Geometry and kinematic evolution of the Wadi Mayh sheath fold, Oman, using 3D mapping from high-resolution photography

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Abstract

The Wadi Mayh sheath fold in north-eastern Oman is one of the largest and best-exposed sheath folds known, and presents a unique opportunity to better understand this somewhat enigmatic style of deformation. We undertook high-resolution photographic surveying along Wadi Mayh to document the sheath fold in 61 georeferenced panoramic photomerges. Here we present ten such images which provide a structural interpretation of the sheath fold and surrounding structure. We resolve this structure in a simplified three-dimensional model and in two orthogonal cross sections, and propose a kinematic evolution to explain the geometry. The Wadi Mayh sheath fold is the most prominent example in what we suggest is a composite sequence of sheath folds, which is enclosed within a SSW-closing recumbent syncline at the base of the major Saih Hatat nappe. Sheath folding is accommodated within Permian Saiq Formation limestones showing carpholite assemblages (6-8 kbar; 275-375^{o}C). A major discontinuity separates this sequence from enveloping older rock units. The sequence formed during progressive top-to-north, ductile shearing as the overlying nappe migrated northwards with respect to the underthrusting Hulw unit. This process occurred during SSW-directed exhumation of partially subducted continental crust in NE Oman, approximately 15 Ma after obduction of the Oman ophiolite initiated.

1. Introduction

Sheath folds typically form by progressive rotation of fold hinges, initiated orthogonal to shear, towards the transport direction under progressive non-coaxial, high strain, deformation (e.g. Carreras et al., 1977; Cobbold and Quinquis, 1980; Bérthe and Brun, 1980; Ramsay and Huber, 1987; Alsop and Holdsworth, 1999, 2004, 2012; Marques et al., 2008; Wex et al., 2014). Sheath fold formation generally involves: (1) initial buckling of layers, largely controlled by lithological contrasts; and (2) amplification and rotation of fold axes as shear strain increases (Carreras et al., 1977; Alsop & Holdsworth, 2012). While sheath folds do not require constriction to form (eg. Cobbold and Quinquis, 1980; Alsop and Holdsworth, 2006), sheaths can also form under constrictional regimes (Borradaile, 1972; Ez, 2002).

Sheath folds are defined by curvilinear fold axes with more than 90^{O} curvature (Ramsay and Huber, 1987), and result in a map pattern showing curvilinear traces of fold hinges, frequently aligning into ductile shear zones (Alsop and Holdsworth, 2004, 2006). They have been described on scales from outcrop to kilometre scale (Lacassin and Mattauer, 1985; Searle and Alsop 2007), from regional Barrovian facies metamorphic terranes (Alsop and Holdsworth, 2004) and high-pressure blueschist (Quinquis et al., 1978), and eclogite (Searle et al., 2004) facies terranes. They are also known from salt diapirs (e.g. Talbot, 1979), sub-glacial sediments (Hudleston, 1992), and many terranes associated with ductile flow processes. Alsop et al. (2007) note that the variety in scale and materials encompassed by sheath folds suggests that sheath folding is a fundamental mode of viscous response to strain. The amount and type of strain is the primary control on geometry, while rheological layering contrasts affects the original buckle fold dimensions and the ellipticity ratios between sheath fold rings. Geometrically, sheath folds are generally described using a Cartesian coordinate system where the x axis lies parallel to the long axis of the fold and the main lineation direction, y axis is intermediate and the z axis the short axis (Fig. 1). The z-axis cannot be larger than the shear zone within which it forms (Alsop et al., 2007).

Few, if any, sheath folds are exposed as well as the Wadi Mayh sheath fold in NE Oman (Searle, 2007; Searle and Alsop, 2007; Agard et al., 2010). This sheath fold is part of a massive composite series of sheath folds that outcrop over at least 10-15 km along Wadi Mayh (Fig. 2). We have mapped the southern part of the structure in the Wadi Mayh gorge in detail using both ground- and aerial-based photographic surveys. The resultant panoramas are a high-resolution platform for structural analysis, on which we base a geometrical and kinematic interpretation of the structure. We place these results in the context of the exhumation of eclogite and blueschist facies rocks from a Late Cretaceous subduction zone beneath the obducted Semail ophiolite.

Previous field-based studies across northern Saih Hatat have involved regional structural mapping (LeMétour et al., 1986, 1990; Michard et al., 1984; Searle et al., 1994, 2004; Gregory et al., 1998; Miller et al., 1998, 2002; Warren and Miller, 2007), combined with metamorphic petrology and thermobarometry (e.g. Goffé et al., 1988; El-Shazli et al., 1990; Searle et al., 1994; Warren and Waters, 2006; Yamato et al., 2007; Agard et al., 2010; Massone et al., 2013) as well as U-Pb dating (e.g. Warren et al., 2003; Gray et al., 2004).

In this paper we first describe the stratigraphic, structural and metamorphic context of the rocks that make up the North Oman Mountains (Fig. 2) and then describe the detailed internal geometry of the Wadi Mayh sheath fold. We then infer the kinematic evolution of the structure and present an approximate restoration. Finally, we discuss the regional tectonic implications of sheath folding in the context of ophiolite obduction and UHP exhumation processes.

2. Tectono-stratigraphy of the North Oman Mountains

2.1. Pre-Permian basement

In the Saih Hatat region, northern Oman, the oldest rocks exposed are a thick sequence of greenschist facies greywackes, shales and cherts of late Proterozoic to early Cambrian age (Hatat schists) with a prominent horizon of transitional alkaline-tholeiitic basalts (Jahlut member; LeMétour et al., 1986). The Hatat schists are overlain by ~500 m thickness of grey and yellow dolomite (Hijam Fm.) and a sequence of quartzites with minor shaley siltstone horizons containing trilobites of Ordovician age (Amdeh Fm.; Lovelock et al., 1981). The Amdeh Formation varies in thickness considerably across the Saih Hatat window, up to ~2300 m in the southeast but markedly thinner in the Wadi Mayh region (Miller et al., 2002). All the rocks have been overprinted by a regional Pre-Permian greenschist facies event with strong cleavage development formed during a phase of NE-vergent folding.

2.2. Permian-Mesozoic shelf carbonates

A regional unconformity separates the pre-Permian basement rocks from the overlying Middle Permian to Cenomanian carbonates of the Arabian shelf sequence (Glennie et al., 1974,1975; Fig. 3). In the Saih Hatat region the Permian Saiq Formation consists of a basal sequence of conglomerates, tuffaceous sediments and dolomites (Sq1) that is overlain by approximately 500 m thickness of carbonates (Sq2-Sq3). A distinctive volcanic horizon including basaltic flows and sills occurs within Sq2 and is interpreted as the metabasic protolith of similar rocks within the structurally deeper blueschist (Hulw unit) and eclogite (As Sifah unit) rocks (Searle et al., 1994, 2004; Miller et al., 2002). Permian volcanism includes high-Ti alkali basalts and tuffaceous flows both within the Saiq Formation and in the allochthonous Hawasina and Haybi complexes (Searle et al., 1980; Maury et al., 2003; Chauvet et al., 2009), concurrent with the break-up and rifting of Gondwana.

A stable carbonate platform was present along the Arabian plate margin from Middle Permian (Saiq Fm.) right through the Triassic (Mahil Fm.), Jurassic (Sahtan Group), Early Cretaceous (Kahmah Group) and Aptian-Cenomanian (Wasia-Thamama Group) (Glennie et al., 1973, 1974). Reconstruction of the Oman Mountains thrust sheets reveals the progressive facies changes outboard of the continental margin with the Sumeini Group (proximal slope), Hamrat Duru Group (outer slope) and Hawasina and Haybi thrust sheets (distal ocean) being time-equivalent units in the reconstructed continental margin (Glennie et al., 1974; Searle, 2007). Stable carbonate sedimentation on the shelf ended abruptly at the Cenomanian-Turonian boundary (93.5 Ma) when the shelf margin collapsed, and a foreland basin (the Aruma basin) developed in front of the allochtonous Tethyan thrust sheets above, emplaced from NE to SW (Warburton et al., 1990).

2.3. Allochtonous Hawasina and Haybi thrust sheets

Overlying the Permian – Mesozoic shelf carbonate sequence is a series of thin-skinned thrust sheets composed of Tethyan sedimentary rocks which were deposited offshore on the Oman continental margin. The Hawasina complex comprises several distinct thrust sheets of proximal (Hamrat Duru Group limestone, sandstone turbidites; Cooper, 1988) to distal (Halfa, Hulw Fm cherts) deposits, overlain by the most distal Haybi complex thrust sheet, which is interpreted as comprising trench deposits with mélanges, exotic limestone blocks, alkali basalts and shales (Searle, 1985, 2007). The Hawasina and Haybi thrust sheets underlie the massive Semail ophiolite, which forms the uppermost thrust sheet. All these allochthonous units have been emplaced a minimum of 150 km, more likely 200-300 km, from NE to SW over the previously passive margin shelf carbonates during the period from 95 – 80 Ma (Cooper, 1988).

2.4. Semail Ophiolite thrust sheet

The Semail ophiolite consists of at least a 6-7 km thickness of Tethyan oceanic crust (gabbros, sheeted dykes, pillow lavas, deep-sea sediments) overlying a >10 km thickness of mantle peridotites, mainly harzburgite and dunite. U-Pb zircon ages of gabbros, trondhjemites and tonalitic dykes are all 96.5-95.5 Ma, indicating a narrow time span of ophiolite crustal formation (Rioux et al., 2013, 2015). The ophiolite extends at least 150 km across the Oman continental margin as a thin sheet, thinning towards the continental interior. The whole allochthon has been folded around two extremely large scale anticlines, the Jebel Akhdar and Saih Hatat anticlines, both of which are cored by pre-Permian basement inliers. In the central Oman Mountains, the complete ophiolite sequence dips offshore towards the NE, but the thrust sheet extends at least 150 km across the Arabian margin and tapers towards the foreland in the SW. In the eastern part of the Oman Mountains, the complete ophiolite sequence is exposed both south of the Saih Hatat culmination and along the northern margin around the Muscat – Darsayt area.

3. Structural - Metamorphic Overview of the North Oman Mountains

Apart from the pre-Permian greenschist facies metamorphism observed in the cores of the Jebel Akhdar and Saih Hatat culminations, all metamorphism is related to the obduction of the Semail Ophiolite and its underlying allochthonous Tethyan thrust sheets, and subsequent deformation episodes. A thin metamorphic sole along the base of the ophiolite shows an inverted PT gradient from amphibolite/granulite facies immediately beneath the peridotite down to a sequence of greenschist facies meta-sediments, mainly quartzite and carbonate (Searle and Cox, 1999, 2002; Cowan et al., 2014). U-Pb zircon ages from garnet and clinopyroxene amphibolites are almost identical to the age range of the ophiolite (Rioux et al., 2015) suggesting that metamorphism occurred in a subduction zone environment during ophiolite formation (Searle & Malpas, 1982; Searle & Cox, 1999) formation. The inverted thermal gradient suggests that heat was derived from the hot overlying mantle wedge.

The northern Saih Hatat region shows a regional high-pressure terrane in all rocks beneath the Muscat peridotite (Fig. 2). The deepest structural units are exposed around As Sifah where eclogites contain the assemblage: garnet + clinopyroxene + glaucophane + phengite + epidote. The meta-basic and meta-tuffaceous eclogites form large-scale boudins within highly sheared meta-carbonates and quartz phengite schists. The protolith of the meta-carbonates is thought to have been Permian Fm. limestones, while the quartz + phengite schists were likely derived from Ordovician Amdeh Fm. sandstones. Peak PT conditions of 20-23 kbar indicate that the continental margin was taken to depths of >90 km in a NE-dipping subduction zone (Searle et al., 1994; Warren & Waters, 2006). A major pressure jump exists across the normal sense As Sheik shear zone, which separates the As Sifah eclogite and garnet-bearing blueschists from the overlying Hulw unit. Garnet-bearing blueschists indicate retrogressed eclogites but most of the Hulw unit shows glaucophane or crossite without garnet. Doming of the Hulw unit gently folded the overlying Wadi Mayh sheath fold above.

A series of shear zone bounded units structurally overlie the Hulw and Sifah units. The Wadi Mayh, Yenkit-Yiti and Ruwi units all contain carpholite and formed at similar intermediate high pressure (6-~10 kbar; Goffé et al., 1988; Yamato et al., 2007; Agard et al., 2010). Extreme ductile shearing occurred during exhumation of the eclogites and blueschists as these rocks were expelled back up the same subduction zone (Searle et al., 1994, 2004; Agard et al., 2010). The prominent top-to-NNE shear fabrics across the entire HP zone are indicative of normal-sense motion accommodating extrusion of the HP rocks beneath a passive roof fault in the upper portion of the subduction channel. The Wadi Mayh sheath fold shows extreme ductile folding in rocks buried to about 8-10 kbar, equivalent to depths of burial of ~28-35 km (Agard et al., 2010). During the Late Cretaceous the overburden above the sheath fold structures probably included up to ~4 km thickness of shelf carbonates, doubled by recumbent folding to ~8 km, with a further 2-5 km thickness of Hawasina and Haybi thrust sheets and then at least 10-15 km thickness of ophiolite thrust sheet.

4. Geometry of the Wadi Mayh mega-sheath fold

Structurally, the Wadi Mayh sheath fold sequence is situated within a recumbent syncline immediately below the major north-verging northern Saih Hatat recumbent anticlinal fold nappe, and immediately above the UP-LP discontinuity of Miller et al. (1998, 1999, 2002) (Fig. 2). This anticlinal nappe is NNE-facing, and formed during top-to-NNE or base-to-SSW motion across the upper plate-lower plate (UP-LP) discontinuity. The syncline within which the sheath fold sequence is situated is kinematically complimentary to the overlying anticline.

Wadi Mayh cuts through the sheath fold sequence in more than one orientation, allowing unique views into the heart of such a structure (Fig. 4). We here present 10 georeferenced panoramas of the Wadi Mayh sheath fold and surrounding structures (Figs. 5-8), showing where bedding planes (white lines) and shears or detachment horizons (blue lines) intersect the topographic surface. The process of resolving the geometry of the sheath fold incorporated analysis of a dataset of 61 discrete panoramic perspectives of the Wadi Mayh structure, 10 of which were structurally interpreted (Figs. 4a, 5-8).

The folds we describe affect original bedding and compositional differences (fig. 9a). In places, a shear fabric is present (fig. 9b), and the more incompetent horizons often host local discontinuities. Rheological contrasts between beds clearly affected fold geometries; the morphology of a competent bed defining a blunt-nosed isoclinal fold and wrapped around by incompetent material that extends the fold hinge along its axis, is common (eg. fig. 5, WM10, centre of frame). Shears must accommodate the differential motions of these horizons. Sheath folds generated during heterogeneous deformation, with rheological layering resulting in local discontinuities around (sheath) fold closures are termed ‘active’ sheath folds (Alsop & Holdsworth, 2012).

Structure from Motion (SfM) has become a widely recognised tool for geological applications (Westoby et al., 2012; Bemis et al., 2014). SfM uses the stereoscopic photogrammetry principle that 3D structure can be deduced from multiple overlapping, offset images. We undertook 3D SfM visualisation using the computer program Agisoft Photoscan, in order to allow adoption of a continuum of perspectives and orthographic views. Orthographic views artificially position the viewer at an infinitely distant viewpoint, thereby removing perspective distortion of geometries. This valuable perspective is impossible to replicate in the field. Careful study of all visible faces in the gorge walls was undertaken to reduce the geometric ambiguity in interpreting three-dimensional structure.

The sheath fold with cat’s eye exposure northern face of the eastern wall of the Wadi Mayh gorge is the clearest and best-exposed sheath in the series of folds enveloped by the regional recumbent syncline (Fig. 5). Searle & Alsop (2007) determined that this sheath fold closes to the SSW based on measurements of its hinge lineations converging towards the SSW. By tracing beds outwards from the core of this sheath fold, and with the information that the stratigraphy on the upper limb of the encompassing syncline is inverted (Searle et al., 2004), it follows that this sheath fold is a SSW-closing syncline in the X-axis cross section.

Lying atop the limbs which wrap around the western side of this synclinal sheath is a recumbent anticline, which based on its trend on a range of gorge wall surface, we interpret as having a curvilinear hinge, which curves more gently than the hinge of the underlying synclinal sheath. Above this anticline is a curvilinear syncline that is truncated by a major discontinuity, separating the highly deformed limestones from an apparently more competent layer of brown dolomite above, which is the basal part of the Saiq Formation. Limestone beds are truncated along this discontinuity, a result of extreme thinning along the upper limb of the syncline that balances the thickening in the syncline interior with respect to the dolomite layer.

At the southern end of the gorge, the brown dolomite curves steeply down to the road level, in the manner of a tight flat-lying syncline hinge. Continuation of the limestone sequence immediately south of this feature, at a lower level than in the gorge, is evidence for top-to-N rolling of the overarching syncline hinge. Along strike to the east, however, the hinge of this syncline curves from the southern end of the gorge where it runs WNW-ESE across the gorge, to a N-S trend leading into what we suggest is a synclinal sheath in the cliffs southeast of the gorge (it is not clear how the hinge trends further east; fig. 6, WM15).

Structural overlays, which establish the relative stratigraphic positions of beds, were produced on the basis that: a) stepping out, upwards or downwards, from the sheath fold core selects progressively older beds; b) beds can be traced along the gorge walls as per the interpreted panoramas; c) competent beds may become boudinaged but these boudins ordinarily lie in a consistent shear plane, which is also traceable; d) common features can be found on either side of the gorge walls, allowing link-up of the structure and assisting with interpretation.

The structural overlays are draped onto the orthographic views of each gorge wall, as constructed in Agisoft Photoscan (Fig. 10). Competent beds are grouped into bands of different colour; the blank spaces predominantly cover incompetent material. Competency contrast in a deforming body of rock affects the resulting deformed geometry, with incompetent material tending to wrap around competent boudins in thinned fold limbs, and thicken in fold hinges. While the grouping scheme shown indicates stratigraphic order, it does not refer to any previously documented stratigraphic grouping; it was designed purely for structural analysis in this study. Unlike the interpreted panoramas (Figs. 5-8), these structural overlays were not designed for precision, but for construction of a broadly accurate, stratigraphically-referenced model of the structure.

Using the range of panoramic perspectives and structural overlays, we present a sketch 3D interpretation of the basic structure of the sheath fold sequence (fig. 11). The single layer we have chosen corresponds to approximately the upper part of the orange bed group in the overlays, and stratigraphically younger horizons are presented to show the form of the main synclinal sheath.

While it is the 3D structure that is paramount when assessing curvilinear fold geometries and kinematics, we also considered the 2D structure as seen through two simplified orthogonal sections (fig. 12), because this is also a useful perspective for visualising the structure, and it is possible to depict many layers. The geometries in these sections are highly sensitive to the position and orientation of the section with respect to the three dimensional structure.

6. Kinematic evolution

The kinematic evolution is constrained by the regional structural context of the sheath fold sequence: within a recumbent syncline beneath a major recumbent anticlinal nappe and above a regional-scale top-to-NNE discontinuity, the UP-LP discontinuity of Gregory et al. (1998) and Miller et al. (1998, 2002). Age constraints of deformation place UP-LP shearing at c. 75 Ma and fold nappe development at c. 70 Ma (Gray et al., 2005), such that fold nappe growth became the more favourable mode to accommodate shear than motion along the UP-LP discontinuity with time.

The model presented here is that northward relative motion of the northern Saih Hatat anticline tightened a syncline at the base of the nappe, above the UP-LP discontinuity. As the anticline moved northwards relative to the lower plate (as the lower plate moved relatively southwards), the syncline tightened into an isoclinal fold, and was progressively sheared in a top-to-NNE velocity gradient. This led to the thinning and boudinage observed on the upper limb of the major syncline and of subsidiary synclines (equivalent to the lower limb of anticlines). A kinematic study of part of the structure is presented in Fig. 12, showing how progressive shear strain can lead to shearing through forelimbs of originally asymmetric folds, a process that can lead to boudinage along these shear planes. This is a fundamental feature of progressive simple (and general) shear: line elements initially in an instantaneous shortening field can rotate into an instantaneous extensional field, but not the other way around (Davis and Reynolds, 1996). The larger scale kinematic evolution of the syncline is schematically illustrated in Fig. 13.

There is an upper segment of syncline hinge defined by the enveloping brown dolomite at the southern end of the gorge, followed by continuation of the folded limestone sequence immediately south of the gorge at a lower level. This pattern indicates rolling and shearing of the syncline hinge under progressive top-to-N shear strain. Thinning and boudinage of the brown dolomite, as well as thinning of the upper limb of an inferred syncline below the ground level in the highly deformed limestones, is required to accommodate and balance the offset produced by hinge rolling and shearing. Boudinage of the relatively competent brown dolomite may explain why it is not present between Saiq limestone and the Amdeh quartz-mica schist at the c. 2 km mark in x-axis section (as documented in the field). We therefore propose that there is no need to infer south-dipping normal faults as suggested by Miller et al. (2002) to unroof the Saiq limestone in this location.

A major discontinuity separates the highly deformed limestones from a layer of brown dolomite that envelopes the structure. The fact that this dolomite has not been drawn into the tight-to-isoclinal folding below the discontinuity suggests a mechanical difference between the dolomite and the limestone that is part of the sheath fold. Experimental physical modelling of sheath fold development in silicone multilayers by Marques et al. (2008) indicates that the more viscous layer does not become involved in the sheath folding once the viscosity contrast reaches roughly an order of magnitude. By analogy to this experimental modelling, we suggest that the viscosity of the dolomite may have been at least an order of magnitude greater than the viscosity of the limestone during deformation. Truncation of limestone bed groups along the discontinuity balanced the disparity in deformation with the enveloping brown dolomite. The dolomite is relatively unshortened above the area of intense shortening in the limestone below the discontinuity; shearing out of limestone along the discontinuity moving away from the hinge and into the upper limb of the syncline balances this shortening.

Two different models can satisfy the geometries we have documented. In the first, progressive, extreme non-coaxial shear led to sheath fold genesis, perhaps by irregular flow velocities, after an initial buckling of layers (Alsop et al., 2007). Indeed, the complex deformation patterns of sheath folds are often compatible with bulk progressive simple shear, rather than requiring multiple phases of folding (Carreras et al., 1977). If it can be shown that the dome-and-basin interference pattern evidenced in NE Oman (Searle, 2007) was produced after ophiolite obduction but prior to fold-nappe growth at c. 70 Ma, then this may have provided hemispherical perturbations for sheath fold growth upon shearing (Ez, 2000). The sheath fold exposure at the northern end of the gorge is highly elliptical (R_{yz}=5), and shows 'cat's eye' ellipticity ratios (Searle & Alsop, 2007). It is therefore consistent with the Alsop & Holdsworth (2004) criteria for a simple or general shear model of formation. In this model, deformation seen in the lateral section is explained by progressive simple shear in the perpendicular section (X-axis section).

In the second model, deformation seen in the lateral section is partially a result of lateral shortening. Although the cat's eye ellipticity ratios are not consistent with the Alsop & Holdsworth (2004) criteria for constrictional deformation, simple three-dimensional balancing would suggest the contrary, as there appears to be a net surplus of Permian rock volume along the sheath fold sequence and a net deficit on either side.

Given the inherent ambiguity of interpreting the flow geometries of rock during deformation from views of the present structure alone, we do not dismiss the possibility of a lateral component of shortening contributing to some of the deformation seen in the lateral section in Fig. 10, though we stress that this section is not a plane strain section, and that material has flowed into the section from original positions behind it.

While the classic cat's eye exposures at the northern end of the gorge provide the best examples of what are unequivocally paired sheath folds, as part of a larger sheath (Figs. 5, 10), there are other exposures showing highly curvilinear folds, some of which are discussed above. The direction of sheath fold closure does not specify shear sense (Skjernaa, 1989; Alsop & Holdsworth, 2004), thus alternating closure directions is compatible with general/simple shear. We suggest that the large-scale syncline contains a composite series of sheaths, whereby connectivity of the folds may occur as illustrated in fig. 11. This hypothesis is in line with sheath fold models based on smaller-scale observations (Alsop & Holdsworth, 2006; Fig. 1b), and the mechanical basis that it is unlikely that one highly curvilinear (non-cylindrical) structure should be entirely surrounded by cylindrical structures.

The observations and age constraints described above are consistent with the schematic kinematic model of the larger scale evolution presented in Fig. 14. The essential feature of the kinematic evolution is progressive simple or general shear in a strong top-to-N velocity gradient, such that thinning and elongation affected already folded and shortened structures during the later stages of deformation (as seen in Fig. 12).

7. Regional tectonic implications

Two orogenic episodes have been well documented in the Northern Oman Mountains: (1) during the Late Cretaceous with NE to SW emplacement of the Semail ophiolite and underlying Tethyan oceanic thrust sheets onto the previously stable Arabian continental margin in the northern mountains, and ESE to WNW emplacement of the Masirah ophiolite along the southeast coast of Arabia, and (2) during the Late Cenozoic, after deposition of the neo-autochthonous Maastrichtian – Palaeocene – Eocene shallow water limestones that unconformably overlie all tectonic units across the Oman Mountains. This latter episode produced the folds with N-S aligned axes visible on the coast around Bandar Jissah and Ras al Hamra (Fig. 2).

7.1. Late Cretaceous stress field

The maximum shortening axis during the Late Cretaceous for the northeastern Oman Mountains was ~035 NE-SW, at right angles to thrusts and major fold axes in all allochthonous rocks beneath the Semail ophiolite. The Wadi Mayh sheath fold axes and stretching lineations are aligned NNE-SSW, close to parallel with the inferred maximum regional compressive stress axis. From the deepest level As Sifah eclogites up to the Wadi Mayh unit, deformation occurred during syn- to post- peak HP metamorphism (79.1 Ma; Warren et al., 2003). Deformation ended prior to the 70 Ma Lower/Upper Maastrichtian unconformity that truncates all structures beneath (Glennie et al., 1974; Fournier et al., 2006; Searle, 2007). Structures within eclogite (As Sifah) blueschist (Hulw) and carpholite-grade (Wadi Mayh, Yenkit-Yiti and Ruwi units) commonly show two phases of deformation: (1) SSW-verging folds and thrusts during continental subduction, coeval with ophiolite obduction, deformed by (2) later base-SSW, top-NNE normal-sense structures that formed during the exhumation-related phase (Searle et al., 2004; Agard et al., 2010).

The variety in size, shape, structural settings and exhumation rates of continental HP and UHP terranes around the world suggests that a variety of mechanisms may facilitate their exhumation (Hacker et al., 2013). However, the basic control on exhumation from a subduction zone is the balance between down-channel shear traction and up-channel buoyancy (Warren et al., 2008). Rather than accommodating extension, the normal-sense shears described here are related to expulsion tectonics of footwall units beneath passive roof faults (Searle et al., 1994, 2004; Searle 2007; Agard et al., 2010), as can be expected to happen in the upper portion of an exhuming channel. A channelised model of exhumation (Warren et al., 2008; Beaumont et al., 2009) explains the ductile juxtaposition of HP rocks in NE Oman beneath lower-grade units, and the doming of HP units. The predicted lower portion of the channel, showing structures of the opposite shear sense (thrusting) is structurally deeper and not exposed.

The Late Cretaceous Hawasina, Haybi and Semail ophiolite thrust sheets have all been folded above the large-scale anticlines of Jebel Akhdar and Saih Hatat, with a prominent lateral ramp along the Jebel Nakhl – Semail Gap trend (Searle, 2007; Fig. 14). There is debate as to whether these folds are the latest part of the Late Cretaceous thrusting event, or whether they are a mid-Cenozoic event, or both. Hilgers et al. (2006), Holland et al. (2009) and Gomez-Rivas et al. (2014) measured fracture systems along the southern flank of Jebel Akhdar and concluded that the structures formed as a consequence of horizontal principal compression in three phases: NW-SE, E-W and finally N-S to NE-SW. Most of the veins and fractures were repeatedly opened and then sealed as a result of a changing dynamic high-fluid pressure cell system during the Late Cretaceous to Miocene.

In the foreland region SW of the mountains, the Late Cretaceous fracture pattern interpreted from 3D seismic and stress field is different (Fig. 14). Two dominant fault sets are aligned WNW-ESE (~100-110º; dextral) and NNW-SSE (~130-160º; sinistral) and regional maximum compressive stress is reported as NW-SE (Johnson et al., 2005; Filbrandt et al., 2006). These authors related the fracture patterns and stress field to a glancing collision of the Indian plate with Arabia, despite the geology of the Batain coast of south Oman showing practically no Cenozoic deformation at all. Searle (2007) interpreted the fault sets as Reidel fractures associated with the main NE-SW compression in the Oman Mountains, noting that some WNW-ESE compression may also be necessary to explain the biaxial fold interference pattern. The WNW-ESE compression was probably related to the WNW emplacement of the Masirah ophiolite offshore south of Oman during the Latest Cretaceous. Following obduction of the Semail ophiolite and underlying thrust sheets along northern Oman and the obduction of the Masirah ophiolite along the SE coast of Oman during the Late Cretaceous, all rocks were covered by Late Maastrichtian and Palaeocene-Eocene shallow marine limestones. These highly fossiliferous rocks are well dated and record a 25 Ma period (from 70 Ma to at least 45 Ma) of stability with stable carbonate sedimentation and no tectonic activity.

7.2. Late Cenozoic stress field

In the Oman Mountains compressional folds in the post-obduction Maastrichtian – Eocene limestones also have NW-SE aligned fold axes that mimic the NE-SW principle shortening axis in the Late Cretaceous. These structures are mainly open periclines to box folds that show a minor amount of crustal shortening but up to 2 km of vertical uplift in the far northeastern part of the mountains (Searle, 2007). The two great culminations of Jebel Akhdar and Saih Hatat show Cenozoic rocks only along the flanks, so it is not possible to know precisely how much of each culmination was related to late-stage thrust culmination during the Late Cretaceous or to the second phase of post-Eocene shortening and uplift. The regional map pattern of the central and eastern Oman Mountains shows a biaxial fold interference pattern with a dominant NE-SW maximum shortening axis (Jebel Akhdar trend) and a secondary WNW-ESE shortening axis (Masirah – Batain coast trend), resulting in a dome and basin fold interference pattern (Fig. 14). The Late Cenozoic stress field mimicked the Late Cretaceous one with prominent NNE-aligned fold axes in the Palaeocene – Eocene limestones in the Muscat region. The precise cause of the WNW-ESE compression during the post-Eocene period remains unresolved.

Fournier et al. (2006) described two sets of extensional faults, an older ENE-WSW oriented set resulting in NNW aligned faults and a younger NNE-SSW oriented extensional set resulting in WNW-ESE (N100ºE) aligned faults. Compressional tectonics during the latest Oligocene and into the Miocene are evident throughout the northern Oman Mountains, increasing in importance to the north where the Musandam culmination and related thick-skinned thrusts have been related to the earliest Arabia – Central Iran collision (Searle et al., 2014, 2015).

8. Conclusions

The Wadi Mayh mega-sheath fold in north Oman shows spectacular outcrops of multi-phase ductile folding, sheath folding, ductile shearing and boudinage in Permian limestones buried to ca 6-8 kbar, equivalent to depths of ca 25-35 km. The sheath fold shows the classic 'cat's eyes' closures in the core of the main sheath. We have documented the main sheath fold in detail and surrounding structures in Wadi Mayh.

The sheath fold sequence formed as fold nappe growth in the major Saih Hatat anticline above overtook motion on the UP-LP discontinuity, both of which accommodated bottom-to-S underthrusting of the lower plate during HP exhumation (Gray et al., 2005). As the fold nappe grew, the syncline at its base tightened, developing tight folds in its core. Progressive nappe propagation under top-to-N simple shear led to isoclinal folding and extreme thinning of rotated beds. Extreme simple shear of a ductile material provided the basis for sheath fold formation. Dominant compressional stress aligned NNE-SSW resulted in large-scale NNE-facing folds, top-to-NNE "extensional" fabrics, actually related to base-to-SSW shearing in the underlying eclogite and blueschist facies units (Searle et al., 2004; Agard et al., 2010).

Sheath folding does not require a lateral component of compression (Cobbold & Quinquis, 1980) and indeed the Wadi Mayh sheath fold morphology is consistent with formation under simple/general shear (Alsop & Holdsworth, 2004). It is, however geometrically possible that some of the deformation seen in our lateral section was produced by a secondary component of WNW-ESE compression that occurred during the Latest Cretaceous. Although this could possibly be related to far-field stresses resulting from the emplacement of the Masirah ophiolite in SE Oman (Marquer et al., 1995; Immenhauser et al., 2000), this explanation seems unlikely given the relatively undeformed shelf platform sequence along the southeast Arabian coast.

The Wadi Mayh sheath fold shows dominant NNE – SSW aligned stretching lineations with fold closure towards the SSW. This direction is the same as the overall Late Cretaceous fold-thrust belt and similar to the structures observed in the deepest As Sifah eclogite units (Searle et al., 2004), all related to ophiolite emplacement, late-stage subduction and exhumation of the continental margin. The dome-and-basin fold interference pattern present throughout the northern Oman Mountains during the Late Cretaceous required a secondary WNW-ESE compression. This Late Cretaceous bi-axial fold interference pattern was mimicked in the post-Eocene-Oligocene structures seen in the Maastrichtian – Eocene neo-autochthonous limestones above the ophiolite. The precise cause of this WNW-ESE compression and why the same stress field became re-established during the Late Cenozoic remains unknown.

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FIGURE CAPTIONS

Fig. 1. Experimentally and naturally observed sheath fold morphologies. a) Schematic of a simple sheath arising from experimental shearing of a hemispherical deflection in a plane. Modified from Marques et al (2008, fig. 4) b) Schematic showing compound sheath formation in which synformal and antiformal sheaths are connected, from natural examples. From Alsop & Holdsworth (2006, fig. 9)

Fig. 2. Geological sketch map and cross-section through the Saih Hatat window, modified after Searle et al. (2004). a) Sketch geological map showing the principle tectonic units and shear zones. b) Cross-section through *a* along line indicated. Units are labelled as per fig. 3 (conventions of Miller et al., 2002).

Fig. 3. Stratigraphic column, modified from the ‘upper plate stratigraphy’ of Miller et al. (2002, fig. 5). This stratigraphy is relevant for the northern part of the Saih Hatat window,

where this study focusses. In this area the Amdeh unit is much thinner than elsewhere in the Saih Hatat window. Approximate scale given.

Fig. 4. a) Locality map of the Wadi Mayh gorge, showing points at which (sometimes several) panoramas were made. Further panoramas of were made out of view to the SW in Wadi Mayh. Panoramas from localities marked in bold were structurally interpreted and are presented in this paper. Viewing angles over which the structure is analysed in each panorama are indicated.

b) Simplified structural map of the Wadi Mayh gorge. Map conventions as follows: white lines, bedding; blue lines, shears; dashed white lines, stratigraphic boundaries; thick blue line, shear zone separating the sheathed Permian Saiq limestones from enveloping basal Permian brown dolomite. Abbreviations are as per fig. 3, BrDol is brown dolomite. Dotted black lines are tie lines indicating continuity in the structure across the gorge. These lines do not predict the form of these features but simply indicate that they connect.

Fig. 5

Panoramas from WM1, WM5 and WM10. WM1 shows the classic cat's eye sheath fold exposures reported by Searle & Alsop (2007). Two distinct sheaths are stacked atop one another but are wrapped around by continuous beds; these two sheaths represent W-folds in the core of a greater synclinal sheath. WM5 shows a large cascading limb that wraps around the cat's eye sheaths. Boudinage is evident on the upper limb of the synclinal sheath. The line of sight in the centre of WM10 is roughly perpendicular to the x-axis and shows isoclinal folds with boudinaged syncline upper limbs, as well as the part of the major syncline-anticline pairing shown in fig. 10. Annotation conventions as per fig. 4b.

Fig. 6

Panoramas from WM13, WM15 and WM18. A major flat-lying anticline with attenuated lower limb is visible in the centre of WM13. WM15 shows the southern end of the gorge sheath fold sequence, with the upper limb of a syncline truncated by the brown dolomite detachment. WM18 shows the view looking north from the main cat's eye exposures.

Fig. 7

Panoramas from WM20, WM23 and WM27. These panoramas show the structure of the west side of the gorge. WM20 shows the same cascading fold limb wrapping around the cat's eye exposures as in WM5. WM23 shows the equivalent anticline with lower limb attenuation as in WM13. WM27 depicts the end of the gorge sequence, where the partial syncline hinge plunges down to the south.

Fig. 8

Panoramic perspective from WMT22, showing the gorge sheath fold sequence to the SSW, and continuation of sheath folding to the NNE.

Fig. 9

Interpreted structural overlays onto orthographic views of 3D meshes created using SfM software (Agisoft Photoscan). All coloured units are Permian Saiq Formation. The brown outer layer is the competent brown dolomite unit, and is separated from the more deformed younger beds by a ductile detachment (marked as a blue line). Stratigraphy youngs from brown to light green on a progressive colour scale. a) E side of the gorge. b) W side of the gorge.

Fig. 10

Long and short axis sections through the Wadi Mayh Gorge. Stratigraphy shown on the side of each section. Blank spaces represent incompetent material. a) X-axis section. Schematic expression of boudinaged lower limb of the anticline beneath near the base of the section satisfies the necessity for thinning of this limb with progressive migration of the upper portion of the fold in the transport direction as discussed in the text. b) Y-axis section. Thickening of c. 56% calculated from a comparison of the deformed section and estimated stratigraphy. c) Map with section lines indicated.

Fig. 11

X-section and restoration. a) X-axis section, as per fig. 11a. b) Restored section of the main sheath fold section, between pin points A and A'. Note that the whole sequence is folded over, as indicated by the arrow, such that inter-bed group shearing has the sense shown by the thin blue lines. The cross section shows the upper portion of the syncline; beds are overturned. Thick blue lines indicate shearing along the base of the brown dolomite. Bed group cutoffs by the thick blue line are angled such that they match the X-section after folding. Translucent extensions of the bed groups indicate that the predicted continuations of these bed groups further north in the core of the syncline. They are also truncated schematically indicating that they may be cut by the major shear at the base of the brown dolomite, though this has not been documented. The orange bed group is shortened by c. 50%, though it should be noted that thinning may have been under-accounted for in restoration, which would cause overestimation of the shortening.

Fig. 12

Schematic depicting development of isoclinal, boudinaged folds as seen in panorama WM20. a) Cutout from structurally interpreted panorama WM20. b) Competent bed group picked out, as in fig. 9. c) Schematic evolution of this type of feature involving top-to-NE progressive shear. d) Schematic indicating how progressive simple shear can lead to a shear fabric, with shears propagating through forelimbs.

Fig. 13

Kinematic model of growth of Saih Hatat anticline and underlying syncline. Northwards fold nappe motion is relative to the lower plate only, which was underthrusting beneath the nappe. a) Seven schematic snapshots in the growth of the anticline/syncline pair. Coloured circles indicate changing morphology of the anticline, coloured triangles show progression of motion on the UP-LP discontinuity. Motion becomes inefficient on the UP-LP and progressively transfers to the anticline growth and syncline development, tightening, then thinning. b) Schematic showing how the observed deformation in the Wadi Mayh Gorge is compatible with the simple model in *a*. Syncline hinge shearing occurs as part of progressive hinge rolling and syncline thinning during the later stages (5,6,7 in *a*) of fold nappe development.

Fig. 14

a) Simplified geological map showing the Saih Hatat and Al Jabal al Akhdar culminations, the Hawasina Window, ophiolite blocks in structural depressions and the fold interference pattern creating a large-scale dome and basin structure. Modified from Searle (2007). b) Geometry of the finite strain ellipse for the Central Oman Mountains. The shaded area represents the range of fold axes orientations generally oriented 125±10°. Minor east-west or WNW-ESE aligned fractures on Al Jabal al Akhdar have a small component of sinistral shear (Filbrandt et al., 2004, figure 35). c) Geometry of the finite strain ellipse for the Oman foreland, south and southwest of the Oman Mountains, after Filbrandt et al. (2004). d) Model showing present-day map pattern of the biaxial fold interference pattern.