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Sequence of thrusting and origin of culminations in the northern and central Oman Mountains

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Abstract—Detailed mapping and structural analysis of three large-scale culminations (Sumeini and Asjudi half-windows and Haybi–Hawasina window) in the Oman Mountains shows a considerably more complex history of deformation than a simple foreland (or downward) sequence of thrust development. Early thrusting processes tended to create a regular stacking order of imbricate slices and major thrust sheets, complying with the 'rules' of thrust propagation, assembled progressively downwards and forwards in the direction of translation. 'Out-of-sequence' thrusts can also be demonstrated in places by truncation of footwall structures (folds, imbricate slices, etc.), gross strain differences between thrust sheets, downward-facing structures in footwall units and elimination of thrust sheets beneath. Late stage thrusts frequently cut up-section through the previously assembled stack putting previously younger, lower thrust sheets over previously older, higher ones. Many of the culminations in the northern and central Oman Mountains were formed by ramping associated with this late-stage leap-frog rethrusting event.

INTRODUCTION

THE SEQUENCE of thrusting in allochthonous terrains is a major source of controversy in almost every orogenic belt. The crux of the controversy is whether (1) younger thrusts 'overlap' or 'truncate' older, underlying duplexes or imbricate slices in a hindward sequence of imbrication (out-of-sequence model) or (2) whether thrusts propagate in sequence towards the foreland, in the direction of thrusting (piggy-back model).

Some of the earliest detailed mapping and interpretation of thrust belts was done in the Moine thrust belt, NW Scotland, by Peach *et al.* (1907). Their mapping showed the apparent truncation or overlap by the Moine thrust of structures beneath, and led many earlier workers to the belief that the Moine thrust was the last to form. Elliott & Johnson (1978, 1980) considered that this overstep model was a misconception of thrust geometry and instead proposed a 'piggy-back' model, based on the observations of Cadell and Horne in Peach *et al.* (1907), and on their own reinterpretation based on balanced cross-sections. In this model there is a downward propagation of thrusts towards the foreland, in which higher thrusts develop first and are carried passively by lower and later thrusts. Elliott & Johnson (1980) cited the Dundonnell antiformal stack as evidence of this sequence where higher level imbricate slices are folded over lower ones, the folding finally dying out at depth to a horizontal sole thrust. If folding was post-emplacement it would also have folded the sole thrust; instead the antiformal stack was folded prior to emplacement on a flat-lying sole thrust giving good evidence for a downward sequence of thrusting. The 'piggy-back' model has in general terms been accepted by most recent workers on the Moine thrust belt (e.g. Butler 1982a, Coward 1982), and on many other thrust belts as well (e.g. Boyer & Elliott 1982, Butler 1982b, 1983, Coward 1983).

Much of the recent understanding and interpretation of structures in thrust belts originated in the Cordilleran foreland thrust and fold belt of the Canadian Rockies (e.g. Bally *et al.* 1966, Price 1981), where surface structures can be correlated at depth with extensive seismic and oil-well data down to a basal décollement horizon. Balanced cross-sections (Dahlstrom 1969) of the Alberta fold and thrust belt which take into account the deep crustal structure show that approximately 200 km of shortening occurred in supracrustal rocks above autochthonous basement. Thrusts developed progressively downwards and eastwards towards the Alberta foreland (Price 1981).

In the Valley and Ridge province of the southwest Appalachians, Rodgers (1970) and Boyer & Elliott (1982) believed that the general sequence of thrusting was towards the foreland in the direction of transport. Hatcher (1978) proposed two stages of thrusting in which the early thrusts are cut off at the back by younger ones.

The Oman Mountains in SE Arabia (Fig. 1) provide an ideal terrain to examine these models of thrust behaviour. These desert mountains show relief up to 3000 m, exposure is frequently 100% with little soil or vegetation coverage, and main access routes through the mountains run down major wadi systems which flow NE–SW at right angles to the regional strike. Excellent regional maps exist of the whole mountain belt (Glennie *et al.* 1974 at scale 1 : 500,000) and the northern Oman Mountains (Open University Oman Ophiolite map series 1–4 at scale 1 : 100,000). The three major tectonic windows through the ophiolite described here were mapped at 1 : 20,000 (Searle 1980) and this paper is an attempt to determine the structural evolution and the sequence of events during emplacement of the Semail ophiolite and associated Tethyan thrust sheets.

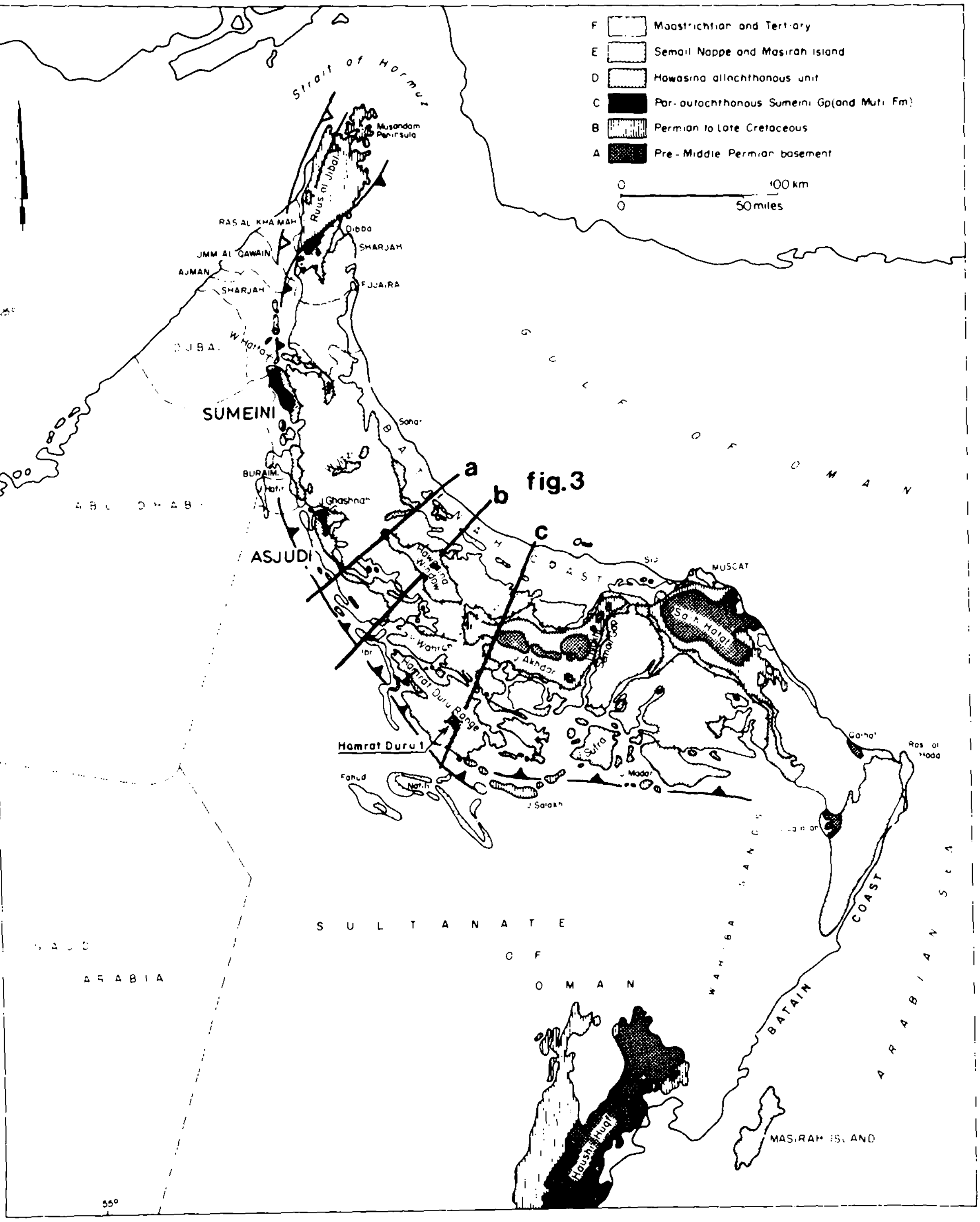


Fig. 1. Geological sketch-map of the Oman Mountains, after Glennie *et al.* (1973, 1974).

OMAN MOUNTAINS ALLOCHTHON

The Oman Mountains in SE Arabia (Fig. 1) are composed of an allochthonous series of thrust sheets of mainly Mesozoic Tethyan oceanic sediments and volcanic rocks overlain by a large obducted ophiolite slab, emplaced onto the passive continental margin during late Cretaceous time (Glennie *et al.* 1973, 1974). The Semail ophiolite sequence is an intact slice of oceanic lithosphere comprising a complete crustal sequence and 9–12 km of mantle material (see *J. geophys. Res.* special issue on the Oman Ophiolite 1981, and Open University–Oman ophiolite map sheets 1–4).

More than 100 Ma of relatively stable sedimentary conditions on the Arabian continental margin and adjacent Tethyan ocean basin from mid-Permian to mid-Cretaceous time ended abruptly in the Turonian. Sedimentation on the shelf, margin and basin ended, and the Aruma basin foredeep developed rapidly to accommodate the large-scale emplacement of all Tethyan

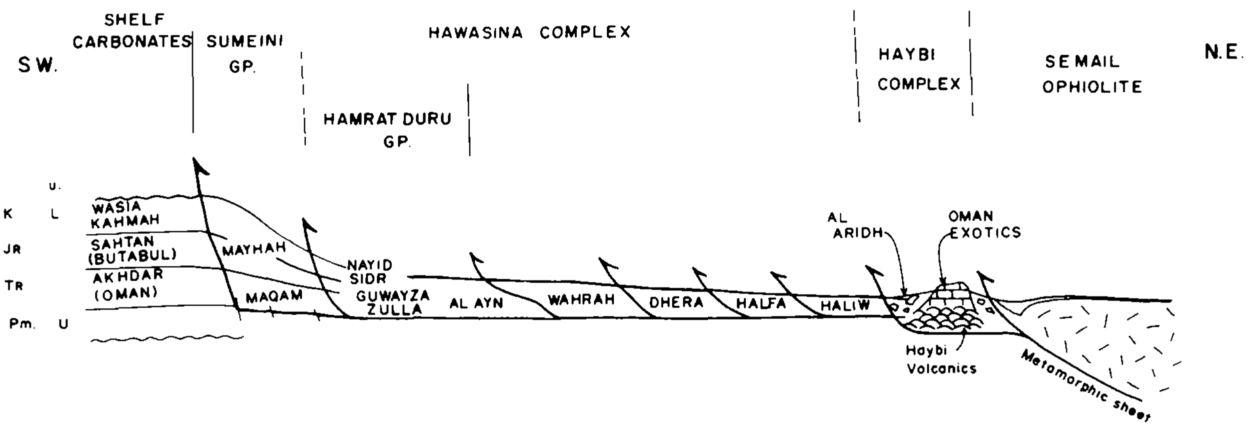


Fig. 2. Palinspastic reconstruction of the Oman continental margin and adjacent Tethyan basin in Cenomanian time, just prior to emplacement. The major stratigraphic formations are shown in their approximate palaeogeographic setting, although not all units are necessarily present in one area. For example the Dhera Formation only occurs in the northern Oman Mountains, north of Wadi Jizzi; the Al Ayn Formation only in the central and south-eastern Oman Mountains. The pre-emplacement position of the major thrusts and the four main duplexes of shelf edge sediments (Sumeini complex), basinal sediments (Hawasina complex), Haybi complex and Semail ophiolite are also shown. Width of section is somewhat in excess of 250 km.

thrust sheets from the northeast. A palinspastic reconstruction of the Oman continental margin showing the major stratigraphic and tectonic units is shown in Fig. 2. The four major thrust slices from bottom to top are (1) Sumeini-shelf edge sediments, (2) Hawasina deep-sea sediments, (3) Haybi complex, comprising Permian and Triassic exotic limestones (Oman Exotics), within-plate off-axis volcanics (Haybi Volcanics), mélanges and sub-ophiolite metamorphic rocks and (4) Semail ophiolite complex. Three cross-sections across the central part of the Oman Mountains are shown in Fig. 3 to illustrate the stacking order of the major thrust

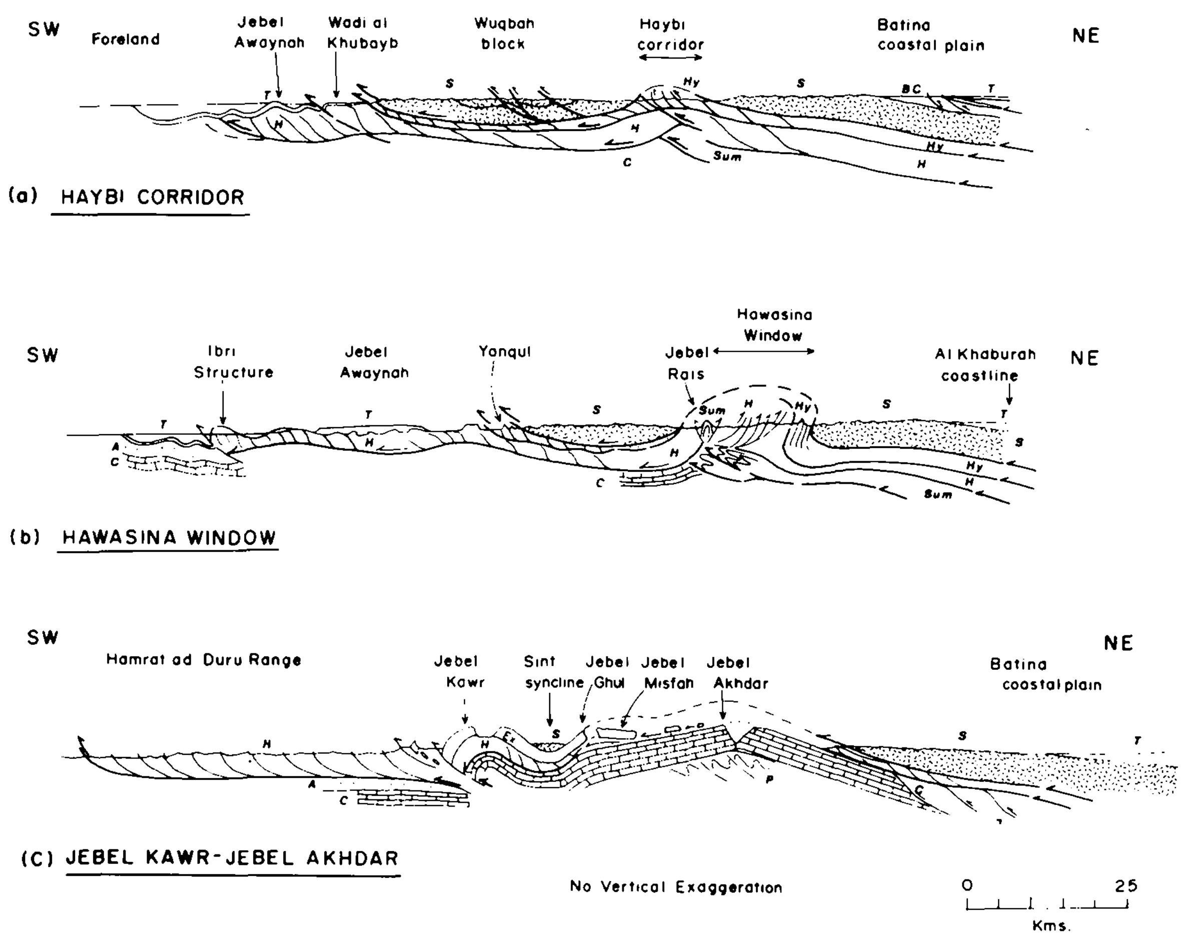


Fig. 3. Cross-section across the northern and central Oman Mountains, showing the stacking order of the major thrust sheets. T, Tertiary and Upper Maastrichtian limestones; BC, Batinah complex; S, Semail ophiolite; Ex, Exotic limestones; Hy, Haybi complex; Sum, Sumeini complex; H, Hawasina complex; A, Aruma Group (Upper Cretaceous); C, Shelf carbonate sequence (mid-Permian to Cenomanian); P, Palaeozoic sequence.

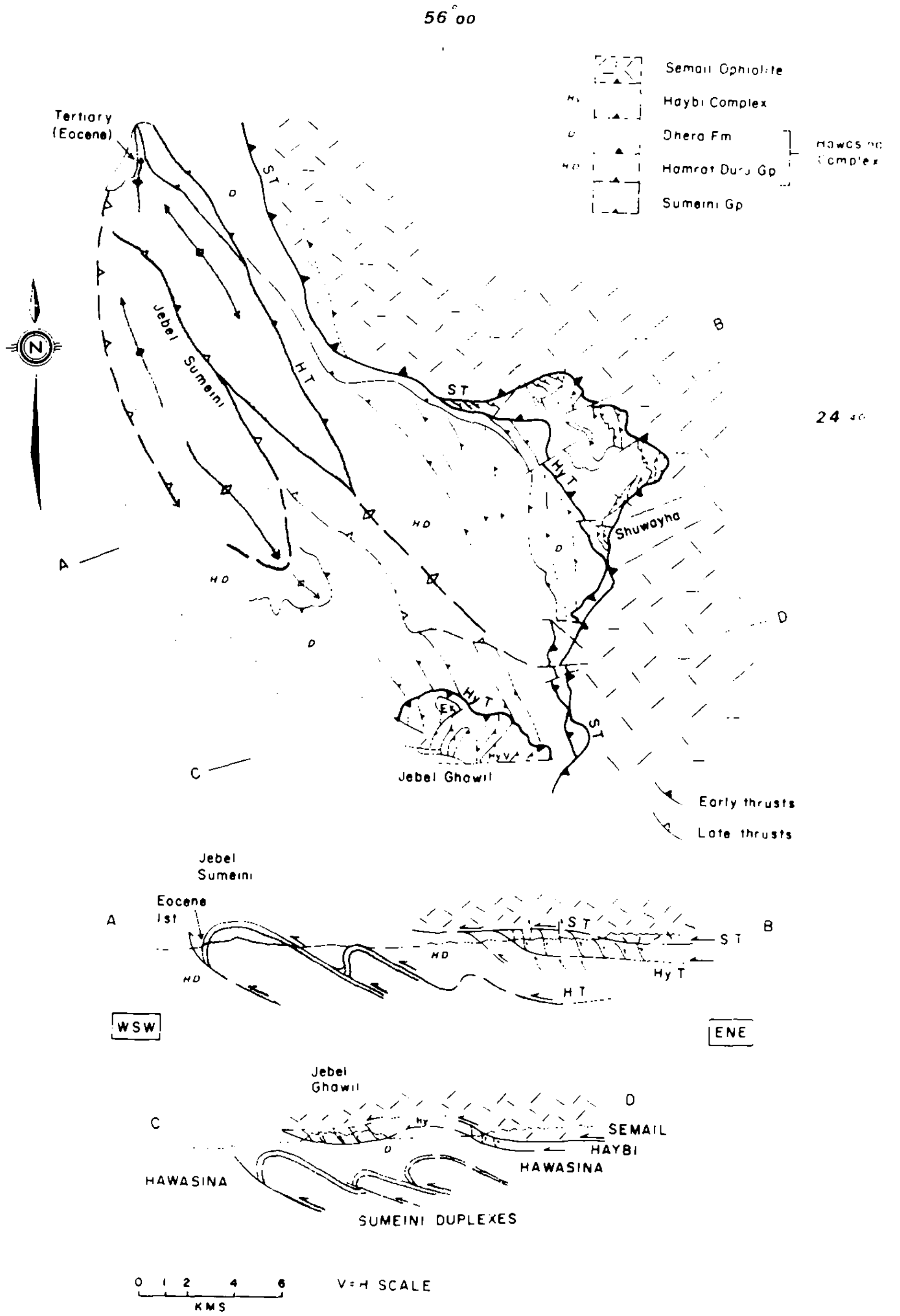


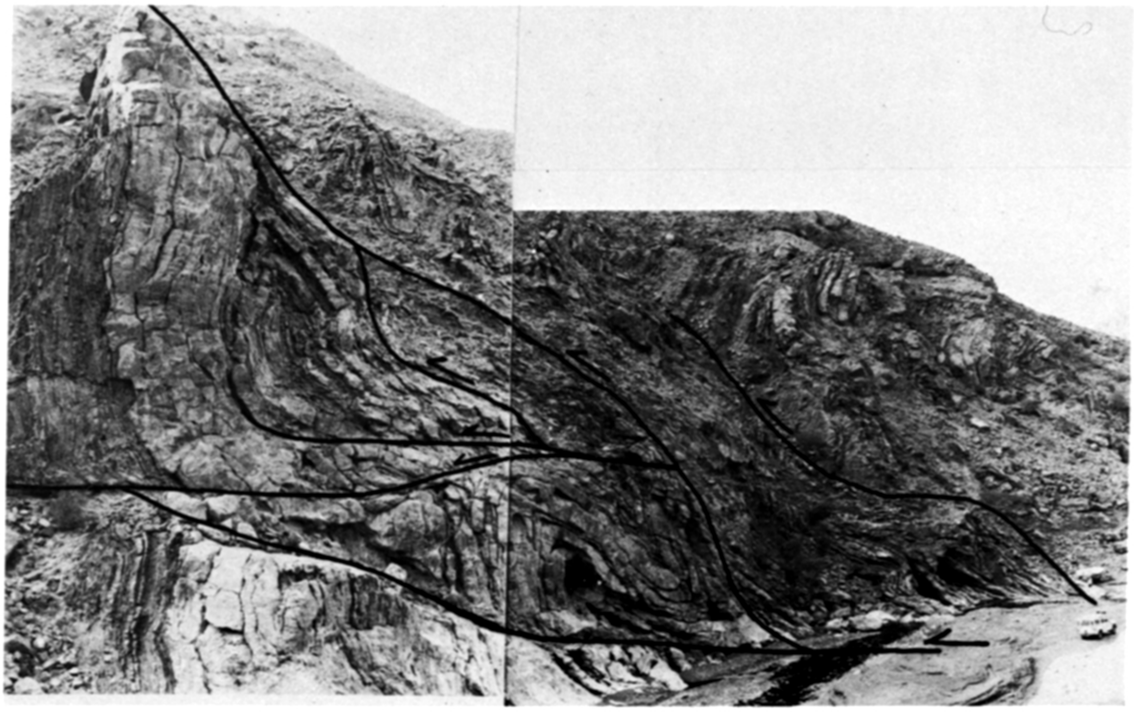
Fig. 4. Sketch map and cross-sections of the Sumeini half-window in the northern Oman Mountains. The Semail thrust S.T. Haybi thrust Hy. T., and Hawasina thrust H.T. are marked in thick black lines with solid teeth marks. The Semail thrust cuts down section towards the west in the northern area, eliminating the Haybi complex rocks to rest directly on the Dhera Formation. It also decapitates folds and imbricate thrusts in the Haybi duplex beneath and has therefore moved later, 'out-of-sequence'. Late-stage leap-frog thrusts associated with culmination of Jebel Sumeini (hollow teeth marks) have re-thrust Sumeini rocks over Hamrat Duru rocks. Eocene limestones with *Nummulites* sp. on the outer frontal fold indicate that culmination of Jebel Sumeini was a Tertiary event.

sheets. Emplacement of these thin-skinned thrust sheets was from the northeast; and along the base of the ophiolite, and in tectonic windows through the ophiolite, there is a regular stacking order of more distal units over more proximal units (Glennie *et al.* 1974, Searle & Malpas 1980, 1982, Searle *et al.* 1980, Graham 1980a,b).

It can be seen from the palinspastic reconstruction of the Oman continental margin (Fig. 2) that rocks spanning the same time period (Permian–Triassic to Cretaceous) occur in each major duplex except the Semail ophiolite, which is of Cenomanian–Turonian age. Thus there is no unique stratigraphy in each duplex—the rocks are in general all time-equivalent but of different palaeogeographic facies and position.

SUMEINI HALF-WINDOW

1:20,000 mapping of the Sumeini half-window in northern Oman (Fig. 4) shows that it was formed by



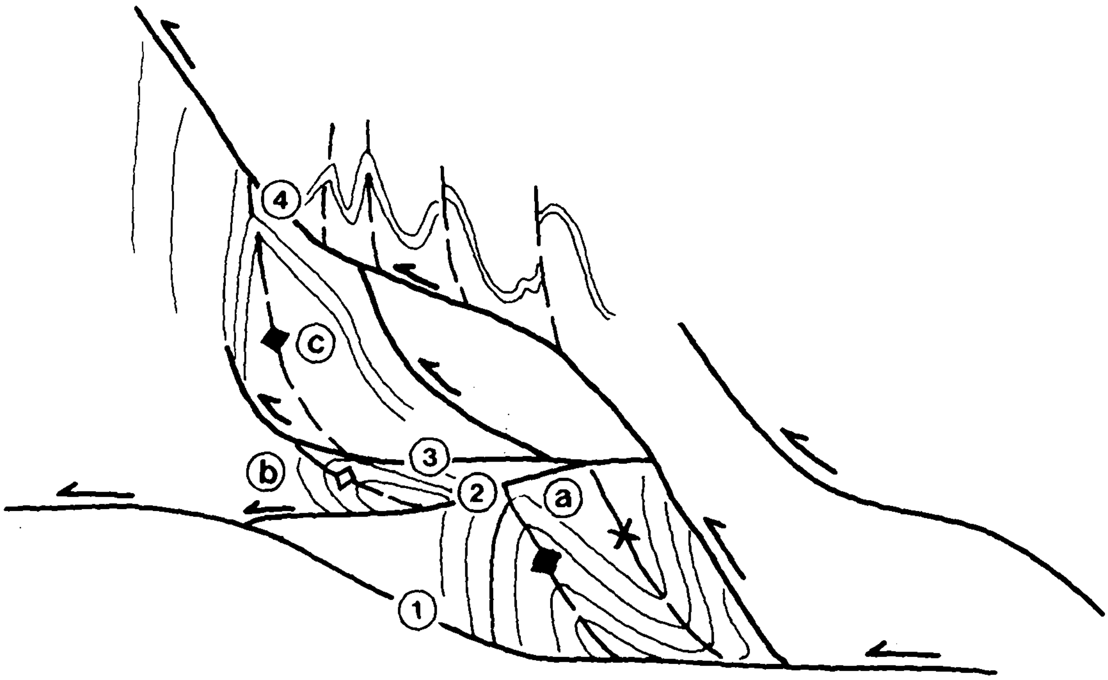


Fig. 5. Truncation of footwall imbricate slices by out-of-sequence thrusts magnificently illustrated in an outcrop of Guwayza Formation limestone (Hamrat Duru Group of proximal Hawasina complex) in Wadi Shafan, Haybi–Hawasina window, central Oman Mountains. Fold axial planes in imbricate slice (a) are truncated at right angles by overlying later thrust plane (2). The folds in imbricate slices (a), (b) and (c) are decapitated by their overlying roof thrusts (2), (3) and (4), respectively, which are all out-of-sequence thrusts. Elimination of rock in the fold hinge area has occurred in the footwall slices of these thrusts. In imbricate slice (c) the right-hand limb of the massive-bedded limestone has been tectonically eliminated by overlying thrust (4). The sequence of deformation in this outcrop has progressed with time starting with folding of imbricate slice (a) and motion on thrust (1) followed subsequently by (b2) to (c3), finally to roof thrust (4). Land Rover for scale in bottom right hand corner.

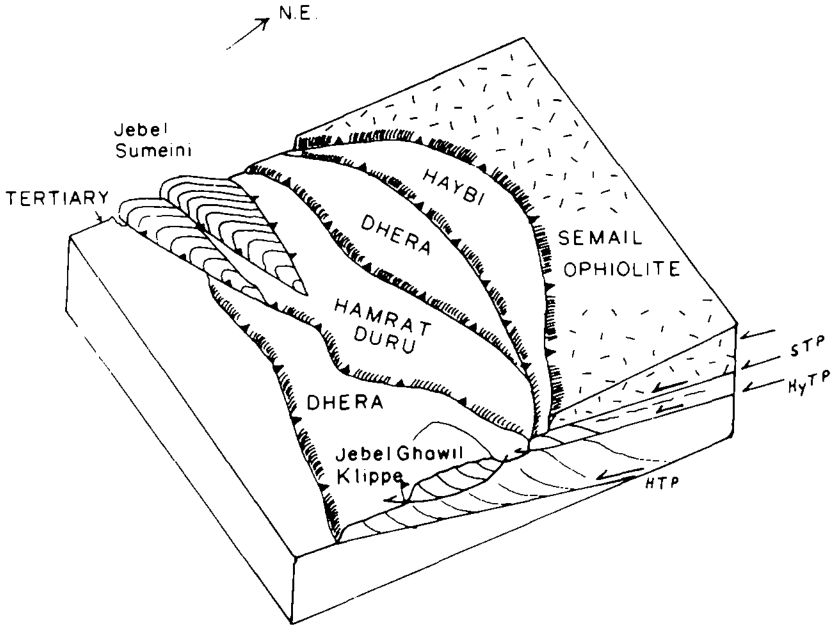


Fig. 6. Block diagram of the Sumeini half window to illustrate geometry of the major thrust sheets. Scale approximately 20 × 20 km.

erosion of the roof (Semail) thrust over a culmination to reveal a series of hinterland-dipping duplexes. These duplexes are from top to bottom the Haybi, Dhera and Hamrat Duru duplexes. Jebel Sumeini is composed of slope facies carbonates of the Maqam and Mayhah Formations (Fig. 2) which form the structurally lowest thrust sheets.

The Haybi complex (Searle & Malpas 1980, 1982, Searle & Graham 1982) is composed of Triassic alkaline and tholeiitic volcanic rocks, late Cretaceous olistostromes, sub-ophiolite metamorphic rocks and basal serpentinite in a series of eastward-dipping horses or imbricate slices. These rocks always underlie the Semail thrust and ophiolite and always overlie the Hawasina thrust sheets. Jebel Ghawil (Fig. 4) is a large klippe composed of Haybi volcanic rocks and Oman Exotic limestone that is infolded with amphibolites and greenschists of the sub-ophiolite metamorphic sheet resting on top of imbricated Dhera Formation sediments. The Dhera Formation and Hamrat Duru Group comprise a sequence of highly imbricated and folded continental slope and proximal basin sediments (Glennie *et al.* 1973, 1974, Graham 1980a,b).

The roof thrust of the Sumeini half-window is the Semail thrust which carries the complete ophiolite slab as a relatively intact thrust sheet. The ophiolite crops out over a width of about 40 km, and progressively higher levels occur towards the northeast. The trailing edge is nowhere seen but is assumed to dip gently NE beneath the Batinah coastal plain. The base of the Semail ophiolite is a sequence of dunites and harzburgites showing strong shearing fabrics and preferential serpentinization, termed the Banded Ultramafic Unit (Searle & Malpas 1980). A thin zone of basal serpentinite showing ductile deformation with conspicuous flow folding usually marks the actual décollement horizon.

Within the Sumeini half-window a regular stacking order is maintained with regard to the original palaeogeographic position of each major unit in Tethys. However, mapping shows definite time relationships with younger thrusts cutting older thrusts. Both the Semail thrust and the Haybi thrust truncate imbricate faults, folds, schistosity or cleavage and minor structures in the underlying duplex and are regarded as 'out-of-sequence' thrusts (Fig. 5). Along the north margin of the window the Semail thrust cuts progressively down to lower thrust sheets towards the west. The metamorphic sheet and Haybi volcanics have been structurally eliminated, and the ophiolite rests directly on the Dhera Formation. Elimination of section in footwall rocks can happen either through out-of-sequence thrusting, or in this case can be explained by an ENE-trending lateral ramp. The flat-lying Semail thrust can be seen to truncate, at right angles, the imbricate structures in the underlying Haybi complex. If stratigraphic section in the Haybi complex footwall has been eliminated during thrusting, the section cannot be balanced accurately.

Late-stage re-thrusting of the early thrust sheet pile can be ascertained from the Jebel Sumeini structures. Jebel Sumeini shows two major W-facing and W-verging hanging-wall anticlines above major thrusts (Fig. 6). The eastern one has re-thrust Sumeini Group (Maqam Formation) shelf edge carbonates over Hawasina (Hamrat Duru Group) proximal basin sediments that were earlier thrust on top of Sumeini rocks. Along the NW margin of Jebel Sumeini, Eocene nummulitic limestones crop out on the overturned limb of the W-facing frontal fold. Upper Triassic Jebel Wasa Formation (Sumeini Group) reefal carbonates have been thrust westwards over Lower Tertiary rocks. This would suggest a correlation of the late-stage re-thrusting event with the crustal-scale W-facing folds and thrusts of the Musandam peninsula to the north (Searle *et al.* 1983).

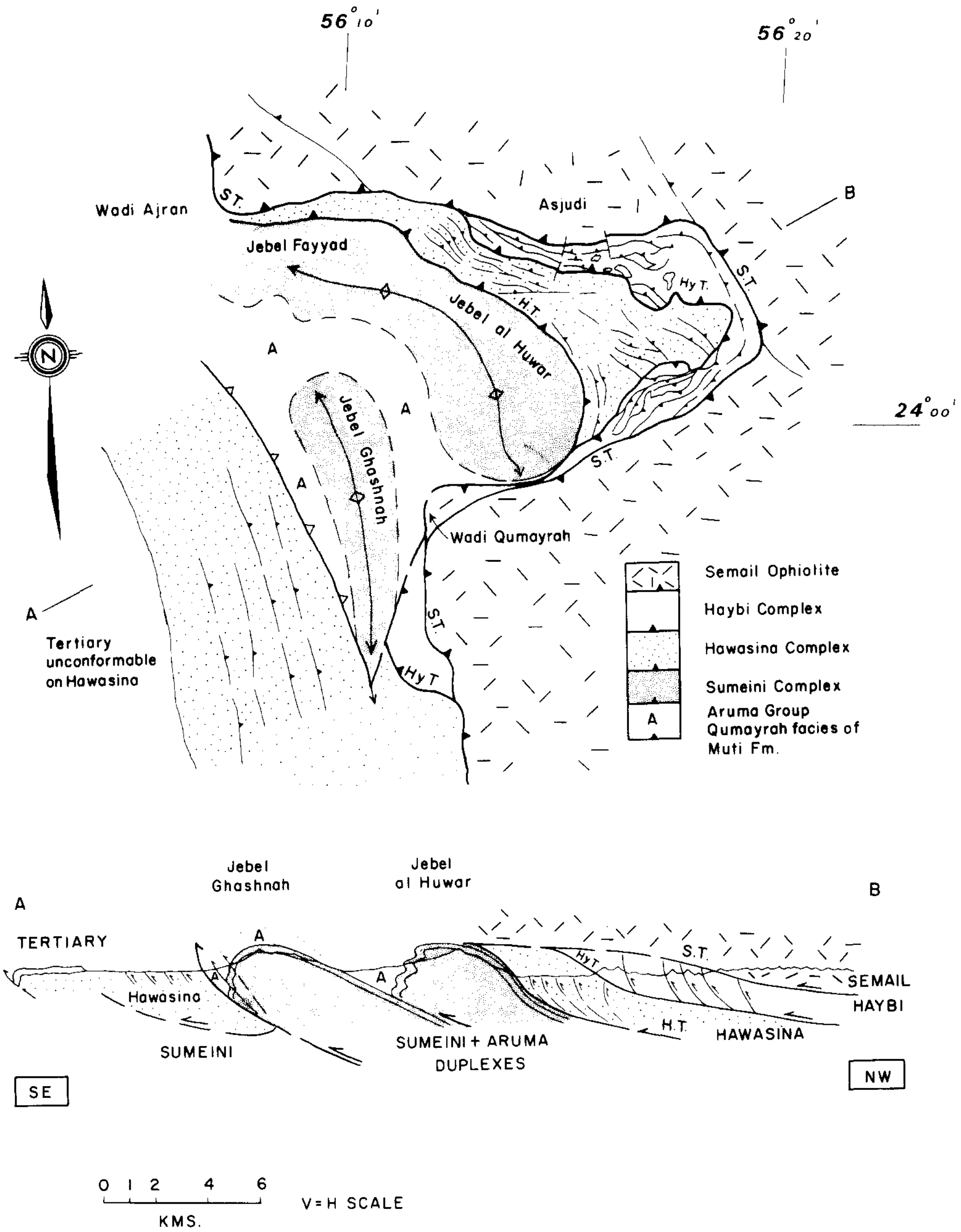


Fig. 7. Sketch map and cross-section of the Asjudi half-window in the central Oman Mountains. Symbols are same as for Fig. 4. The Semail thrust cuts down-section to the west eliminating Haybi complex and Hamrat Duru rocks to rest ophiolite directly on Sumeini Group shelf edge carbonates. Elimination of section and truncation of structures below indicate that the Semail thrust is an 'out-of-sequence' thrust. Late-stage culmination of Jebel Ghashnah and Jebel al Huwar also affects Muti Formation (Qumayrah facies, cherts, etc.) rocks of late Cretaceous (Coniacian to Campanian) age. The late-stage leap-frog thrusts that put Sumeini Group rocks over previously higher allochthonous Hamrat Duru rocks therefore must be Maastrichtian or early Tertiary in age. The nearest Tertiary rocks are 4 km west of Jebel Ghashnah and are flat-lying unconformably on imbricated Hamrat Duru. Further south in Jebel Awaynah the Tertiary rocks show a steeply inclined SW-verging frontal fold extending for 45 km along strike with a short-distance blind thrust at depth.

ASJUDI HALF-WINDOW

This is another culmination on the west side of the Oman Mountains, approximately 20 km south of Wadi Jizzi (Fig. 7). Mapping of the Asjudi half-window at 1:20,000 scale (Searle 1980) shows that, like the Sumeini half-window, it is composed of a series of E-dipping duplexes of Haybi, Hamrat Duru and Sumeini rocks. In this area the Haybi complex is a large-scale tectonic mélange with blocks of sub-ophiolite amphibolite and greenschist up to 1 km diameter, and smaller blocks of Haybi volcanic rocks, Oman Exotics and sediments all enclosed in a basal serpentinite matrix. The Semail thrust here also truncates underlying structures and the Haybi complex rocks have been progressively eliminated towards the west. Hamrat Duru rocks within the Asjudi window have also been progressively eliminated to the west until in the northern and southern parts of the window the Semail ophiolite rests directly on the Sumeini rocks of Jebel Fayyad.

Jebel Fayyad–Jebel al Huwar is a large-scale culmination of what is normally the lowest level thrust sheet of

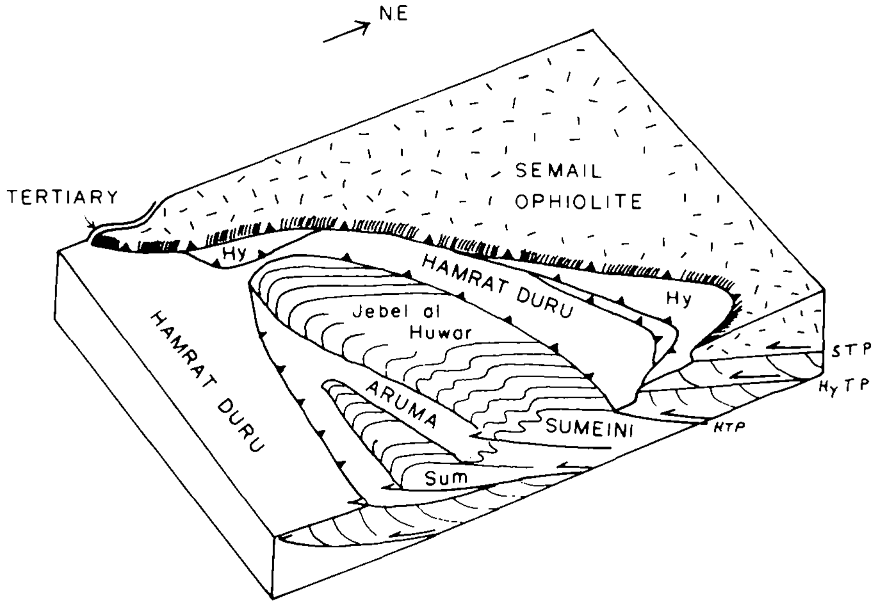


Fig. 8. Block diagram of the Asqudi half-window in the Central Oman Mountains to illustrate geometry of the major thrust sheets. Scale approximately 20 km length

Sumeini Group rocks. It shows two massive W-verging and W-facing inclined folds (Fig. 8), similar in style to Jebel Sumeini, and is surrounded by Hawasina complex rocks (K. Watts pers. comm. 1983). Culmination of these Sumeini structures was a late event during the emplacement history, because the overlying Hamrat Duru sole thrust is folded around the culmination along the east margin of the mountain. The two hanging-wall W-facing anticlines of Jebel Ghashnah and Jebel al Huwar show Mayhah Formation slope carbonates (Sumeini Group) thrust over Qumayrah facies rocks of the Muti Formation (Aruma Group), which are composed of deep-water radiolarian chert, conglomerate and shale of Cenomanian–Turonian age (K. Watts pers. comm. 1983). These rocks mark the deepening of the late Cretaceous foredeep—the Aruma basin, and have been incorporated into the thrust stack during later stages of the initial emplacement history. This Sumeini + Aruma package has been subsequently thrust westwards over normally higher Hamrat Duru rocks, thus reversing the normal stacking sequence.

Palaeogeographic irregularities cannot explain the thrust stacking here. The facies of the Hamrat Duru rocks clearly indicate a proximal slope environment; that is, deeper water (further northeast) than the shelf edge Sumeini rocks (D. J. W. Cooper pers. comm. 1983). Early thrusting events placed the more distal thrust sheets over the more proximal ones, so that the thrusts propagated downwards, piggy-back style, placing for example Hawasina over Sumeini over Aruma. Late-stage thrusts cutting up section through this stack then placed Sumeini + Aruma over Hawasina in a leapfrog style.

HAYBI CORRIDOR

The Haybi corridor (Fig. 9) is the northern extension of the Hawasina window, and the two together form one enormous window approximately 750 km^2 in area beneath the Semail ophiolite. The Haybi corridor was first mapped at 1:20,000 scale by Searle (1980), and the Hawasina window at 1:60,000 scale by Graham (1980). Both areas have recently been re-investigated in some detail and the structural evolution of the Hawasina window will be the subject of a separate paper (Searle & Cooper in preparation).

The eastern limit of the Haybi corridor is defined by the Haybi thrust (Searle 1980), which forms the roof thrust for the Hawasina thrust sheets in the Hawasina window, and the floor thrust for the rocks of the Haybi complex above. Progressively higher thrust sheets in the Haybi complex crop out towards the northwest as the main Hawasina–Haybi fold culmination plunges in that direction. This folding affects the Semail (roof) thrust and Haybi (floor) thrust and must post-date emplacement of the upper two major thrust sheets.

Within the Haybi duplex, all the imbricate thrusts that repeat the metamorphic sheet, the Haybi volcanic rocks and the mélange units dip NE with SW-facing folds and SW-directed thrust motion. A normal stacking order of major thrust sheets is apparent with Semail ophiolite overlying Haybi overlying Hawasina (Hamrat Duru Group) thrust sheets.

A late-stage secondary thrust has brought a Mayhah Formation (Sumeini Group) slope carbonate duplex (Jebel Sham) to high structural levels immediately beneath the Semail thrust (Fig. 10). This re-thrusting event put a previously lower Sumeini thrust sheet over previously higher Hamrat Duru and Haybi thrust sheets. Above the line of surface erosion (Fig. 10) the Jebel Sham thrust probably also cuts the ophiolite. The frontal fold is overturned towards the SW and thin overlying Aruma shales are also affected by the folds. The fold in the Semail thrust, which is also somewhat asymmetric, verging SW, and the Haybi corridor culmination were

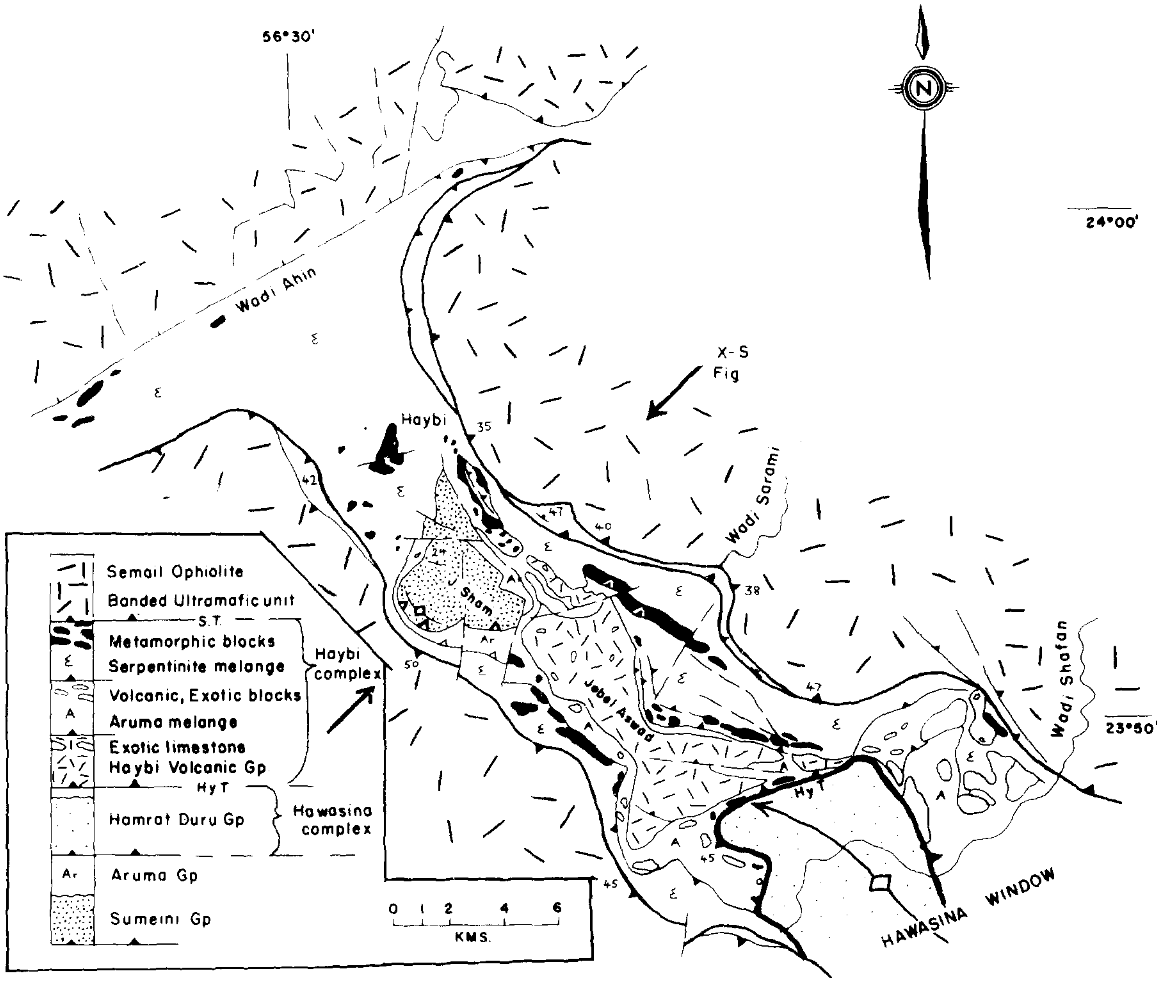


Fig. 9. Sketch map of the Haybi corridor, northward extension of the Hawasina window in the central Oman Mountains.

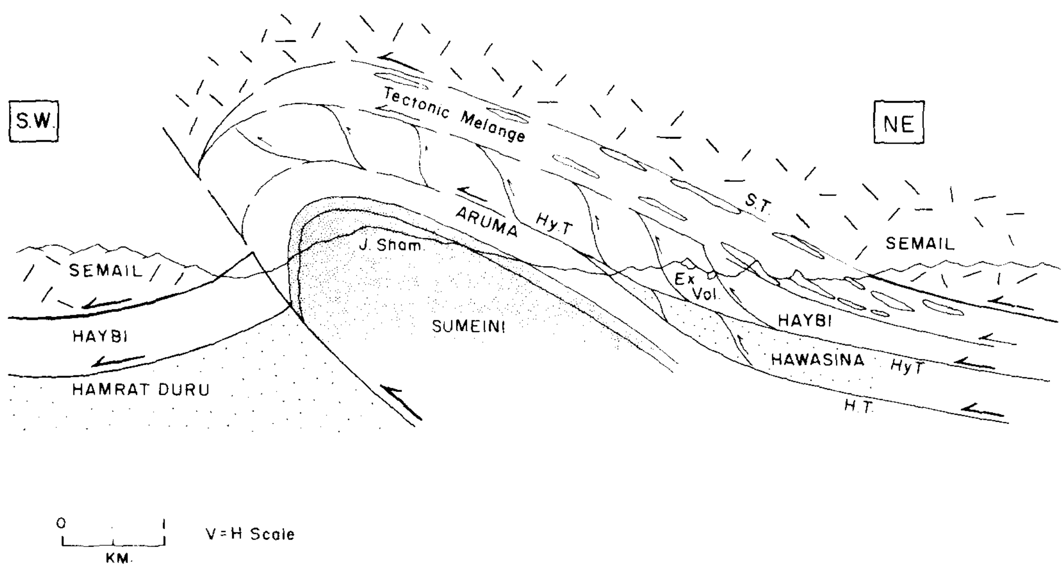


Fig. 10. Cross-section of the Haybi corridor-window. Normal stacking order of Semail ophiolite overlying Haybi complex overlying Hawasina (Hamrat Duru Group) overlying Sumeini complex is apparent. The Semail and Haybi thrusts show truncation of footwall folds, imbricate thrusts and schistosity and are interpreted as 'out-of-sequence thrusts' at least in the final motion. A late-stage Sumeini duplex of Mayhah Formation slope carbonates overlain by Upper Cretaceous (Coniacian to Campanian) Muti Formation (Qumayrah facies cherts) of the Aruma Group is exposed on Jebel Sham. This re-thrusting event puts a previously lower Sumeini thrust sheet over previously higher Hamrat Duru and Haybi thrust sheets and also probably cuts the base of the ophiolite above the line of erosion. Folding of the Semail (roof) thrust, which is somewhat asymmetric verging SW, was caused by the late-stage (post-Campanian) re-thrusting of the Sumeini duplex. The high structural level of the lowest Sumeini duplex may indicate deeper level thrusting in the shelf carbonates beneath the Haybi culmination coincident in time with or later than the leap-frog re-thrusting event.

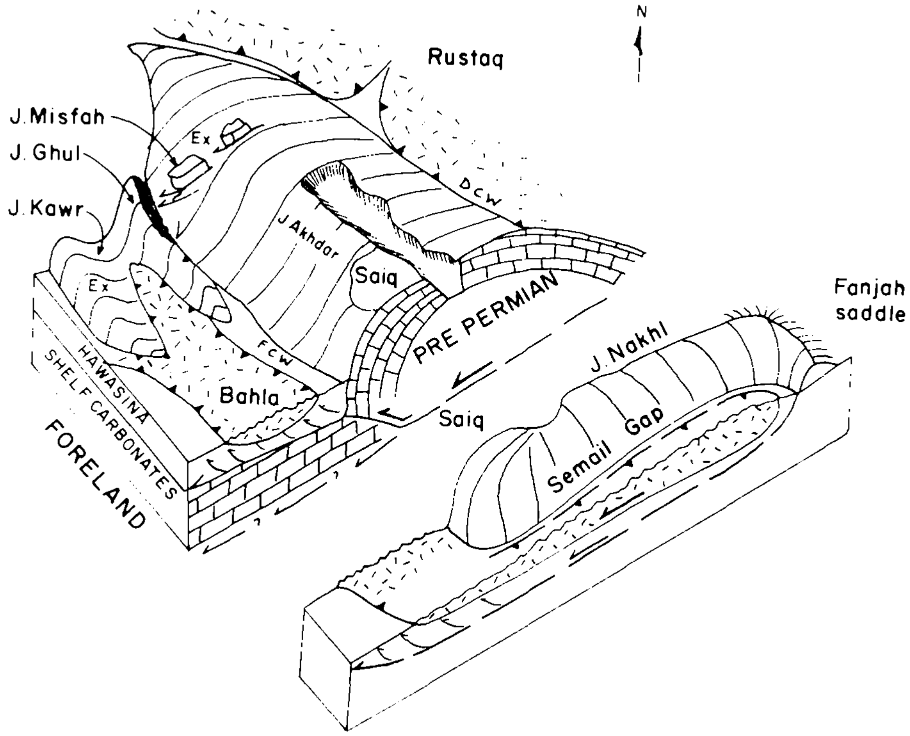


Fig. 11. Block diagram of the Jebel Akhdar anticline. Frontal ramp and blind thrust in the pre-Permian basement is taken from D. Bernoulli (1982) FCW, Frontal Culmination Wall; DCW, Dorsal Culmination Wall. Scale is approximately 70 km NE–SW length.

probably caused by the late-stage re-thrusting event of the Jebel Sham Sumeini duplex.

The high structural level of the normally lowest Sumeini thrust sheets may indicate deeper-level thrusting in the shelf carbonates beneath the Haybi culmination coincident in time with, or later than the Jebel Sham re-thrusting event.

JEBEL AKHDAR INLIER

The massive Jebel Akhdar anticline (35 km half-wavelength and more than 3 km amplitude) clearly formed after emplacement as the Hawasina, Haybi and Semail thrust sheets have been similarly affected and crop out all around the Jebel Akhdar massif (Fig. 1). At the western end, the anticline axis plunges gently NW beneath the Hawasina window indicating that at least part of the Hawasina Haybi window uplift must be related to the Jebel Akhdar doming. At the eastern end the NW–SE Jebel Akhdar anticline axis swings around to align NE–SW along the Jebel Nakhl axis which parallels the Semail Gap (Fig. 1).

The Jebel Akhdar massif shows the complete 5 km thick Permian to Cenomanian shelf carbonate sequence unconformably overlying folded and imbricated pre-Permian rocks. The deformation in the latter must be pre-middle Permian (?Hercynian) because structures are abruptly truncated by the flat-lying unconformity at the base of the Saiq Formation. Glennie *et al.* (1973, 1974) and Open University–Oman ophiolite maps and all previous workers have assumed the Jebel Akhdar shelf carbonates to be autochthonous and continuous south-westwards at depth into the undisturbed Arabian foreland.

Glennie *et al.* (1974) mapped thrusts repeating pre-Permian and Saiq Formation rocks in northern Saih Hatat even though they continually referred to the 'authochthonous' shelf carbonate sequence. In this area east of Muscat numerous high strain calc–mylonite shear zones, glaucophane–garnet–phengite blueschists (Lippard 1983) and intense thrusting indicate extensive deeper level deformation and high pressure metamorphism in the more internal (NE) part of the orogen.

D. Bernoulli (written comm., 1982) first suggested that "uplift of Jebel Akhdar could be related to late thrusting in the basement and to the development of a ramp directed towards the S.W." (Fig. 11). Bernoulli further suggested that "this thrust could follow a shallower décollement plane and emerge at the front of Jebels Salakh and Madmar at the southwest edge of the Mountain belt. The unconformable superposition of post-orogenic Lower Tertiary (Palaeocene to Lower Eocene, Montenat & Blondeau 1977) strata on platform deposits of the Saih Hatat (Glennie *et al.* 1974) suggests that all these movements occurred prior to the post-orogenic deposits" (Bernoulli written comm. 1982).

This geometrically attractive hypothesis cannot unfortunately be tested other than by drilling or deep seismic sounding across Jebel Akhdar. The age of this late compression is uncertain except that it must post-date the emplacement of the higher thrust sheets. No post-orogenic Tertiary sediments occur on the Jebel Akhdar structure, the nearest being over 30 km north of the Jebel Akhdar anticline axis north of Rustaq. Recent structural studies in Saih Hatat, support the contention that both Jebel Akhdar and Saih Hatat are hanging-wall anticlines above major basement thrusts that formed in late Cretaceous time (S. Hanna written comm. 1983).

The map pattern of the central Oman Mountains shows a dome and basin interference pattern resulting in the half-swastika shaped axial trace of the Jebel Akhdar–Jebel Nakhl–Saih Hatat anticline. The major domes, Jebel Akhdar and Saih Hatat are linked by the Fanjah saddle (Fig. 11). The major basins are the Bahla, Semail and Awabi–Rustaq ophiolite blocks. Whether these domes, basins and saddles are hanging-wall structures above a major basal décollement surface, as Bernoulli and Hanna suggested (see above) remains to be proven. The Jebel Akhdar structure may alternatively have been caused by Tertiary compression that followed soon after the main late Cretaceous emplacement of the major Tethyan thrust sheets, and hence be more closely related to the structures in the Musandam peninsula (Searle *et al.* 1983). There is no outcrop evidence for large-scale thrusting of the Jebel Akhdar shelf carbonates, as there is in the Musandam peninsula.

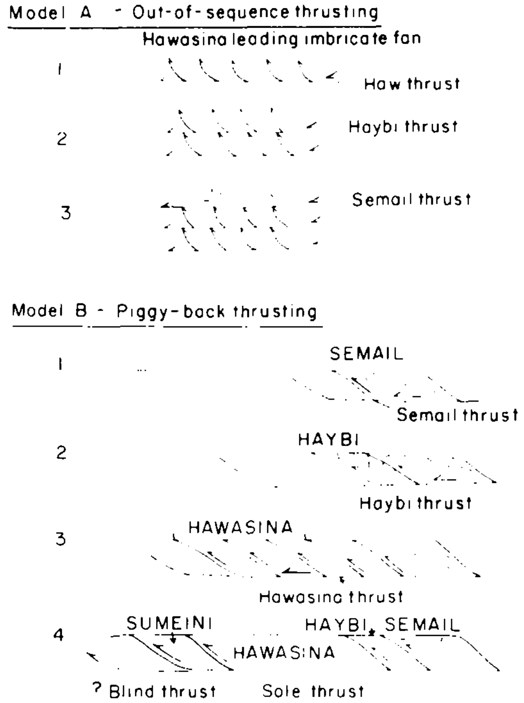


Fig. 12. Two sequential thrusting models (after Boyer & Elliott 1982, Butler 1982b). (Model A) Upward propagation of duplexes with younger, higher thrusts truncating older, lower thrusts. (Model B) Downward propagation of duplexes caused by progressive collapse of footwall ramps and accretion of slices to the hanging-wall.

TIME AND MOTION OF THRUSTS

The foreland propagating 'piggy-back' thrusting model and the hinterland propagating 'out-of-sequence' model (Fig. 12) are here considered as extremes, neither of which wholly match field data and maps of allochthonous terrains. Numerous examples, in the culminations of the Oman Mountains, show thrusts which do not 'obey' the rules of thrust propagation. These can be grouped into two categories: those produced by 'out-of-sequence' thrust processes, and reversals of regular stacking order by leap-frog thrust processes.

'Out-of-sequence' thrusting

'Out-of-sequence' thrusts are thrusts that cut through the hanging-wall of previous thrusts, so that higher nappes or thrust sheets cut lower ones. Evidence for 'out-of-sequence' thrusts is highly ambiguous and inconclusive, but five points may be indicative of 'out-of-sequence' character. (1) Thrusting of younger rocks over older. Thrust planes cut down section in the transport direction. (2) Truncation of footwall structures (folds, imbricates, etc.) by the floor thrust (Fig. 13). (3) Gross strain difference between upper relatively undeformed 'out-of-sequence' thrust sheet and lower highly deformed units. (4) Downward-facing structures in footwall units; upward facing structures in hanging-wall units (Fig. 14). (5) Elimination of stratigraphic section in footwall rocks.

Most late-stage backthrusting is 'out-of-sequence' related to continued compressive stress after the initial thrusting. The most spectacular example of this is the 10–30 km wide zone of backthrusting along the Indus suture zone and northern margin of the Tibetan-Tethys zone (Indian plate) in the Ladakh and Zanskar Trans-Himalayan region (Searle 1983).

'Out-of-sequence' thrusting has also been described from California where the Palaeocene–Eocene Coast Range thrust, now separating the Coast Range ophiolite from the Franciscan accretionary prism (Korsch 1983), developed late in the sequence near the first-formed

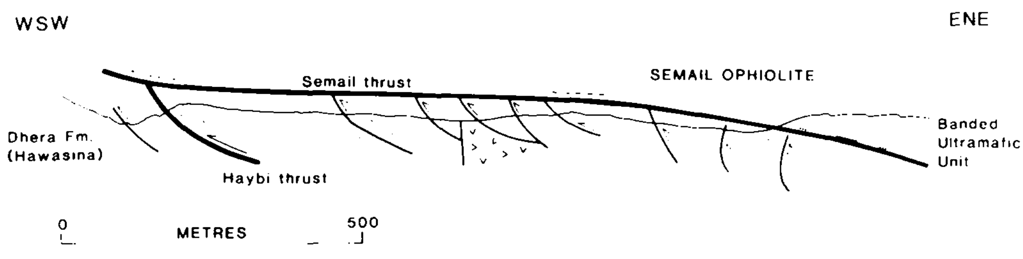


Fig. 13. Truncation of structures in the Haybi complex by the flat-lying out-of-sequence Semail thrust illustrated in a cross-section along the northern margin of the Sumeini Window. Dashes, amphibolites and greenschists of metamorphic sheet; v, Haybi volcanic rocks; dots, late Cretaceous olistostromes and mélange units.

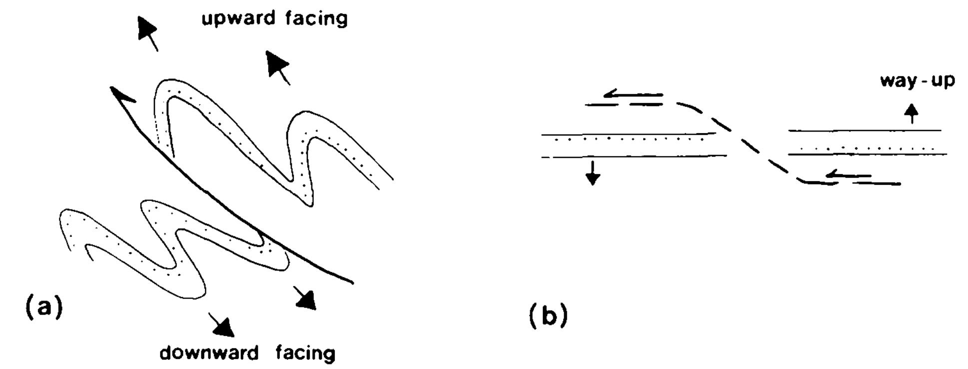


Fig. 14. (a) Opposing facing directions (thick arrows) of folds on either side of a thrust plane indicate out-of-sequence character of thrust plane. (b) The sketch indicates the impossibility of inverted beds passing into right way-up beds in the restored section.

Mesozoic thrusts of the Franciscan. In gravity sliding terrains such as the Maritime Alps in southern France (Graham 1981), most of the thrusting is 'out-of-sequence'. The lower nappes are the farthest travelled and the higher nappes cut the lower ones.

The Moine thrust of NW Scotland also shows 'out-of-sequence' characteristics in some anomalous regions, in that it seems to have moved later than the underlying structures. Coward (1983) shows a map (fig. 5, p. 800) and cross-section (fig. 7, p. 801) in the Elphin area of the Assynt half-window, of the later Moine thrust cutting previously formed folds and slicing off imbricates beneath. Late-stage surge zones associated frequently with culmination collapse are also underlain by 'out-of-sequence' listric faults, such as those described from the Assynt region by Coward (1982).

The downward-propagating piggy-back thrust sequence does not allow for elimination of underlying rocks if the section is to balance correctly. If thrusts develop downwards in sequence the volume of rock beneath the roof thrust must remain constant, and hence the area of a duplex in cross-section must balance the undeformed area prior to thrusting (Dahlstrom 1969, Hossack 1979, Elliott & Johnston 1980). If structural elimination of rock has occurred below a roof thrust it may have been caused by 'out-of-sequence' thrusting, and a cross-section cannot therefore be balanced accurately. The eliminated rock must either have been eroded away from leading edges of thrust sheets, or it must have been sliced off mechanically by the later, higher 'roof' thrust.

In Oman, elimination of underlying thrust slices has occurred in all the culminations beneath the Semail ophiolite studied. The Semail thrust has cut down section as far as the Dhera thrust sheet in the Sumeini half-window (Figs. 4 and 6) and as far as the Sumeini thrust sheet in the Asjudi half-window (Figs. 7 and 8). Around Jebel Akhdar the Semail ophiolite rests directly on the shelf carbonate sequence; all the lower thrust sheets in between except for a thin mélange zone have been structurally thinned or eliminated. The elimination of some of the Hawasina rocks could be accounted for by local palaeogeographic or bathymetric anomalies in the Tethyan ocean but most of the elimination appears to have been structural.

Leap-frog thrusting

Since the work of Glennie *et al.* (1973, 1974) a regular stacking order of major thrust sheets with more distal stacked over more proximal units has been known. Mapping in the Sumeini, Asjudi and Haybi–Hawasina culminations has shown common reversals of the normal stacking order. A schematic hanging-wall evolution diagram (Fig. 15) shows how culminations and folds of the roof thrust formed by development of secondary thrusts cutting through the already assembled allochthon. This diagram explains why, in Oman, at least two stages of thrusting must be inferred: (1) normal stacking of Semail ophiolite thrust over distal Hawasina sediments thrust over Sumeini Group shelf edge carbonates thrust over autochthonous shelf and (2) re-thrusting of previously lower more proximal nappes over previously higher

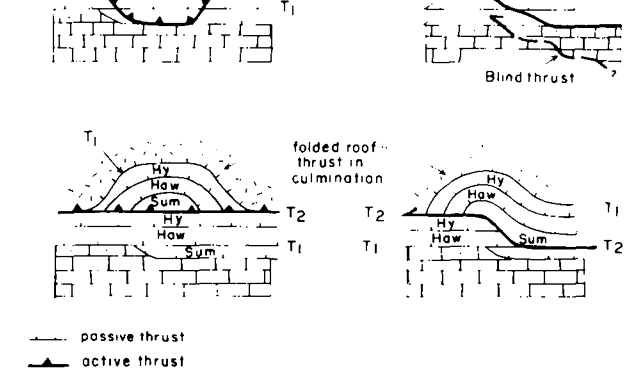


Fig. 15. Schematic hanging-wall evolution diagram (after Elliott & Johnson 1980) showing development of culminations during late-stage re-thrusting at depth and folding of the roof thrust. (a) Viewed looking down plunge (NE) from frontal part of the thrust sheet. (b) Cross-section showing late thrusts (T_2) cutting through earlier formed duplexes. HWR, hanging-wall ramp.

more distal units. Palaeogeographic irregularities prior to thrusting cannot be inferred; otherwise in Oman a chaotic pattern of isolated Arabian shelf and slope carbonates would have to have been separated by small distal chert basins to account for the stacking order. It is absolutely clear that at least two, and probably more, episodes of thrust stacking have occurred in a leap-frog fashion.

The critical localities where this leap-frog thrusting can be demonstrated are (a) Jebel Sumeini (Fig. 4), (b) Jebel Fayyad–Jebel al Huwar (Fig. 7), (c) Jebel Sham, Haybi (Fig. 9), (d) Wadi Jizzi where the Semail ophiolite has been duplicated by later thrusting (Open University Oman Ophiolite map sheet 2) and (e) Wadi Ham (UAE) where the metamorphic sheet and mantle sequence has been re-thrust, duplicating the sequence (Searle & Malpas 1980).

The most spectacular example of leap-frog re-thrusting occurs in the Musandam mountains in the far north of the Oman Mountain belt (Searle *et al.* 1983). The shelf carbonates that comprise the Musandam Mountains can be correlated almost exactly with the Permian to Cenomanian succession exposed in Jebel Akhdar and in the UAE–Oman foreland; they were clearly part of the stable Mesozoic Arabian passive margin. In common with the rest of the Oman Mountains the Musandam shelf carbonates were overthrust by the Hawasina Tethyan basin sediments during Turonian–Early Maastrichtian time. These rocks are now exposed in a series of ESE-dipping thrust sheets in the Dibba zone (Searle *et al.* 1983).

After emplacement of Tethyan basin rocks and the Semail ophiolite, stable shallow marine carbonates were deposited during late Maastrichtian to early Eocene time. Subsequent compression during post–middle Eocene time caused thrusting of the complete Musandam shelf carbonate sequence up to 15 km eastwards over previously allochthonous Hawasina cherts along the Hagab thrust (Hudson *et al.* 1954, Searle *et al.* 1983). This Zagros orogenic phase shows crustal-scale thrusts and may reflect the actual time of collision of the Oman continental margin with the NE-dipping subduction zone in the Gulf of Oman.

CONCLUSIONS

The structural development of the Oman Mountains allochthon can be discussed in a chronological sequence.

(1) The first stage was a sequence of thrusting that propagated downwards and towards the foreland. The inverted metamorphic sole of the ophiolite records the earliest sequence of deformation. This involved underplating of Tethyan oceanic volcanics and sediments beneath the young hot ophiolite, probably in some sort of Cenomanian–Turonian subduction zone (Searle & Malpas 1980, 1982). The underlying Haybi, Hawasina and Sumeini thrust slices were probably assembled by successive propagation of footwall ramps in the direction of emplacement from NE to SW. Processes may have been similar to those operating in modern accretionary prisms above subduction zones (Seely *et al.* 1974). Complexities in thrust sheet geometry, as in every thrust belt, were caused by an irregular footwall topography of the sole thrust, mainly frontal and oblique ramps, which may have been the actual Cretaceous shelf edge.

(2) Later stages of motion must have occurred on the basal Semail, Haybi, Hawasina and Sumeini thrusts, with each major duplex acting as an independent body. The surface traces of these thrusts are mappable along the length of the mountains where exposed, and all minor structures within these duplexes are truncated abruptly at the thrust contact. Detailed mapping in the Sumeini, Asjudi and Haybi–Hawasina windows (Searle 1980) shows clear evidence of truncation of footwall folds, imbricate thrusts and all minor structures by the roof thrust.

The Semail thrust (the roof thrust of the Haybi complex and the floor thrust of the ophiolite) seems to fit the criteria for 'out-of-sequence' thrusts. Even though the rocks are lithologically very different, there is a great difference in strain between the relatively undeformed ophiolite slab (approximately 450 × 90 × 1 14 km) above the Semail thrust and the intensely imbricated and deformed rocks of the Haybi and Hawasina thrust sheets beneath. The Semail thrust also truncates all lower thrust sheets and may rest on any lower duplex or even directly on the shelf carbonate sequence. The elimination of over 5 km thickness of sub-ophiolite thrust sheets occurs along the north, east and south margins of the Jebel Akhdar Massif and cannot be accounted for by lateral ramps. Structural elimination of rock beneath the Semail thrust has occurred; this cannot have happened if lower thrusts developed after the latest movement along the higher Semail thrust. In the Asjudi and Sumeini half-windows it can be demonstrated that the Semail thrust cuts down section towards the southwest in the direction of emplacement. It is therefore proposed that the Semail thrust is out-of-sequence. The Haybi thrust and a few Hawasina thrusts also truncate underlying folds and imbricates, and these may also have been out-of-sequence thrusts.

(3) The final stage was a leap-frog re-thrusting event, usually of deeper level thrust sheets (e.g. the Musandam shelf carbonates, and the Sumeini thrust sheets in Jebels Sumeini, Fayyad and Sham). It is suggested that many of the culminations in the northern Oman Mountains, notably the Musandam peninsula, the Haybi–Hawasina window, the Sumeini and Asjudi half-windows and the Jebel Kawr culmination, were formed by ramping associated with late-stage leap-frog re-thrusting. In all these areas it can be demonstrated that late thrusts cut up-section through an already assembled thrust stack, putting previously younger and lower duplexes over previously older and higher duplexes. Whereas translation on early stage (1) thrusts is of the order of 100 km or more, the translation on stage (3) leap-frog thrusts is generally only 15 km or less, sometimes less than 1 km.

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