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Re-imbrication of the Hawasina allochthons in the Sufrat ad Dawh range, Oman Mountains

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Abstract—The Hawasina complex consists of deformed slope to basinal sedimentary rocks of Mesozoic age, emplaced on the Arabian continental margin in the Late Cretaceous as a series of nappes. This complex is well exposed in the Sufrat ad Dawh range where it is represented by the Hamrat Duru Group and the Wahrah Formation. Two generations of imbricate faults are recognized in this area. The first is the imbrication of the Hamrat Duru and the Wahrah units into two separate nappes. These nappes were then folded and cross-cut by a second set of imbricate faults, resulting in the systematic tectonic repetition of the Wahrah–Hamrat Duru Nappe stratigraphy. The late-stage faulting event correlates with the origin of re-imbrication structures documented from other parts of the Oman orogen, interpreted to be of a post-emplacement, Early Tertiary age. This implies that Tertiary deformation of the Oman allochthons was expressed at least in part as a continuation of nappe development, initiated during the Late Cretaceous orogeny.

INTRODUCTION

AT THE END of the Cretaceous, the Semail ophiolite and a telescoped Mesozoic succession of slope and basinal rocks (the Hawasina complex) was thrust from the northeast onto the Arabian continental margin (Lees 1928, Morton 1959, Allemann & Peters 1972, Glennie *et al.* 1973, 1974). The Hawasina complex is now superbly exposed in the western foothills of the Oman Mountains and in tectonic windows centered along major antiformal culminations (Figs. 1 and 2). Regional geological investigations conducted by Glennie *et al.* (1973, 1974) have shown that the Hawasina complex is a series of tectono-stratigraphic units, or nappes, each containing a distinct sedimentological facies. Several units were recognized. The most extensive ones are shown in a summary of the Oman stratigraphy listed in Fig. 3. The stacking of the nappes follows a consistent order, with successively higher nappes representing more distal facies (Glennie *et al.* 1973, 1974). The Hawasina complex lies in thrust contact above shelf carbonates of the Arabian platform (the Hajar Supergroup), easterly-derived syn-orogenic flysch (the Aruma Group) and, locally, slope carbonates of the Sumeini Group (Figs. 1–3) (Glennie *et al.* 1973, 1974). It is overlain by remnants of an oceanic island or seamounts (the Haybi complex) and by the Semail ophiolite (Lees 1928, Morton 1959, Wilson 1969, Allemann & Peters 1972, Glennie *et al.* 1973, 1974, Searle & Malpas 1980, 1982). The emplacement of the allochthons was followed in the Maastrichtian and Early Tertiary by marine transgression and deposition of carbonate rocks (Lees 1928, Morton 1959, Tschopp 1967).

The Sufrat ad Dawh range

The Sufrat ad Dawh range exposes a continuous segment of the Hawasina complex, extending 20–30 km across strike in the western foothills of the Oman Mountains (Fig. 1). It comprises two units of the Hawasina complex: the Hamrat Duru Group and the Wahrah Formation. The Hamrat Duru Group occurs along two E–W-trending belts in the north and the south parts of the range, while the Wahrah Formation occupies the remainder of the area (Fig. 4). The Hamrat Duru Group contains two sequences of cm- to m-bedded turbiditic grainstone with minor lime mudstone and conglomerate. These are separated by more distal, largely silicified, cm-bedded sequences of grainstone and mudtone. In the Sufrat ad Dawh range, the thickness of the Hamrat Duru Group varies from 250 m at the south end to 450 m at the north end (D. Cooper personal communication 1984). The Wahrah Formation is represented predominantly by sequences of cm-bedded red radiolarian chert, mudstone and shale, along with 1–10 cm lithoclastic grainstone beds. This formation is thought to exceed 200 m in thickness (Glennie *et al.* 1974).

The Hamrat Duru Group and the Wahrah Formation occur throughout the Oman Mountains. On the basis of lithology, faunal assemblages and paleocurrent indicators, Glennie *et al.* (1974) interpreted the Hamrat Duru Group as the most proximal of the Hawasina sequences, and the Wahrah Formation as a distal equivalent. These workers have shown that, regionally, the Hamrat Duru and the Wahrah units exist as two distinct nappes, with the Wahrah Nappe overlying the Hamrat

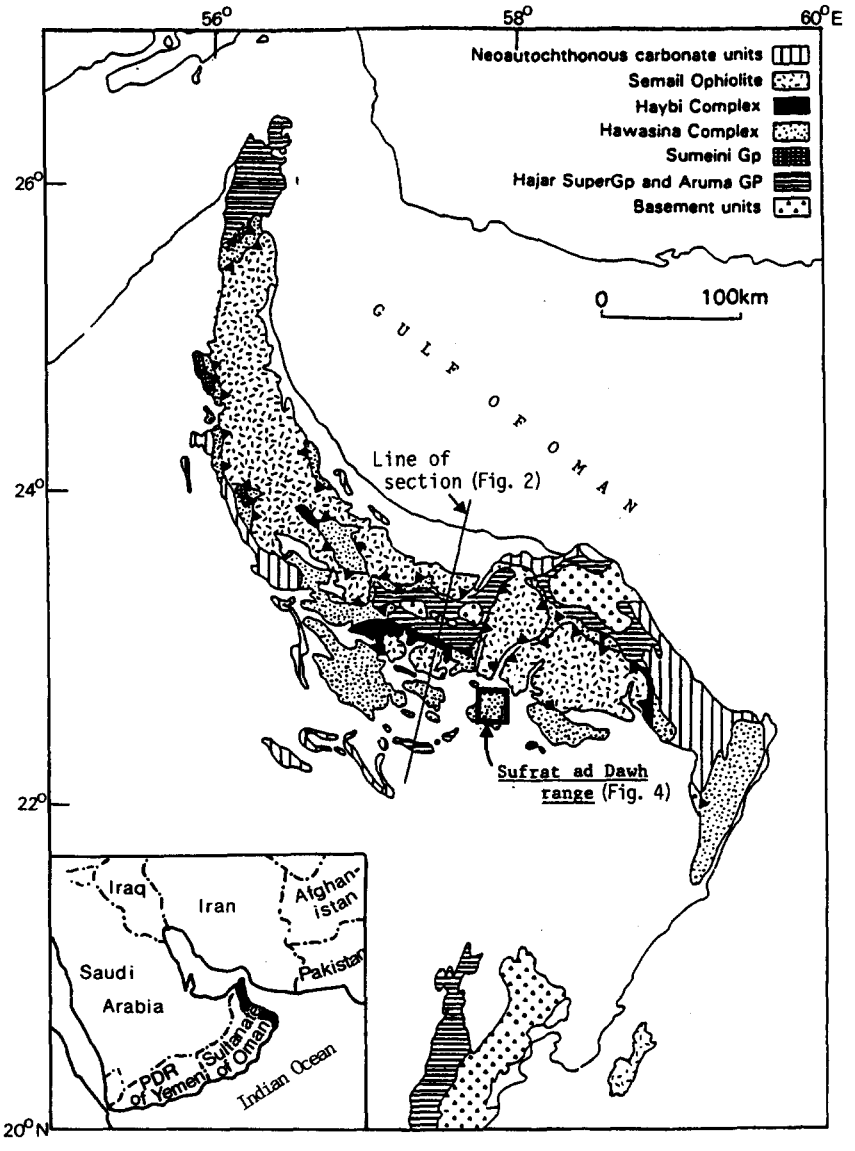


Fig. 1. Generalized geological map of the Oman Mountains (modified after Glennie *et al.* 1973, 1974) showing the location of the Sufrat ad Dawh range. Tectonic contacts are shown (teeth in hanging wall). Ages and rock types of the various map units are presented in Fig. 3.

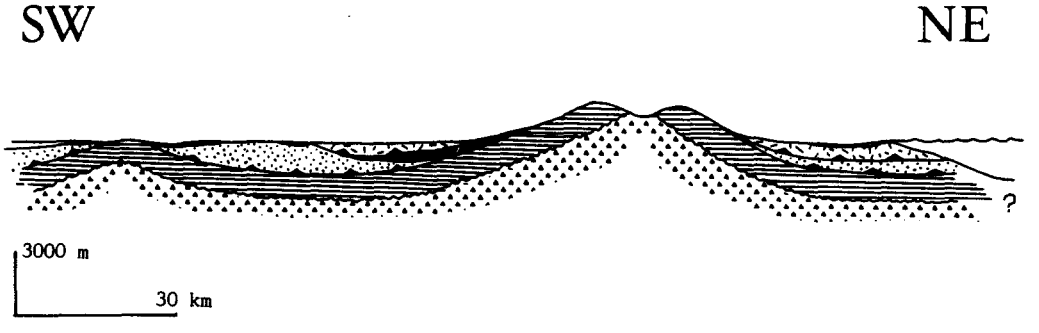


Fig. 2. Schematic geological cross-section of the Oman Mountains (from Glennie *et al.* 1973, 1974). The lithological symbols are the same as those used in Fig. 1. This section displays two major culmination trends. The largest one, seated in the central part of the mountains, exposes the entire stratigraphy of Oman.

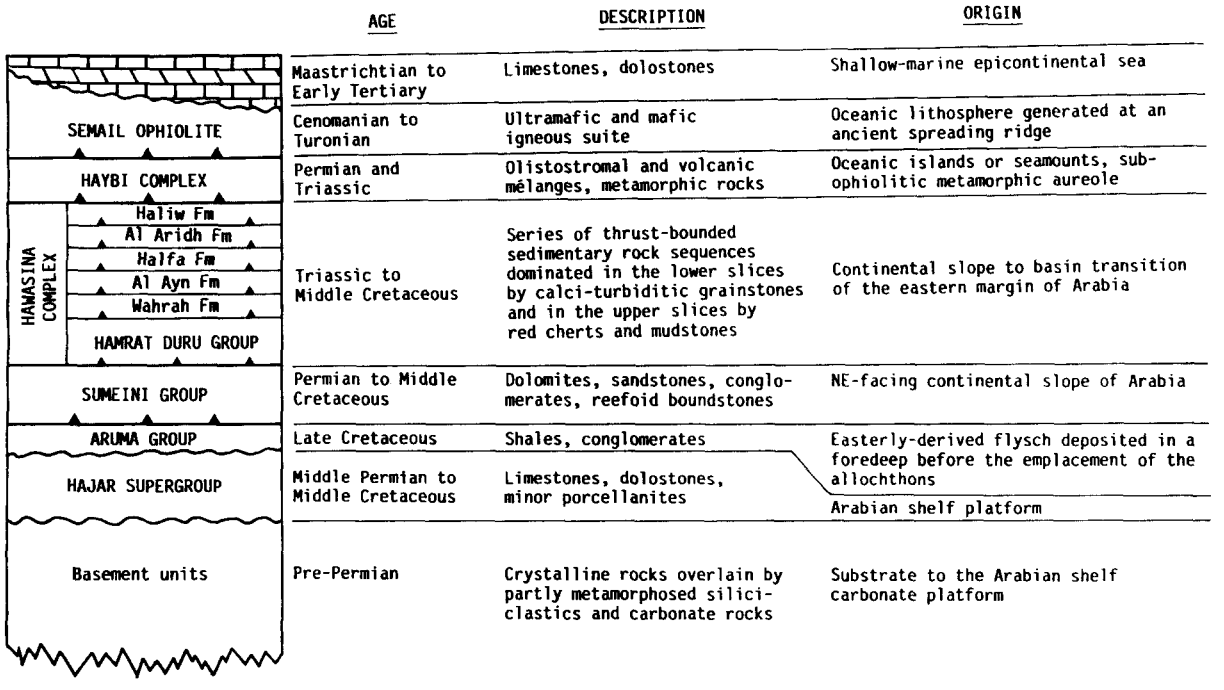


Fig. 3. Stratigraphy of the Oman Mountains (modified after Glennie *et al.* 1973, 1974, Searle & Malpas 1980, 1982). The shelf carbonate sequences of the Hajar Supergroup and the Aruma flysch unconformably overlie the basement units and are in turn tectonically overlain by a series of allochthons. These are, from bottom to top, the Sumeini Group, the Hawasina complex, the Haybi complex and the Semail ophiolite. Maastrichtian and Early Tertiary neo-autochthonous carbonate rocks are known to overlie most of the older stratigraphy unconformably.

Duru Nappe. Glennie *et al.* (1974), however, described the occurrence of a reversal in the usual superposition of these nappes along the southern margin of the southern Hamrat Duru belt in the Sufrat ad Dawh range, where the Hamrat Duru Nappe overlies the Wahrah Nappe. This occurrence was referred to as one of several local exceptions to an otherwise consistent pattern in the Oman orogen. Furthermore, these workers interpreted the northern Hamrat Duru belt as an E–W-trending culmination in the roof thrust of the Hamrat Duru Nappe, which is now exposed in a window. This culmination is not characteristic of the deformational style of the Hawasina complex in other parts of the Oman orogen, where it is dominated by regularly spaced thrusts dipping N–NE, and by S–SW-verging folds.

This paper presents the result of field investigations carried out in an attempt to clarify the structural history of the Hawasina complex in the Sufrat ad Dawh range.

STRUCTURE

Figure 4 is a geological map representing a N–S transect running across the Sufrat ad Dawh range. Figure 5 is a structural cross-section through the Hawasina allochthons in this area, obtained by projection of the map structures.

The northern Hamrat Duru belt

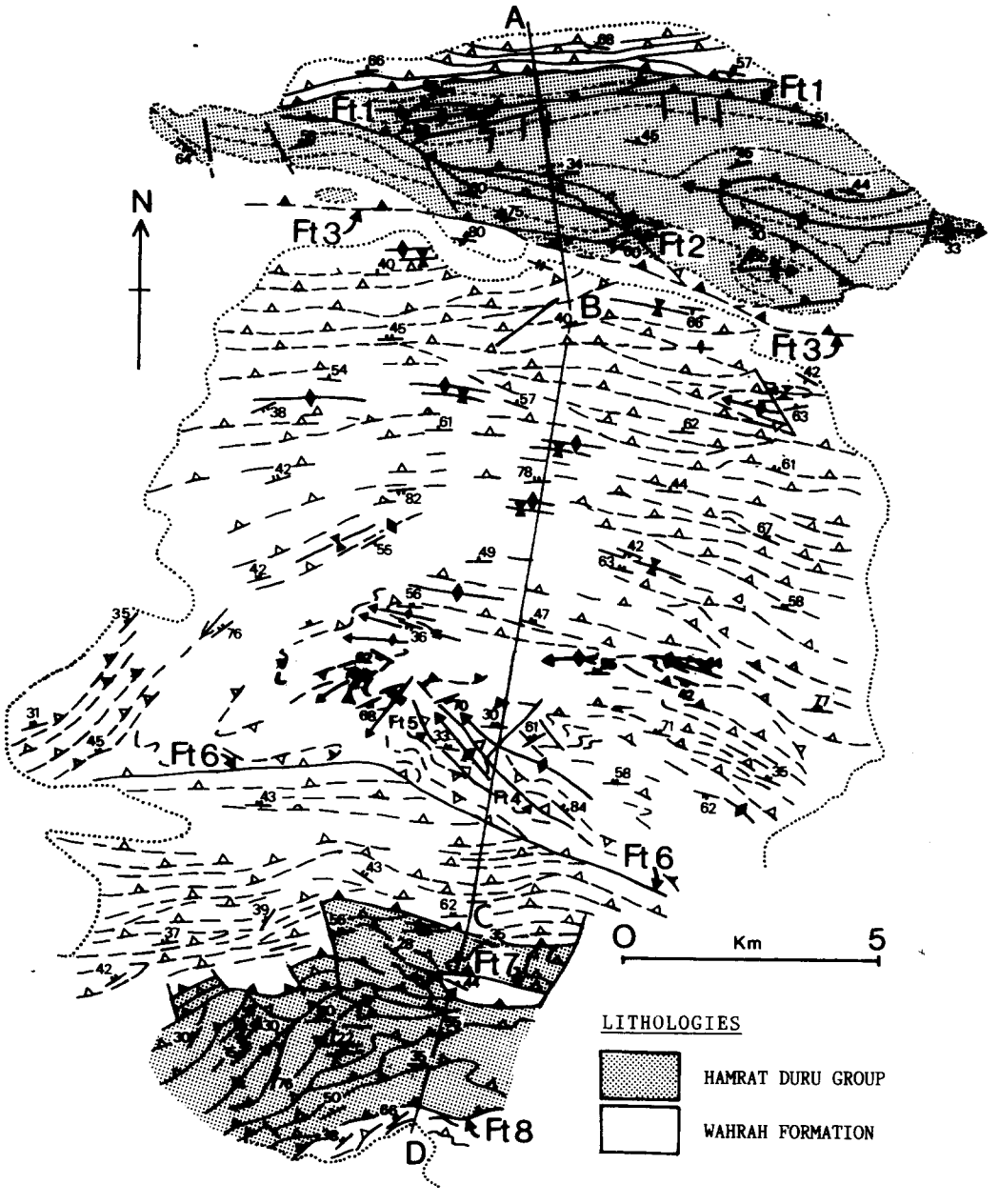
The structure in the northern Hamrat Duru belt defines an E–W-trending culmination formed of a zig-zag pattern of two left-hand en-échelon anticlines (Campbell 1958), which is disrupted by a series of high-angle reverse faults. The eastern anticline is doubly-plunging and folds an early thrust plane at the core of the structure. An E-plunging syncline occurs on the southern limb of this anticline. The western anticline plunges E and folds two imbricate thrust planes. However, this anticline is transected by three E–W-striking reverse faults (faults Ft1, Ft2 and Ft3 in Fig. 5). The imbricate thrust planes at the core of the eastern and western anticlines are recognized on the basis of the repetition of the Hamrat Duru lithostratigraphy.

Fault Ft1 truncates the eastern and western ends of a syncline–anticline pair on the northern limb of the western anticline and is thus considered to be a later feature (Fig. 6a). Fault Ft2 merges with fault Ft1 to the west and with fault Ft3 to the east. Hence, Ft2 defines a connecting splay between Ft1 and Ft3 (Boyer & Elliott 1982).

Dips and younging directions indicate that the northern Hamrat Duru belt is overlain along its northern boundary by imbricates of the Wahrah Formation (Figs. 4, 5, and 6a). Along the southern boundary of the belt, the folded Hamrat Duru imbricates are thrust southward over the Wahrah imbricates on a third high-angle reverse fault, Ft3.

The central Sufrat ad Dawh range

The central Sufrat ad Dawh range lies between the northern and the southern Hamrat Duru belts (Fig. 5). This part of the study area is characterized by the intense imbrication of the Wahrah Formation, as indicated by



SYMBOLS

- LIMIT OF EXPOSURE
- THRUST FAULT (DEFINED, APPROXIMATE)
- FLOOR THRUST OF MAJOR TECTONOSTRATIGRAPHIC UNIT (DEFINED, INFERRED)
- STRATIGRAPHIC HORIZON
- BEDDING: STRATIGRAPHIC TOPS KNOWN (INCLINED, VERTICAL, OVERTURNED)
- BEDDING: STRATIGRAPHIC TOPS UNKNOWN (INCLINED, VERTICAL)
- HIGH ANGLE STRIKE-SLIP FAULT (DEFINED, INFERRED)
- HIGH ANGLE DIP-SLIP FAULT: SOLID CIRCLE ON DOWNTHROWN SIDE (DEFINED, INFERRED)
- HIGH ANGLE FAULT: NET SLIP UNKNOWN (DEFINED, INFERRED)
- ANTIFORM WITH PLUNGING DIRECTION (DEFINED, INFERRED)
- SYNFORM WITH PLUNGING DIRECTION (DEFINED, INFERRED)

Fig. 4. Structural transect of the Hawasina complex in the Sufrat ad Dawh range showing the location of cross-section ABCD (Fig. 5). See text for discussion.

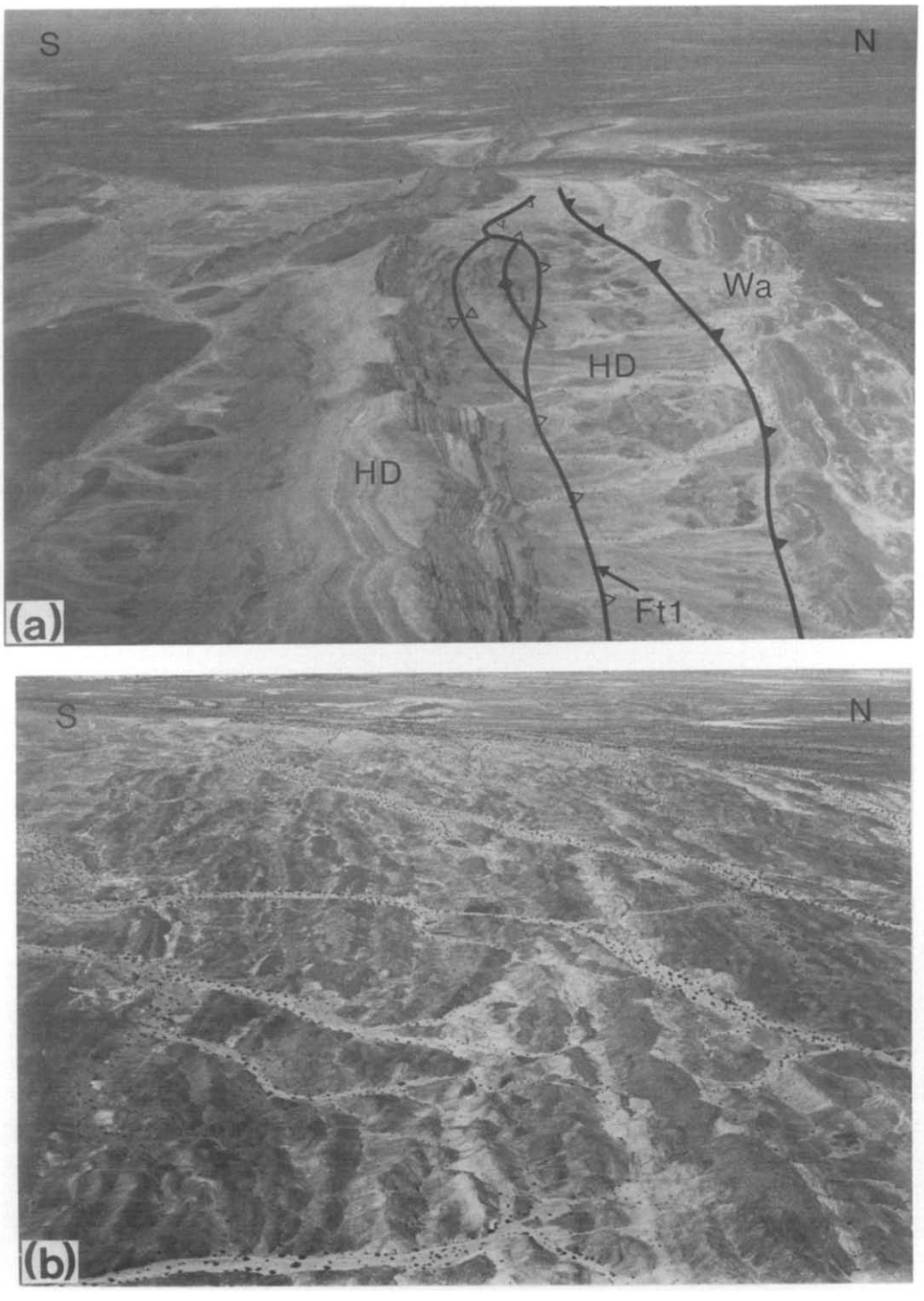


Fig. 6(a). Oblique aerial view of the north-western part of the northern Hamrat Duru belt. The northern Wahrah imbricates (Wa) tectonically overlie the Hamrat Duru Group (HD). Ft1 truncates a syncline–anticline pair in its footwall. The main ridge is 200–300 m in height. (b) Oblique aerial view of the imbricates of the Wahrah Formation in the central Sufrat ad Dawh range. The topography consists of numerous E–W-striking ridges parallel to the trend of the imbricates. The area in the lower-right quadrant of the photograph exposes light-coloured mudstones and grainstones. The darker rocks outside this area are red radiolarian cherts and grainstones. The dark speckles along the dry river beds are shrubs averaging 3 m in height.

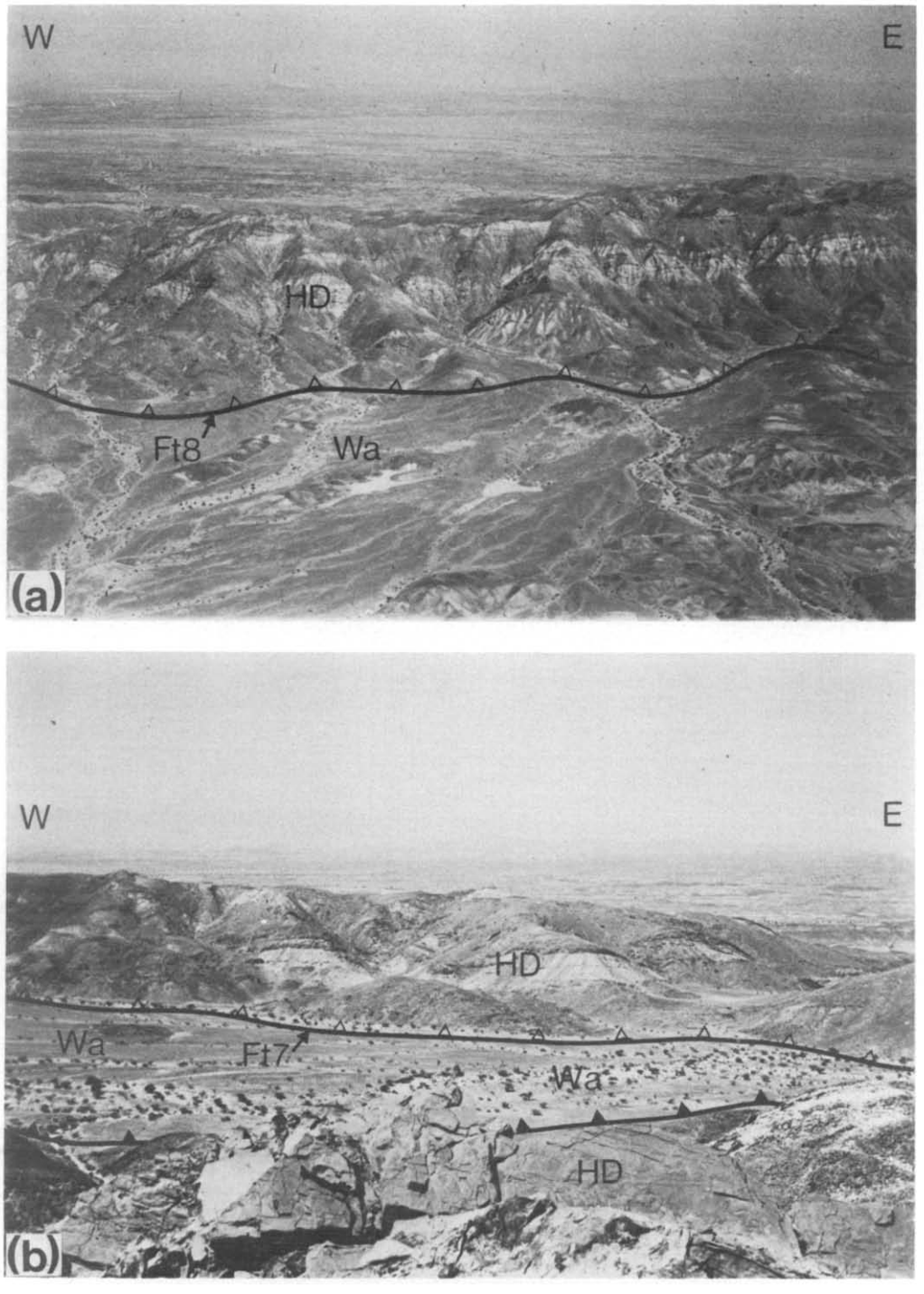


Fig. 7(a). Oblique aerial view of the southern contact of the southern Hamrat Duru belt. The Hamrat Duru unit (HD) in the center of the photograph tectonically overlies the southernmost Wahrah imbricates (Wa) along a re-imbrication fault (Ft8) (shrubs for scale). (b) Area of poor exposure lying within the southern Hamrat Duru belt (HD) and exposing lithologies of the Wahrah Formation (Wa). This represents a Wahrah thrust slice. It is tectonically overlain to the north by the Hamrat Duru unit along a re-imbrication fault (Ft7). To the south, the Wahrah slice overlies the Hamrat Duru unit (shrubs for scale).

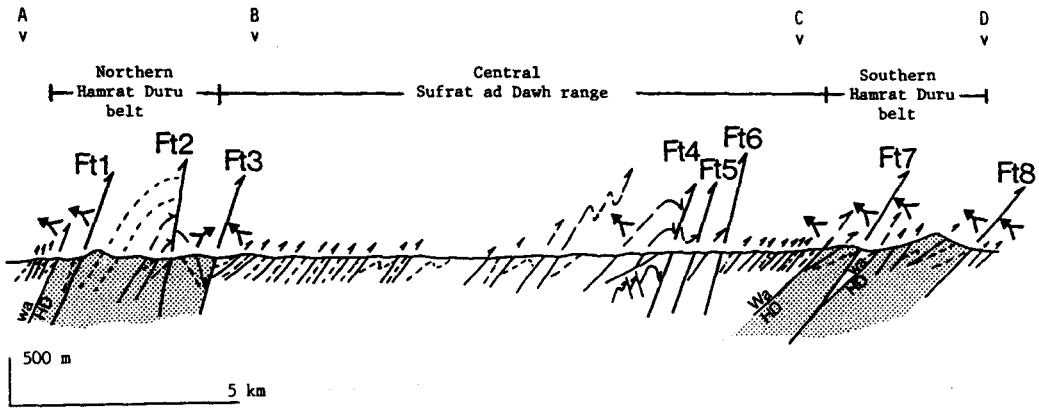


Fig. 5. Structural cross-section of the Sufrat ad Dawh range. The shaded and unshaded areas correspond to the Hamrat Duru Group and the Wahrah Formation, respectively. The dashed lines represent bedding, and the thinner half-arrows are thrust faults of the first generation. Forked arrows indicate younging direction of the units. The normal tectonic relationships of the Wahrah Formation overlying the Hamrat Duru Group are labelled with the 'Wa–HD' abbreviation. The first generation of thrust faults is folded and transected by a series of major re-imbrication faults (thicker half-arrows labelled Ft1–Ft8) at distinct space intervals across the strike of the allochthons. Faults Ft3, Ft7 and Ft8 cause the Hamrat Duru Group to overlie the Wahrah Formation, thereby accounting for reversals in the usual tectonic relationships of these units.

the thickening of the lithostratigraphy and the cross-cutting relationships of the fault surfaces with the bedding (Fig. 8). Evidence for simple shear along the trace of individual thrust faults was rarely observed. Dashed thrust symbols on Fig. 4 were used to show the general trend of imbrication, as displayed on air photos (Fig. 6b).

Folds of bedding are common within individual imbricates but generally do not affect the thrust surfaces. The folds have sub-horizontal, E–W-trending axes, north-dipping axial planes and are usually asymmetric, verging S.

A large tight to isoclinal antiform affects an entire imbricate stack of the Wahrah Formation (Figs. 4 and 5; section BC). The axial plane of this structure dips steeply to the north and the fold axis plunges moderately W. The southern limb of this antiform is transected by two minor NW–SE-striking faults and a major E–W-striking fault (labelled Ft4, Ft5 and Ft6, respectively). These are late-stage features that thrust the antiform over the Wahrah imbricates lying to the south. This geometry is similar to that in the northern Hamrat Duru belt. Despite the intensity of the deformation that these rocks have undergone, planar or linear tectonic fabrics were not observed.

The southern Hamrat Duru belt

The Wahrah imbricates of the central part of the Sufrat ad Dawh range overthrust the southern Hamrat Duru belt along its northern margin (Figs. 4 and 5; section CD). At the southern margin of the belt, the Hamrat Duru Group overthrusts the southernmost Wahrah imbricates exposed in the Sufrat ad Dawh range (Fig. 7a). These relationships are suggested by the consistent northerly dips and younging directions of the turbiditic grainstones of the Hamrat Duru Group and the Wahrah Formation.

The internal structure of the southern Hamrat Duru belt is dominated by a series of E–W-striking thrusts that dip moderately N. Folds with shallow plunging axes, often asymmetric with southward vergence, occur at various scales. Enclosed within the southern Hamrat Duru belt is a thrust slice of Wahrah Formation (Fig. 7b) in which the rocks young and dip N. This occurrence is interpreted in terms of the tectonic repetition of the Wahrah–Hamrat Duru Nappe stratigraphy. Hence, in Fig. 5, fault Ft7 is a late-stage fault thrusting the imbricated Hamrat Duru Group S over the sliver of the Wahrah Formation. As a consequence, the tectonic contact that superposes the Wahrah Formation over the Hamrat Dur Group is duplicated. The southern tectonic contact of the Hamrat Duru belt is also interpreted as a late-stage feature, labelled Ft8, that emplaced the Hamrat Duru Group S over the Wahrah Formation.

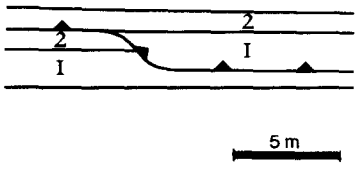


Fig. 8. Map pattern from the central Sufrat ad Dawh range displaying a typical cross-cutting relationship of a thrust fault and an arbitrary (1–2) stratigraphic sequence of the Wahrah formation. The faults are parallel to bedding along most of their length.

DISCUSSION

This study establishes the effect of a second phase of reverse faulting in the Sufrat ad Dawh range. In the northern Hamrat Duru belt and the central Sufrat ad Dawh range, early imbricates are folded and transected by faults of the later phase. There is no evidence for folding of the early imbricates in the southern Hamrat Duru belt. In the northern and southern Hamrat Duru belts, the late faults cause the tectonic repetition of the Wahrah–Hamrat Duru Nappe stratigraphy. Note that late-stage faults may be more common than indicated on

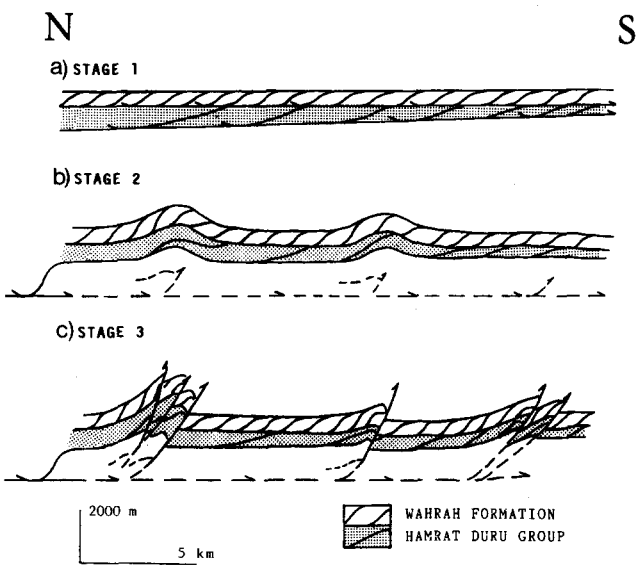


Fig. 9. Deformational history of the Hawasina allochthons in the study area: (a) early imbrication related with the formation and tectonic superposition of the Wahrah Nappe over the Hamrat Duru Nappe; (b) folding of the nappes; (c) disruption of the limbs of the fold structures and systematic re-imbrication of the Wahrah–Hamrat Duru Nappe stratigraphy. The décollement associated with the formation of the nappes is assumed to lie at the base of the Hamrat Duru Nappe which, apart from the Sumeini Group, is the lowest allochthonous unit in Oman (Fig. 3). Stages 1–3 could have been part of a single orogenic phase if, prior to the late-stage imbrication of the allochthons, the décollement migrated to a lower stratigraphic level (as shown in stages 2 and 3). The sequence of late imbrication cannot be determined from the available data.

Fig. 5. They can only be recognized if they cross-cut earlier structures.

In other parts of Oman, the internal imbrication of the Hawasina complex occurred during nappe emplacement on the Arabian continental margin in the Late Cretaceous (Allemann & Peters 1972, Glennie *et al.* 1974, Graham 1980a,b). It is conceivable that the early set of imbricates affecting the Hamrat Duru and the Wahrah units also led to the formation of two distinct nappes (Fig. 9a, stage 1). There is no indication in the study area of the relative timing of formation and emplacement of these nappes.

The folds of the Hamrat Duru and the Wahrah Nappes may represent hangingwall ramp anticlines formed above a deep-seated thrust system (Fig. 9b, stage 2). Additional layer-parallel shortening would result in the upward propagation of the late-stage thrust faults from depth and the systematic re-imbrication of the Wahrah–Hamrat Duru Nappe stratigraphy (Fig. 9c, stage 3). The décollement associated with this re-thrusting event lies at an uncertain depth below the Wahrah floor thrust. In the central Sufrat ad Dawh range, the displacement along the late faults may not have been sufficient to bring the Hamrat Duru Group to the present erosional level.

Both imbrication events shared similar directions of displacement suggesting that they were set within the same kinematic framework. Hence, these events could have been part of a single orogenic phase. In the evolution of an imbricate system, late-stage thrust faults may cross-cut earlier ones if, following transfer of the décollement to a lower stratigraphic horizon, these faults branch upward from this décollement (Fig. 9). This process, invoked by Bally *et al.* (1966) to account for re-imbrication structures in the Canadian Rockies (Fig. 13, p. 370), conforms with the kinematic model of thrust propagation described by Boyer & Elliott (1982).

However, it is also possible that the two sets of faults in the Sufrat ad Dawh range resulted instead from two distinct deformational events. The deformation of the Mesozoic allochthons in other parts of the Oman Mountains were assigned by previous workers to two main orogenic phases (Lees 1928, Morton 1959, Glennie *et al.* 1973, 1974). The first is the Late Cretaceous emplacement of these allochthons on the Arabian continental margin. The other is a regional NE–SW-oriented compressive movement of Paleogene age, correlatable with the Zagros orogeny of Iran (Ricou 1971, 1976, Stocklin 1974). The later phase is considered by most previous workers to be responsible for the formation of major structural culminations in Oman (see Fig. 2). The Paleogene orogenic phase is also recorded by open folding in the Maastrichtian and Early Tertiary neo-autochthonous carbonate sequences sparsely distributed in the Oman Mountains (Fig. 1). Only where these sequences occur is it possible to estimate the relative proportion of the deformation resulting from either of the two main orogenic phases. These rocks, however, do not outcrop in the Sufrat ad Dawh range.

Graham (1980a,b) proposed a two-stage model for the emplacement of the Late Cretaceous allochthons to explain NE-facing folds in the central part of the Oman Mountains, and the truncation of the Hawasina Nappes by the floor thrust of the overlying Semail ophiolite. The first stage is related to continental underthrusting and imbrication of the Sumeini, Hawasina and Haybi Nappes. The later stage is represented by the subsequent emplacement of the Semail ophiolite from the northeast. In addition to those two stages, Searle (1985) identified a later thrusting event related to the origin of antiformal culminations in the central part of the mountain belt, yielding structural configurations similar to those observed in the Sufrat ad Dawh range. Such an event led to the imbrication of an already established nappe stratigraphy. Searle (1985) demonstrated that his late-stage thrusting event post-dates the deposition of the Late Cretaceous Aruma flysch sequences and Eocene nummulitic limestones. He further likens this deformation to structures affecting the Hajar shelf carbonates in the Musandam Peninsula at the northern end of the Oman Mountains and assigned to the Early Tertiary (Searle *et al.* 1983).

A Paleogene age for the late-stage imbrication event in the Sufrat ad Dawh range would imply that deformation of the Oman allochthons in the Tertiary was expressed, at least in part, as a continuation of nappe development initiated during the Late Cretaceous orogeny.

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