoslope during nappe emplacement must have dipped towards the subduction zone at the base of the Semail Ophiolite, precluding gravity sliding.

The development of imbricate fans and duplexes and the distribution of these structural units with respect to the Semail ophiolite shows a clear lithological control. Sections that contain abundant thick-bedded arenites, lime-mudstones and silicified wackestones behaved in a competent manner and their inherent strength allowed them to be pushed ahead of the ophiolite during the emplacement sequence. Thick, competent successions along the leading edge of the HDIF show a resistance to internal imbrication and shortening (*ca* 8–15%) whilst a decrease in unit thickness and competence, and a commensurate increase in incompetent chalky lime-mudstones, cherts and shale, and thinner bedding is associated with closer-spaced thrusts and increased shortening (up to 55%).

Contrasting styles of shortening along the trailing edges of structural section HD1 and HD2 (Fig. 4) again reflect the increased calcarenite component and competence of the stratigraphical sections in the NW arm of the Hamrat ad Duru. The closer-spaced thrusts of HD1 are similar to those of the WIF, reflecting substantial similarities in stratigraphical section between the incompetent trailing edge of the HDIF in the J. Buwaydah area and the WIF.

The shales and cherts of the most distal Halfa and Haliw Formations were either subducted beneath the ophiolite, or closely imbricated as an accretionary wedge along the leading edge of the ophiolite. The competence of these units was insufficient to allow their bulldozing ahead of the ophiolite.

The development of wide imbricate fans, which in the case of the HDIF extended up to 40 km ahead of the Semail Ophiolite, must also reflect the presence of an easy-slip horizon along the Hamrat Duru Group sole thrust (HDtp). This is the lime-mudstone marl and shale-rich Aruma Group. Total displacement along the HDtp must exceed 150 km (the distance from the leading edge of the HDIF to its minimum restored position in the Hawasina Ocean, Fig. 5). This is two orders of magnitude greater than the average displacement along individual thrust surfaces in the HDIF, which must, therefore, have preferentially locked during translation, whilst continued motion occurred along the HDtp. The easy-slip horizon in the Hawasina Ocean is unknown, but it may have been the shale-rich Qumayrah unit of the Muti Formation.

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