Journal of Structural Geology, Vol. 5, No. 1, pp. 1 to 17, 1983
Printed in Great Britain

0191-8141/83/010001-17 $03.00/0
Pergamon Press Ltd.

Genesis of the Batinah mélange above the Semail ophiolite, Oman

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(*Received* 6 *August* 1982; *accepted in revised form* 24 *September* 1982)

Abstract—The Batinah mélange which overlies the late Cretaceous Semail ophiolite in the northern Oman Mountains comprises mostly sedimentary rocks of deep-water facies, alkalic lavas and intrusives, all of continental margin affinities, together with smaller volumes of Semail ophiolitic and metamorphic rocks. Four intergradational textural types of mélange can be recognized. Sheet mélange has large (>1 km) intact sheets either with little intervening matrix or set in other mélange types, and with an organised sheet orientation fabric. Slab mélange is finer textured (>100 m) and more disrupted. Block mélange has smaller (> m) blocks with some matrix and a weak to random block fabric. Clast mélange is matrix-supported rudite with a weak depositional clast fabric. Structural relationships, particularly the absence of tectonic fabrics, the decreasing strength of fragment fabrics with increasing fragmentation, and the abundance of brittle fragmentation, suggest that these mélange types formed by either gravity-driven sedimentary processes or superficial sliding or thrusting of individual rock slabs.

In the slab mélange, long sequences can be pieced together, passing up from Upper Triassic mafic sub-marine extrusives and sediments into radiolarian cherts, hemipelagic and redeposited limestones, and terminating in non-calcareous radiolarities with Mn-deposits of early Cretaceous age. Mafic sills are numerous. These sequences can be matched with sub-ophiolite rocks now exposed in fault corridors through the Semail. These sequences become progressively disrupted upwards in the corridors and can be traced continuously into overlying mélange, which then thins away from the corridors.

We argue that, during late Cretaceous emplacement over the Arabian margin, active fault corridors split the Semail slab and acted as conduits up which sub-ophiolite rocks were supplied to the ophiolite surface. There the rocks were redisributed by superficial processes.

INTRODUCTION

MÉLANGES associated with ophiolites often give a valuable insight into mechanisms and tectonic settings of ophiolite emplacement (e.g. Gansser 1974, Saleeby 1979, Smith *et al.* 1979, Searle & Malpas 1980, Searle *et al.* 1980). Here we focus on the Batinah mélange, composed mostly of sedimentary and igneous continental margin lithologies, which overlies the Semail ophiolite of Oman in an apparently anomalous position. The Semail is regarded as a major example of oceanic crust and mantle tectonically emplaced over an adjacent deformed passive margin (Glennie *et al.* 1974, Graham 1980).

The major problem is to explain how mélange rocks matching those beneath the ophiolite came to overlie it during late Cretaceous time. Here, based on field mapping, correlation of sedimentary logs and structural analysis, we will argue that this unusual mélange formed when the Semail ophiolite broke into separate blocks during its tectonic emplacement over the Arabian continental margin. Sub-ophiolite rocks were able to move up through fault-bounded corridors and be redistributed above the ophiolite by gravity-driven mechanisms. This remarkable process does not seem to have been described elsewhere.

GEOLOGICAL SETTING

We have noted elsewhere (Woodcock & Robertson 1982a) that the Batinah mélange has a consistent position in the structural sequence above the Semail ophiolite (Fig. 1). The extrusives and pelagic sediments of the Semail are overlain first by the Zabyat Formation, ophiolite-derived clastics related to the early stages of emplacement of the Semail Nappe, while it was still in an open oceanic setting (Robertson & Woodcock 1982). The Batinah mélange overlies the Zabyat Formation and is itself structurally overlain by the tectonic sheets forming the upper part of the Batinah Complex (section, Fig. 1). These sheets record the sedimentary transition across the outer part of a Mesozoic passive margin, apparently located northeast of Oman during Mesozoic time (Woodcock & Robertson 1982b). The tectonic stack comprising the Semail and Batinah Complexes is depositionally overlain by open-folded or undeformed late Cretaceous to Recent sediments forming much of the coastal plain.

The marked variation in outcrop width of the Batinah mélange (Fig. 1) mainly reflects thickness variations along strike. The thickest accumulations are above fault zones which cut the Semail ophiolite (Fig. 1). The mélange thins rapidly onto the intervening unfaulted

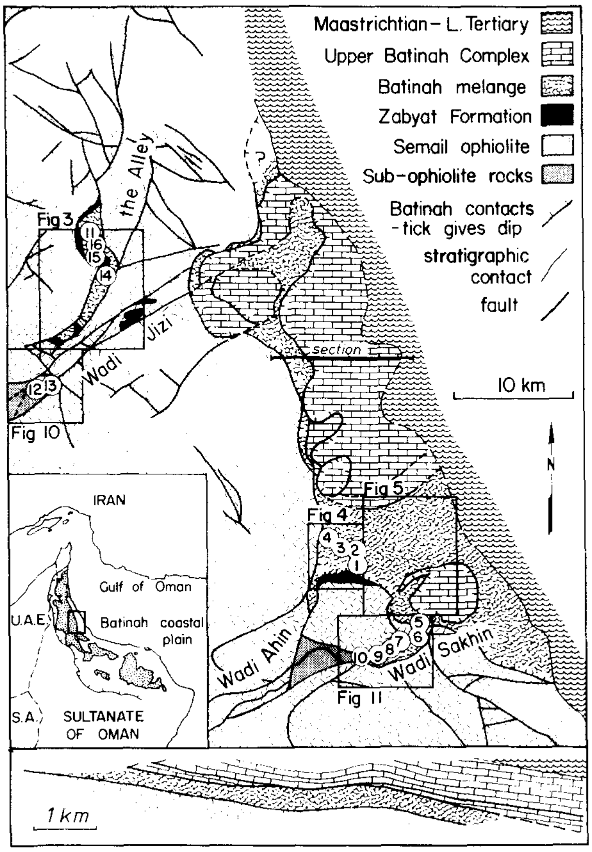

Fig. 1. Map of the best-exposed area of Batinah mélange. Area is marked on inset in relation to Semail ophiolite (stippled) and Hawasina thrust front (ticked). A cover of Tertiary to Recent sediments obscures about 50% of the mélange on the main map. A line on the map locates the true-scale vertical section below the map. Boxes outline the detailed map areas in Figs. 3, 4, 5, 10 and 11. Numbers locate the lithological logs in Figs. 6–8.

ophiolite blocks and is occasionally missing completely. The ENE-trending Wadi Sakhin/Wadi Ahin and Wadi Jizi zones now crop out as fault-bounded, topographically low corridors containing upfaulted rocks from below the ophiolite. These sub-ophiolite rocks match closely the lithologies present in the Batinah mélange. The role of the corridors as possible sources for the mélange material will be discussed later.

Equivalents of the corridor rocks and the Batinah mélange also crop out discontinuously beneath wadi gravels further south in the central Oman Mountains; in part the ‘Oman Mélange’ mapped by Glennie *et al.* (1974).

STRATIGRAPHY AND AGE DATA

The stratigraphy of the Batinah mélange, relative to other units of the Batinah Complex and the Semail ophiolite in shown in Fig. 2. Mélange formation has not been directly dated, for example by fossils from the mélange matrix. However, good age constraints are provided by (a) dated fragments within the mélange, (b) dated sequences stratigraphically below the mélange and (c) dated sequences unconformably overlying the mélange.

Mélange fragments include lavas with interbedded radiolarian cherts and calcilutites yielding Upper Triassic *Halobia*, and separate radiolarian cherts giving a late Valanginian to early Hauterivian (Early Cretaceous) age (E.A. Pessagno, pers. comm. 1980). In the fault corridors lithologies are again mostly Upper Triassic, and radiolaria range to Lower Cretaceous (upper Valanginian–lower Hauterivian, E. A. Pessagno, pers. comm. 1980). The Batinah mélange additionally contains blocks of Upper Triassic reef limestone (Oman exotics, Glennie *et al.* 1974), mafic igneous rocks, matched with the Upper Triassic and Cretaceous Haybi Complex beneath the Semail (Searle *et al.* 1980), and also metamorphic rocks lithologically similar to those of the Semail metamorphic sole, radiometrically dated at between 95 and 72 Ma (Cenomanian to Campanian, Late Cretaceous, Lanphere 1979). The mélange fragments, therefore, range in age from Triassic at least to Early Cretaceous and possibly into Late Cretaceous. Mélange formation must post-date all included fragments.

The mélange stratigraphically overlies either the Zabyat Formation (undated directly) or Semail lavas and pelagic sediments (Cenomanian–Coniacian). The emplacement of the Upper Batinah Complex over the mélange is not directly dated, but the whole complex is unconformably overlain by Palaeocene or locally late Maastrichtian sediments. Given these constraints, the mélange most probably accumulated in late Campanian to early Maastrichtian time.

MÉLANGE TYPES AND COMPOSITION

The important field observations from the mélange are shown on lithological logs (Figs. 6–8) and geological maps with inset equal-area projections of structural data (Figs. 3, 4, 5, 10 and 11). The key to the maps is in Fig. 2, the locations of the maps and logs being in Fig 1. Some minor areas of mélange are not depicted here by detailed maps but appear on previously published maps of the Upper Batinah Complex (Woodcock & Robertson 1982b). The structural fabrics in the mélange are summarized in Fig. 9 and are discussed separately in a later section.

For description we distinguish four intergradational mélange types based on internal texture and structure: (i) sheet mélange, (ii) slab mélange, (iii) block mélange and (iv) clast mélange. Only the clast mélange is consistently matrix-supported and some slab and block mélange apparently has very little matrix. We realize that use of the term ‘mélange’ for such rock bodies seems to conflict with the original and more recent definitions of the term (see Greenly 1919, Hoedemaeker 1973) in which presence of matrix is stressed. We justify our usage in that some matrix is always present, even if it only fills interstices between fragments. In parts of the Batinah mélange ‘soft’ fragments may have partly taken the mechanical role of matrix during mélange formation. All our mélange types have the fragmentary and mixed

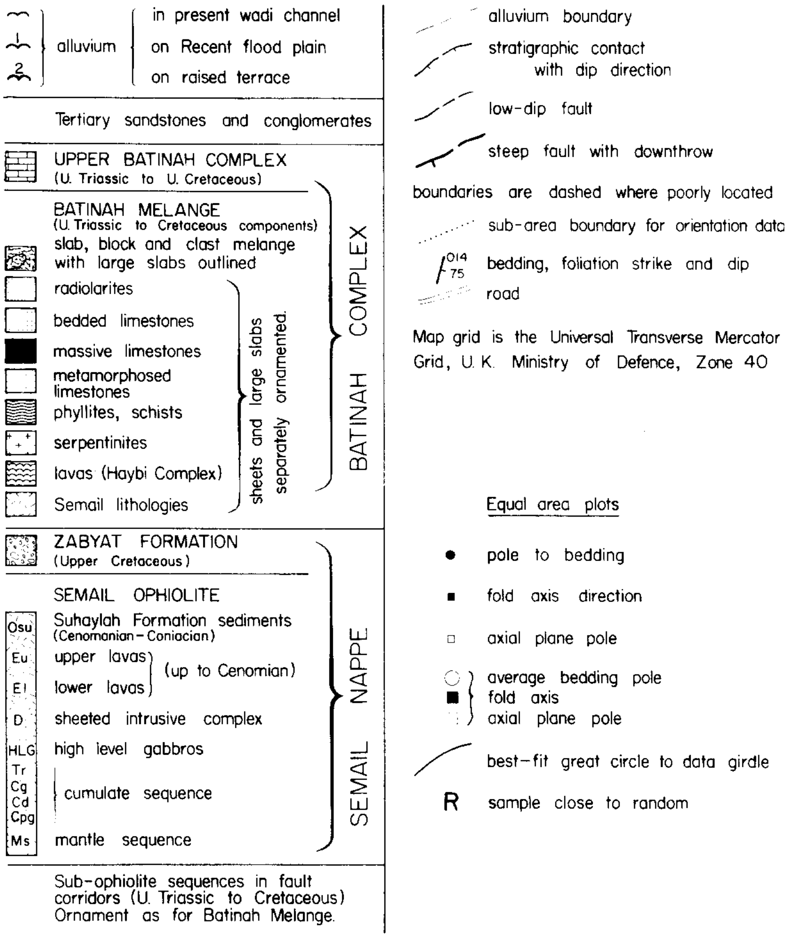

Fig. 2. Stratigraphy of the Semail ophiolite and Batinah Complex with a key to the detailed geological maps and structural insets in Figs. 3, 4, 5, 10 and 11.

nature, the structural complexity and the gross mappability regarded as field characteristics of mélanges.

Sheet mélange

Sheet mélange is characterized by intact sequences which can be mapped laterally over 1 km. On the maps of this account, individual sheets are outlined and ornamented separately. These intact sheets are stacked over and alongside each other, mutually subparallel, some with thinner intervening zones of finer-textured mélange. The resulting coarse sheet mélange terrains may grade either vertically or laterally into other mélange types so that in some places single sheets are completely isolated in surrounding finer mélange.

Typical sheet mélange occurs in places between Wadi Ahin and Wadi Forest (e.g. around 560670, 575660, 580650, Fig. 4). Sheets here contain hemipelagic *Halobia*-bearing limestones and radiolarites, commonly underlain by mafic pillow lavas and lava breccias and intruded by dolerite or pegmatitic gabbro sills (e.g. logs 1, 2, 3 and 4 of Fig. 6). The gabbro sills, up to 25-m thick, are chilled against skarns produced by thermal metamorphism of adjacent siliceous and calcareous pelagic sediments. Traced laterally these sills are variably serpentinized, providing highly incompetent zones of detachment within the mélange. Indeed north of Wadi Ahin much of the serpentine appears to derive from serpentinized gabbro pegmatites rather than true Semail ultramafic rocks. Serpentinite is virtually absent south of Wadi Ahin where thick gabbroic sills have not been recognized.

Between Wadi Sakhin and Wadi Ahin more isolated sheets are surrounded by finer mélange (e.g. around 620645 and 630610, Fig. 5). The sheet sequences comprise similar lavas and pelagic sediments but with fewer intrusives (e.g. log 5, Fig. 7).

The other main developments of sheet mélange are in the southern Alley (e.g. around 375910 and 385885, Fig. 3). The sheets again contain radiolarites and pelagic limestones overlying mafic lavas (logs 14, 15 and 16 of Fig. 8).

Slab mélange

Slab mélange is crudely stratiform mélange dominated by fragments from 100 m up to 1 km in length, and involving sequences several tens of metres thick. On the maps of this account large slabs are outlined but only the largest are separately ornamented. Adjacent slabs may be in direct contact or separated by a zone of either sheared rock or finer-textured mélange.

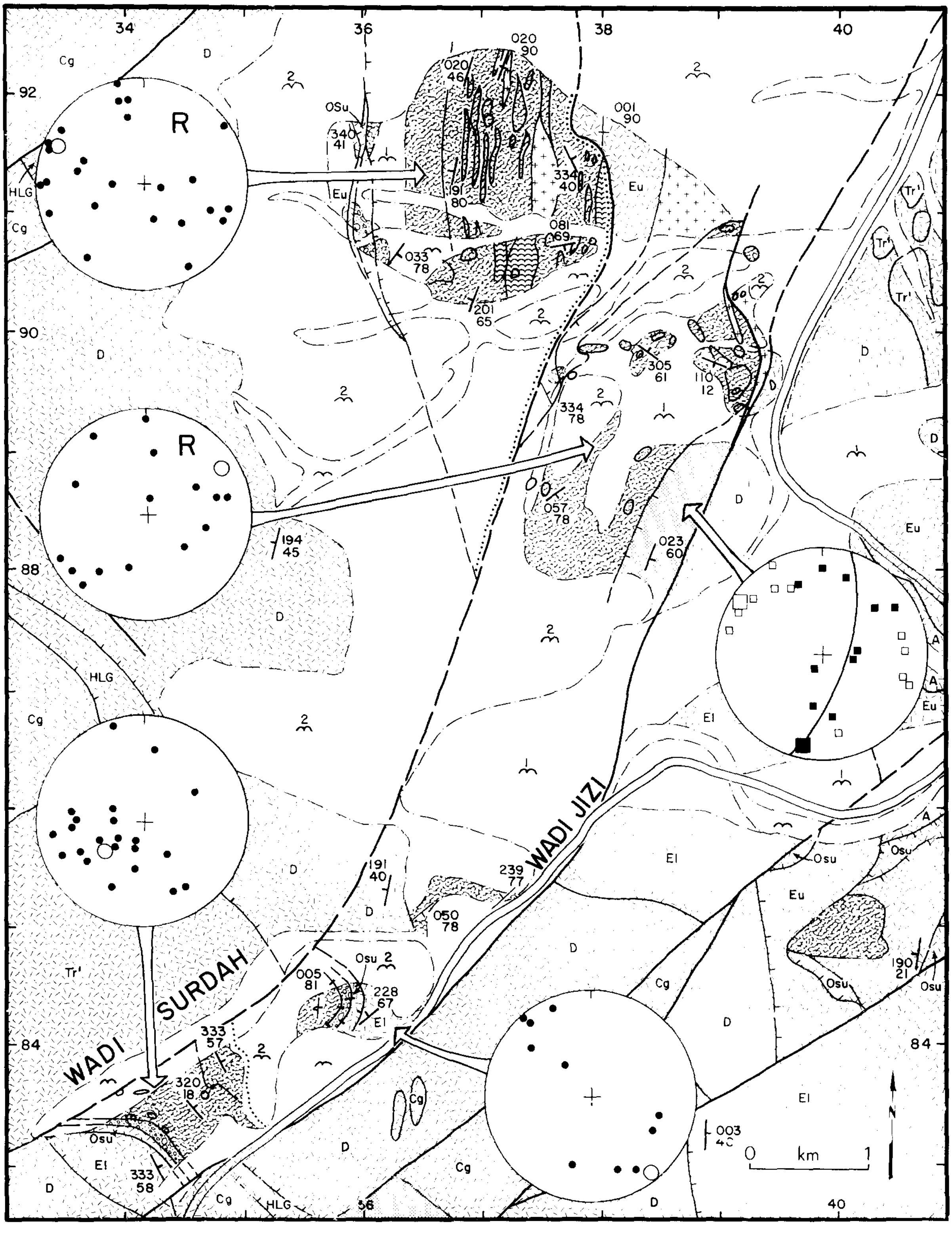

Fig. 3. Map of the Wadi Jizi area. Inset structural data are on lower hemisphere equal-area projections. The map location is in Fig. 1 and the key is in Fig. 2.

Slab mélange occurs extensively northeast of Wadi Ahin (e.g. around 565 650, 575 645, Fig. 4). It comprises short sequences, up to 40 m thick, of radiolarite and *Halobia*-calcilutite, bounded vertically and laterally by up to 1-m thick zones of shattered radiolarite and sheared, locally schistose limestone, which is generally brilliant orange with Fe–Mn segregations. This contrasts with the uniformly grey, pink or dark-grey unaltered *Halobia* limestone.

Slab mélange is the volumetrically dominant type in the Batinah Complex. Other good examples occur in Wadi Jizi (345 835, Fig. 3) and in the Alley (370 915, 390 900, Fig. 3). In contrast to other areas, the slab mélange in the central part of the Alley has been subjected to extensive

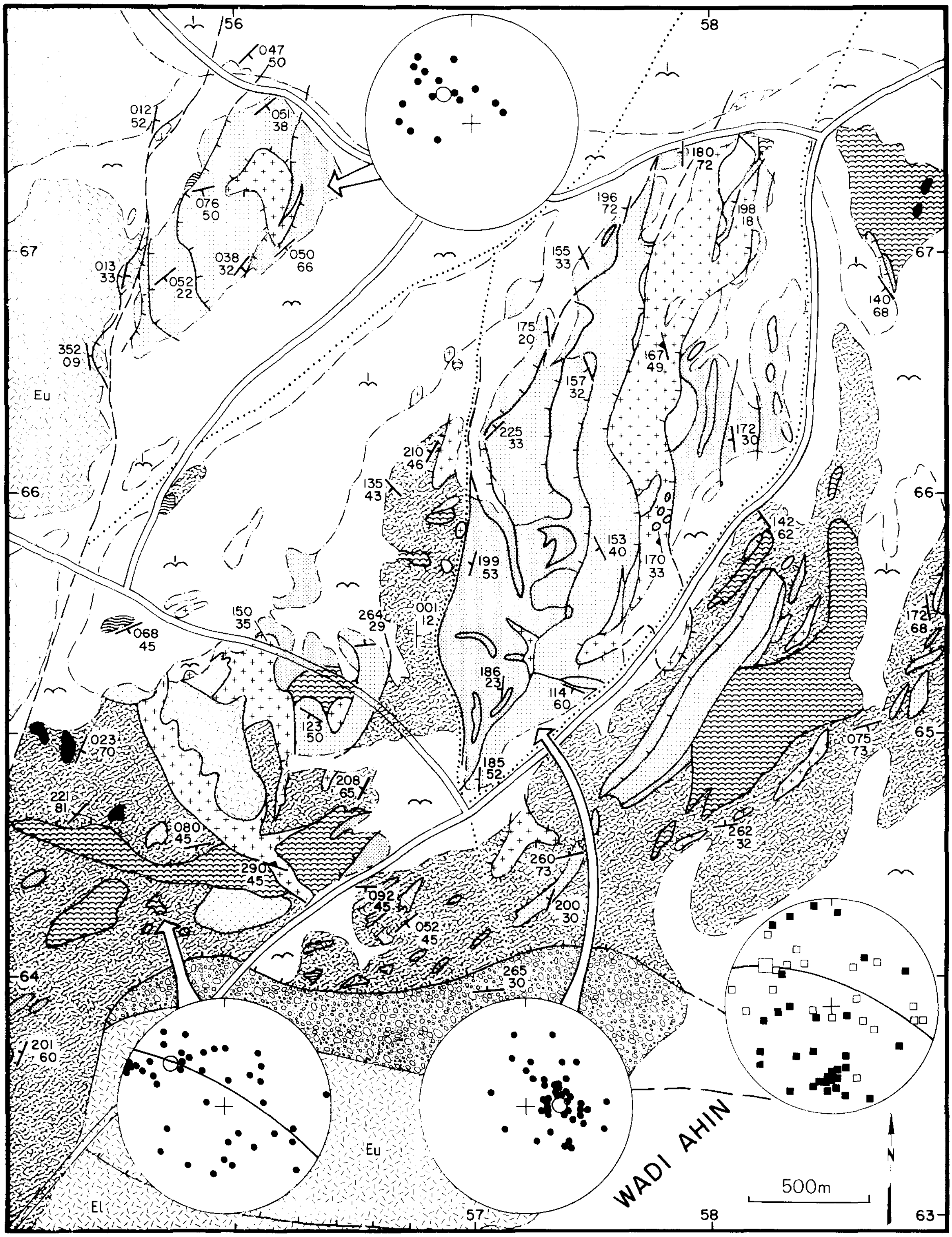

Fig. 4. Map of the area northwest of Wadi Ahin. Inset structural data are on lower hemisphere equal-area projections. The map location is in Fig. 1 and the key is in Fig. 2.

thermal metamorphism up to greenschist grade; several sheets of amphibolite are also present.

Block mélange

Block mélange comprises fragments ranging from several metres up to 100 m in size. Blocks tend to be more equidimensional than sheets or slabs and may be subrounded. The block-against-block fabric, described by Smewing *et al.* (1977) and Smewing (1981), is common where matrix is present only in interstices between touching blocks. Some interstices may apparently be almost filled by originally softer blocks moulded around the resistent lithologies. Two distinct types are present, unordered and stratified block mélange.

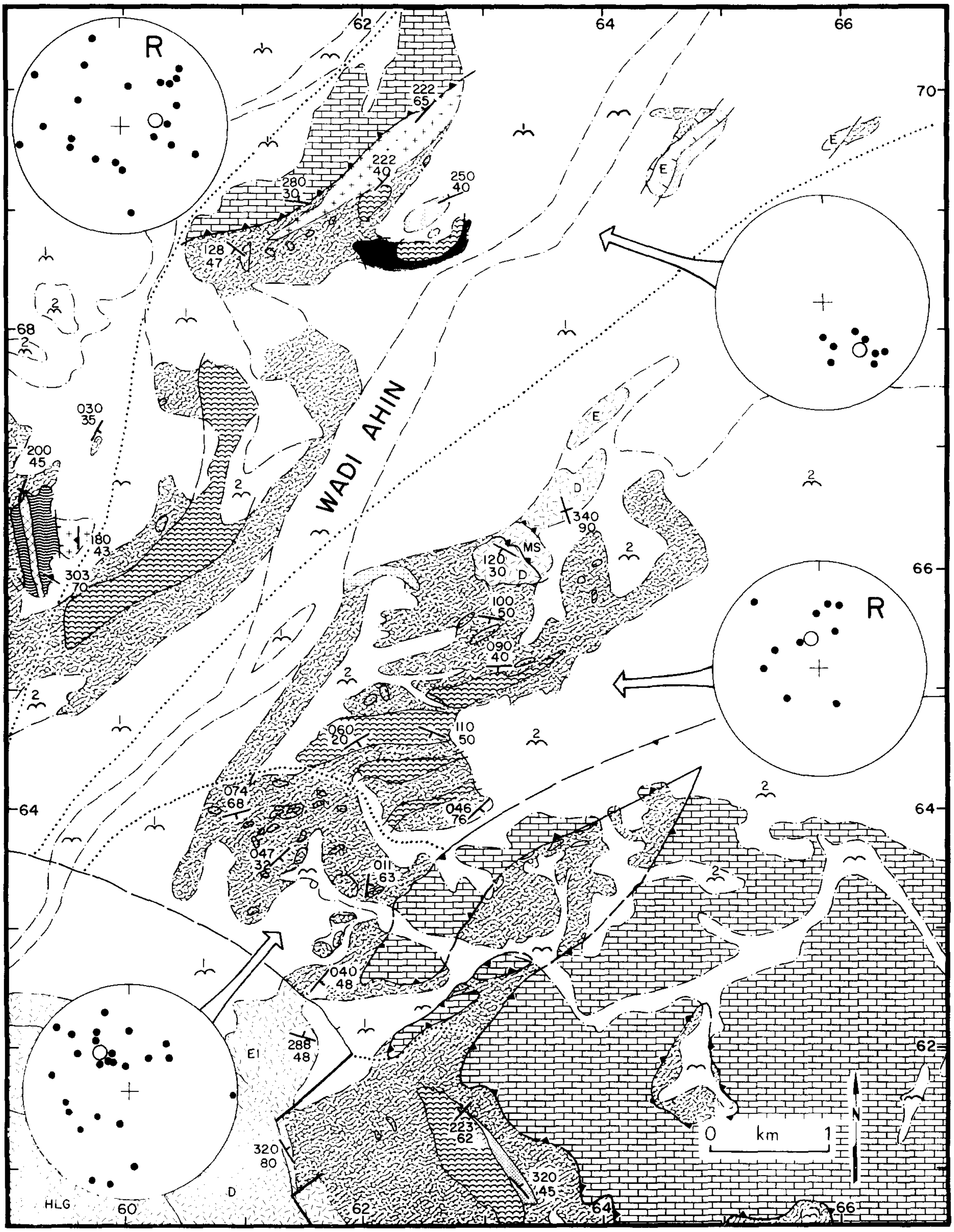

Fig. 5. Map of the Wadi Ahin area. Inset structural data are on lower hemisphere equal-area projections. The map location is in Fig. 1 and the key is in Fig. 2.

The unordered block mélange is best developed in structurally lower levels of the mélange close to the Semail corridors. The best example is north of Wadi Ahin, in stuctural contact with extensive matrix-supported rudites of the Zabyat Formation (around 565 640, Fig. 4). This area comprises irregularly oriented blocks averaging several tens of metres in size but grading up into slab mélange. Lithologies include mafic pillow lava, trachytic lava, lava breccia, red and purple pelite and psammite of greenschist metamorphic grade, white crytalline limestone, dolerite and gabbro pegmatite. In places (e.g. near 560 645, Fig. 4), the blocks are enclosed in serpentinite, but elsewhere the fabric is block-against-block with little matrix. Comparable unordered mélange is seen in places southeast of Wadi Ahin (635 610, Fig. 5), in a thin zone between Semail

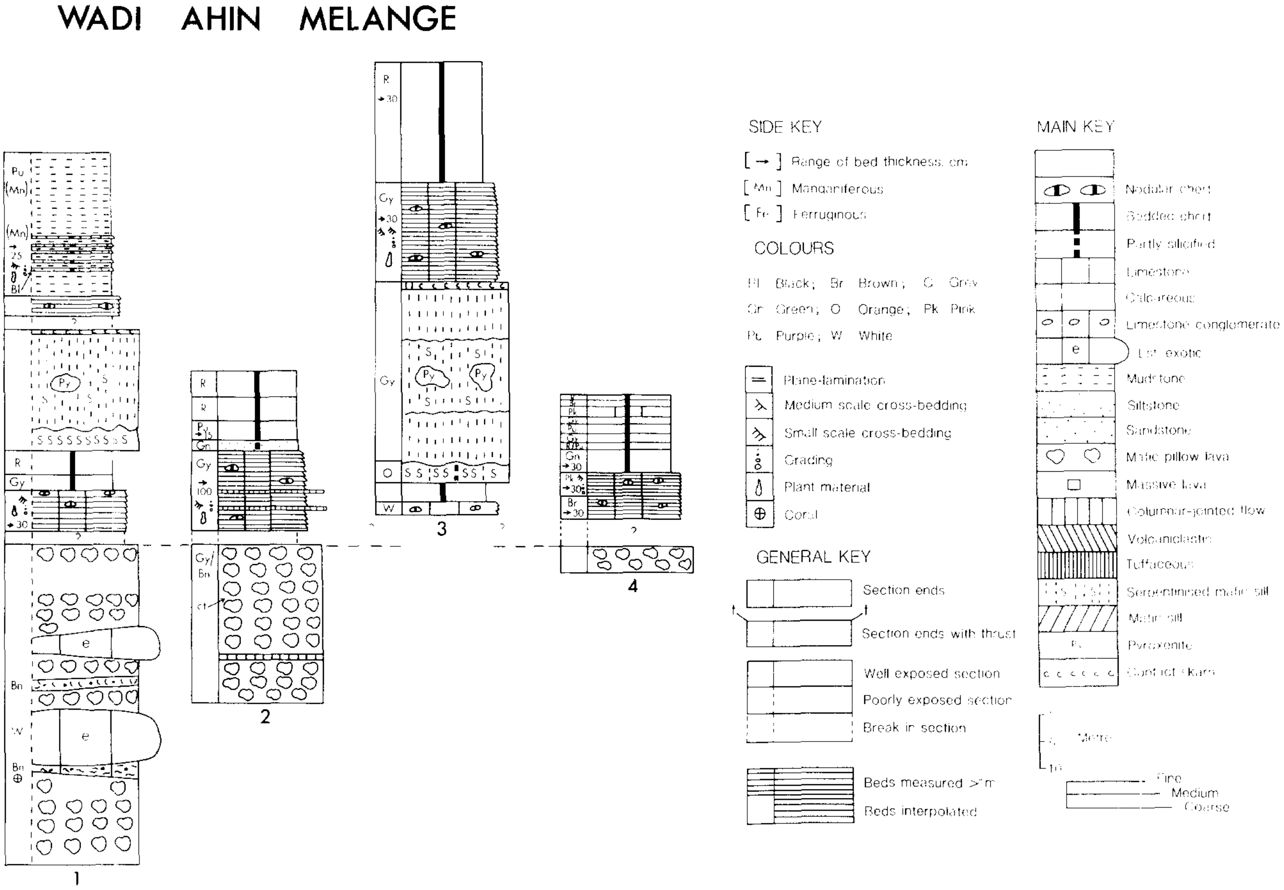

Fig. 6. Lithological logs of sequences from sheets and slabs within mélange in the Wadi Ahin area. Key also applies to Figs. 7 and 8. Logs are located in Fig. 1.

lavas and upper Batinah Complex south of Wadi Jizi (520 840 in fig. 9 of Woodcock & Robertson 1982b), and in the Alley (365 915, Fig. 3).

The stratified block mélange is found within terrains dominated by Upper Triassic mafic lavas (e.g. 625 645, Fig. 5). The blocks comprise white crystalline limestone, limestone breccia, calcirudite and volcaniclastic sediment, mostly several tens of metres or less in size. In contrast to the unordered block mélange, metamorphic rocks and serpentinite are absent. The blocks occur as localized zones within larger scale sheet or slab mélange.

The 'exotic' limestone blocks in the stratified mélange are in places stratigraphically enclosed by the lavas, showing that block formation took place in late Triassic time and not primarily during tectonic emplacement of the ophiolite. The various limestone exotics probably tumbled from larger adjacent shallow-water carbonate build-ups rather than originating as small bodies on the mafic lavas. The extrusives show no evidence of subaerial exposure and are intercalated with pelagic and hemipelagic sediments.

Clast mélange

This mélange type comprises subangular clasts usually less than 1 m in diameter, but more rarely up to 10 m, set in an abundant argillaceous matrix which may be serpentinitic. The mélange is usually matrix-supported. The most extensive area of clast mélange occurs as a thin (10–30 m) blanket overlying the unfaulted Semail ophiolite between the Wadi Ahin and Wadi Jizi corridors (near Wadi Yanbu and Wadi Salahi, Fig. 1). Traced northwards from Wadi Ahin (Fig. 4), typical sheet mélange thins then passes laterally into clast mélange. In places the clast mélange itself thins to zero, and overlying Batinah sheets sit directly on the Semail (Fig. 1 and 540 975 in fig. 7 of Woodcock & Robertson 1982b). Lithologies in the clast mélange include all the other mélange rocks, with abundant orange schistose limestone and low-grade metamorphic rocks. The matrix is serpentinitic argillite, apparently with a sedimentary texture, containing numerous finely comminuted fragments of other mélange rocks. Locally the clast mélange is partly enclosed and underlain by homogeneous serpentinite. Comparable clast mélange is seen above the Semail ophiolite in Wadi Suq (Fig. 1 and 510 945 in fig. 8 of Woodcock & Robertson 1982b).

Semail rocks in the mélange

Semail ophiolitic rocks are found in the mélange only close to the fault corridors, particularly in Wadi Ahin, and in the Alley. Semail rocks on the south side of Wadi Ahin (635 665, Fig. 5), largely obscured by wadi gravel,

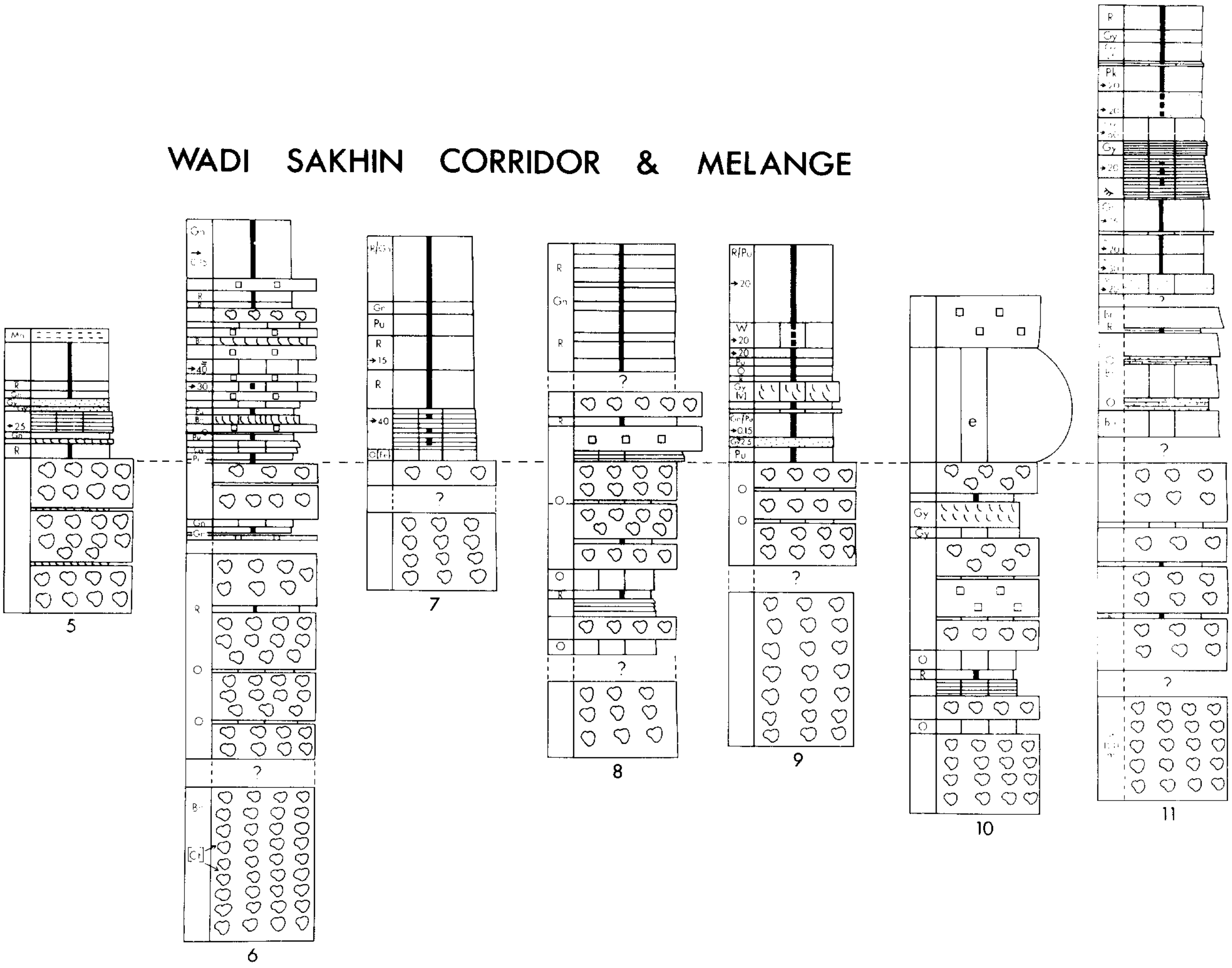

Fig. 7. Lithological logs of sequences in the Wadi Sakhin corridor and from sheets and slabs within adjacent mélange. The key is in Fig. 6. Logs are located in Fig. 1.

include little-serpentinized peridotite in thrust contact with sheeted dykes. There are also scattered outcrops of pyroxene–phyric lavas (653 638, Fig. 5) similar to those described by Pearce *et al.* (1981) from the higher levels of the adjacent Semail extrusive sequence. In the Alley, the mélange outcrop is cut by numerous anastomosing subvertical to subhorizontal sheets of serpentinite, which are probably derived from Semail ultramafic rocks (e.g. 391 900, Fig. 3).

MÉLANGE INTERNAL STRUCTURE

Bedding fabrics

At first sight many parts of the mélange appear to have randomly arranged structure. However, the detailed maps (Figs. 3, 4, 5 and 11) show areas of non-random gross fabric formed by alignment of sheets and slabs. Here we explore this fabric quantitatively and show a correlation of fabric strength with the mélange types previously defined.

Because the mélange generally has little matrix its fabric is determined by the mutual attitudes of its constituent fragments, sheets, slabs, blocks or clasts. In the field it is easier to measure bedding attitudes within the fragments than the fragment attitudes themselves. The two parameters usually match closely, especially for the well-bedded pelagic sediments. The poles to bedding are plotted on lower hemisphere equal-area projections on the maps (Figs. 3, 4, 5 and 11). The mélange has been divided into subareas (marked by dotted lines) each containing, where possible, similar mélange types. The bedding data have been numerically analysed by the method of Watson (1966) to give estimates of the mean direction and any fabric girdle: these are also plotted on the projections. The shapes and strengths of the data fabrics are summarized (Fig. 9) on the eigenvalue ratio plot described by Woodcock (1977). In this technique each data sample is assigned three orthogonal principal axes (calculated as eigenvectors of an orientation matrix). Associated with each axis is an eigenvalue (denoted $S_1 \geqslant S_2 \geqslant S_3$). These express the degree of clustering of data points about that axis. Different shapes of data samples have different relative magnitudes of eigenvalues. This is most easily visualized on the graph (Fig. 9) of S_1/S_2 vs S_2/S_3 where fabric clusters plot above the line of unit gradient and fabric girdles plot below.

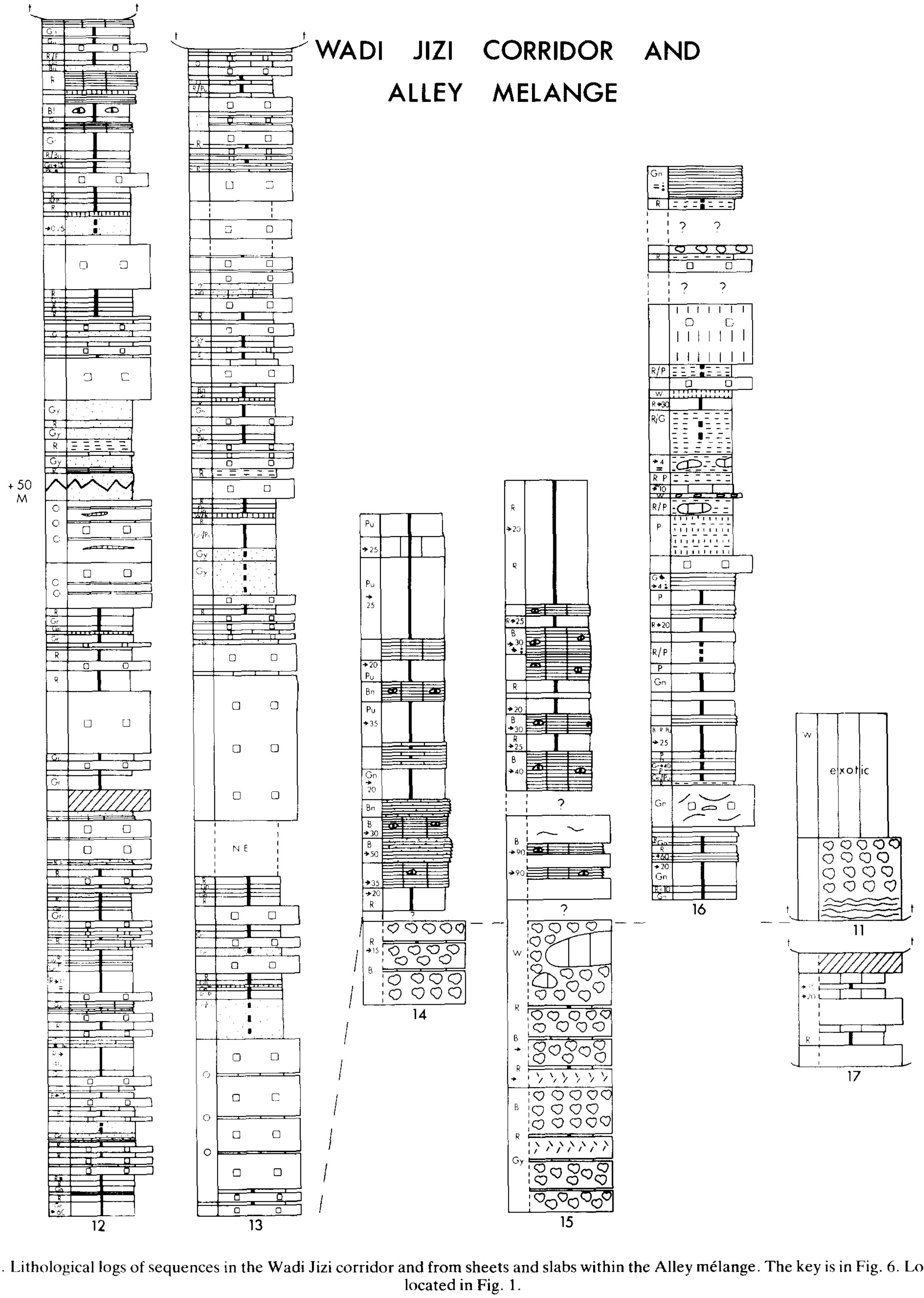

Fig. 8. Lithological logs of sequences in the Wadi Jizi corridor and from sheets and slabs within the Alley mélange. The key is in Fig. 6. Logs are located in Fig. 1.

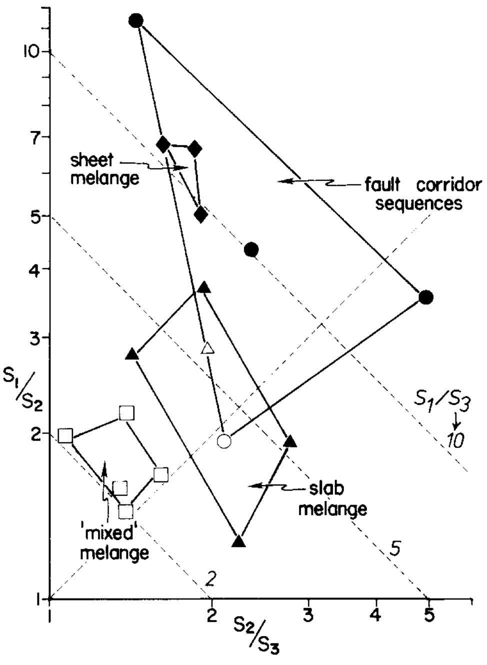

Fig. 9. Plot of eigenvalue ratios (S_1/S_2 vs S_2/S_3, Woodcock 1977) for bedding pole samples in corridor sequences and various mélange types. S_1/S_3 is a measure of fabric strength; line of unit gradient separates fields of clusters above from girdles below (see text). Open symbols indicate samples indistinguishable from random.

Most of the bedding samples from the mélange show weak fabrics and some are close to random. Woodcock (1977) proposed the statistic S_1/S_3, the ratio of the largest to smallest eigenvalue, as a measure of fabric strength and Woodcock & Naylor (in prep.) advocate this same statistic as a test of randomness. Random samples have low S_1/S_3 ratios and plot near the origin of the eigenvalue ratio plot (Fig. 9) whereas stronger fabrics have higher S_1/S_3 ratios and plot progressively further from the origin. Each bedding sample has been tested against the critical S_1/S_3 value (a function of sample size) given by Woodcock & Naylor (in prep.). Samples that cannot be distinguished from random at a 95% confidence level are denoted by 'R' on the projection and with an open symbol on the ratio plot. Seven out of 13 mélange subareas show random bedding fabrics. A striking feature is that these random fabrics do not, with one exception, occur where either sheet mélange or slab mélange dominate. Rather they occur where finer textured block or clast mélange is abundant or where a mixture of mélange types is present. This correlation of fabric strength with mélange type is also shown on the eigenvalue ratio plot (Fig. 9). Sheet mélange shows strong clusters, slab mélange rather weaker clusters and girdles, and 'mixed' mélange shows even weaker fabrics all indistinguishable from random samples.

If we interpret the spectrum of mélange types, that is sheet/slab/block/clast, as the increasing fragmentation and reorganization of a parent stratigraphic sequence, then this process was clearly accompanied by a weakening alignment of fragments and their internal bedding. In a 'tectonic' environment, where fragmentation was taking place by increasing strain, we might expect a progressive increase in fabric strength (e.g. Dimitrijevic & Dimitrijevic 1974, Naylor 1982). The fabric data are more compatible with a superficial origin by processes ranging from weakly constrained thrusting or sliding of sheets through sliding and rolling of slabs or blocks to sediment gravity flow of fine textured material. These possible mechanisms will be detailed later.

Folds

Mesoscopic folds (0.5–5 m wavelength) are another conspicuous element of mélange structure. They are only visible in sheets, slabs or the largest blocks, and are most common in the well-bedded pelagic sediment sequences. The folds are usually angular to subangular, close to tight, with rare or absent axial-plane fabrics. Most are buckle folds formed by flexural slip. Fold trains are uncommon, but individual folds are continuous across the layering, commonly showing kink band geometry. These features all suggest shortening of a multilayer sequence with a high mechanical anisotropy. In areas where fold data are numerous, enough to be analysed statistically (Figs. 3 and 4), the fold axis and axial-plane pole fabrics are dispersed but not random. The typical folds have steep axial planes and axes plunging gently subparallel to the strike of the host sheet or slab.

Role of fault zones

The attitude of the mélange fabric seems to be influenced by two factors; the Semail fault zones and, away from the fault zones, the upper surface of the Semail ophiolite slab.

Fault zone influence is shown in the Wadi Ahin area (Figs. 4 and 5). All non-random bedding fabrics strike between NE–SW and N–S, parallel to the Wadi Ahin fault zone, which presumably extends NE in the dipping ophiolite slab below the mélange. This parallelism is consistent with the hypothesis that the fault corridors acted as conduits for supply of sub-ophiolite rocks to the ophiolite surface. Sequences would be rotated to become parallel to the corridor as they moved upwards and would retain this orientation during the early stages of superficial break-up into sheets and slabs. The minor folds may also have formed during this 'extrusion' process.

The bedding fabrics parallel the fault zone for several kilometres to either side. In places (e.g. around 610 635, Fig. 5 and 570 640, Fig. 4) the fault-controlled fabrics therefore strike at a high angle to the upper surface of the ophiolite. However, away from the fault zone (e.g. 557 670, Fig. 4) sheets and slabs tend to lie subparallel to the ophiolite surface, presumed to be only gently sloping at the time of mélange accumulation.

In Wadi Jizi and the Alley (Fig. 3) bedding fabrics may again be either parallel to faults (385 880) or parallel to the ophiolite surface (545 835). Here the transition from one type to the other is more abrupt. In places (e.g. 565 850) mélange sits on Semail sheet dykes, proving substantial removal of higher parts of the ophiolite within the fault zone before or during mélange accumulation.

FAULT CORRIDOR SEQUENCES

We now compare the Batinah mélange lithologies with sequences exposed in the Wadi Sakhin and Wadi Jizi corridors through the Semail ophiolite.

In the Wadi Jizi corridor (Fig. 10) two E–W to NE–SW steep faults bound a 2–3 km wide strip of upfaulted sub-ophiolite rocks. In contrast to the mélange terrain, sequences are stratigraphically continuous over several kilometres. However they show many mesoscopic folds about NE-plunging axes with dispersed but commonly upright axial planes. Fold axis trends and axial plane strikes parallel the bounding faults to the corridor. Folds have styles comparable with those in the mélange fragments. Discrete zones of clast-supported breccia delimit sheets of unbrecciated rock. A spectrum of breccia types begins with an unsheared 'jigsaw-puzzle' texture suggesting formation by hydraulic fracturing. The brittle fragmentation was probably one of the early processes in the transition to mélange as material moved up the fault corridor, producing for the first time the distinction between fragments and matrix.

Measured logs in Wadi Jizi (logs 12 and 13, Fig. 8) show alternations of pillowed and massive trachytic lavas interbedded with radiolarites and *Halobia* calcilutites, overlain by thick sedimentary sequences terminating in non-calcareous radiolarites. (Early Cretaceous in age, E. A. Pessagno, pers. comm. 1980). Numerous basaltic and doleritic sills locally exceed 50% of the exposure. Sequence logging is complicated by the numerous multiply intruded sills, complex folding and absence of reliable way-up criteria. Five kilometres to the west a similar sedimentary/extrusive sequence is underlain by up to 500 m of pillow basalt and lava breccia. Further west still, metamorphic rocks from the dynamothermal sole to the ophiolite are exposed.

In the Sakhin corridor (Fig. 11) sub-ophiolite rocks are upfaulted in a 1–2 km-wide strip. Here they are continuous eastwards with mélange above the ophiolite slab. This continuity rules out the possibility that the mélange is preserved in downfaulted zones in the ophiolite surface, unconnected with material below the ophiolite. Intact sequences in the west of the corridor strike E–W parallel to the corridor and contain W-plunging mesoscopic folds (equal-area plots, Fig. 11) and shear zones marked by brown staining, recrystallization, pressure solution and Fe-Mn mobilization. Followed eastwards, that is structurally upward within the faulted

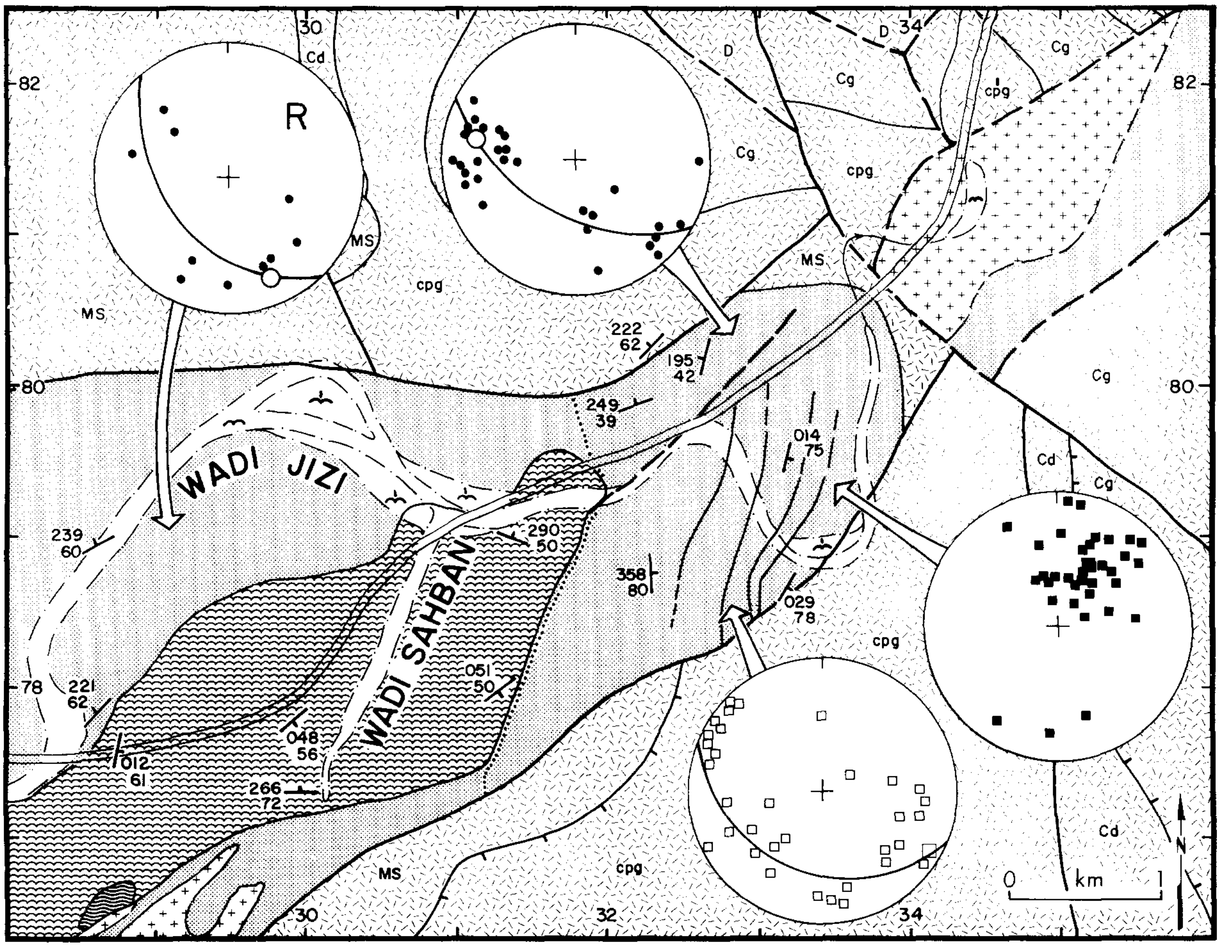

Fig. 10. Map of the Wadi Jizi corridor area. Inset structural data are on lower hemisphere equal-area projections. The map location is in Fig. 1 and the key is in Fig. 2.

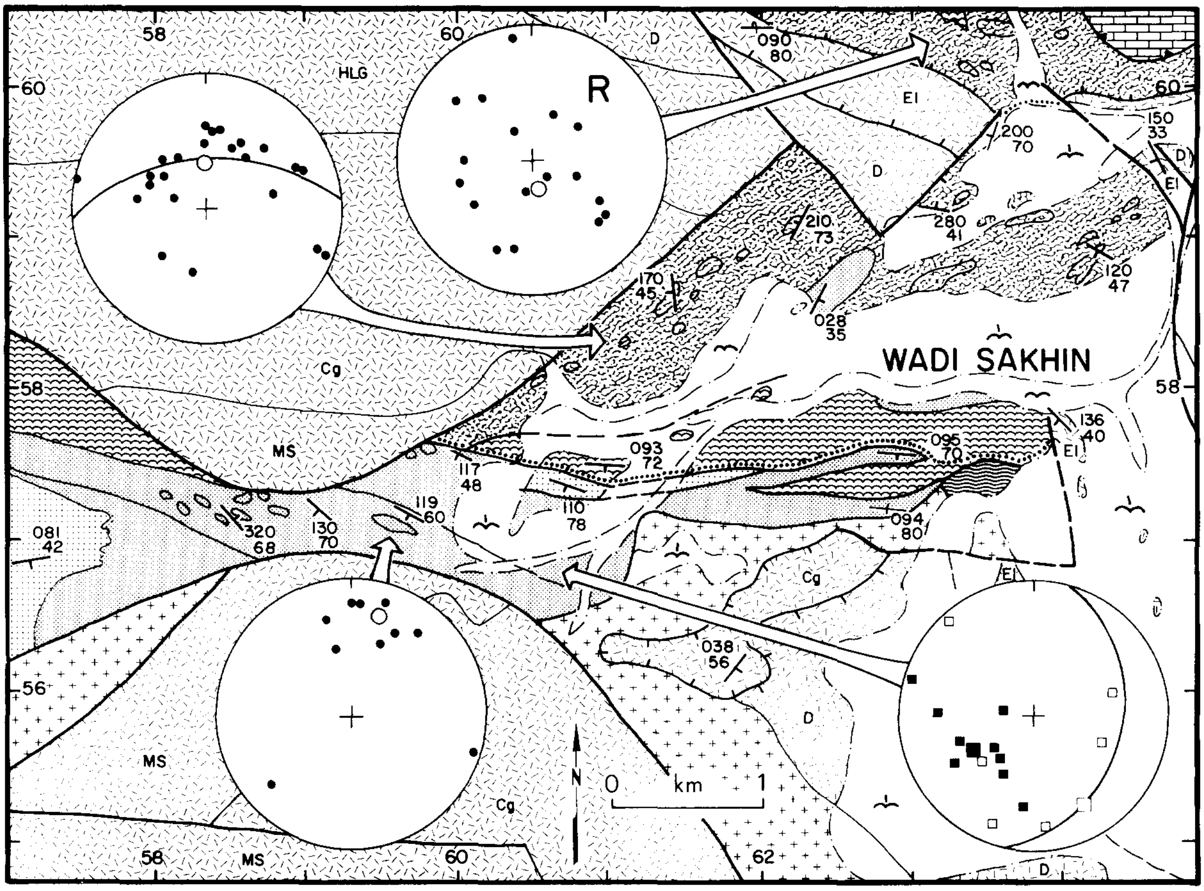

Fig. 11. Map of the Wadi Sakhin area. Inset structural data are on lower hemisphere equal-area projections. The map location is in Fig. 1 and the key is in Fig. 2.

ophiolite, the sequences become progressively more fragmented and eventually are only mappable as mélange. The mélange first has an organized E–W fragment fabric which weakens eastwards and becomes random by the time mélange spills onto the upper surface of the ophiolite.

Measured logs in the neck of the Wadi Sakhin corridor (590 530, Fig. 11) show pillowed mafic lavas up to 150 m thick, intercalated with pelagic sediments and crystalline limestones (log 10, Fig. 7) and overlain by redeposited *Halobia* calcilutites and fine calcarenites passing up into radiolarian cherts. Further west in the Sakhin corridor (575 570, Fig. 11) much thicker sequences (>100 m) of redeposited limestones include turbiditic calcarenites and some calcirudites. This is a more proximal imbricated slice characteristic of the Hawasina exposed west of the Semail Nappe (Glennie *et al.* 1974).

In both the Jizi and Sakhin corridors the bedding fabrics are usually stronger than the mélange fabrics, even those in the sheet mélange. This is again consistent with the formation of the mélange by progressive fragmentation of the corridor sequences.

Reconnaissance further southeast in the central Oman Mountains confirms the existence of more corridors through the Semail Nappe. However, overlying mélange is largely concealed by wadi gravels. In this area, the Semail is split into two major overlapping blocks, the Hawasina block and the Wuqbah block (Graham 1980). South of Ghayzayn (Fig. 1), a long ‘snout’ of the Semail ophiolite block, including sheeted dykes and extrusives, extends about 40 km southeast into the Batinah Plain. In the corridor between the two ophiolite block serpentinite, gabbro, folded radiolarite, crystalline limestone and metamorphic rocks are present. Close to the western Hawasina Block contact, relatively long intact sequences of red and green radiolarite are associated with Upper Triassic extrusives and limestone exotics.

FORMATION OF THE BATINAH MÉLANGE

Sub-ophiolite sequences as the mélange source

The mélange sequences can be correlated closely with the intact sequences of the Semail corridors. These in turn are similar to parts of the main sub-ophiolite sequences west and southwest of the Semail Nappe outcrop (Glennie *et al.* 1972, Searle 1980) and in the central Oman mountains further south. There, the sub-ophiolite sequence comprises tectonically imbricated proximal then distal Hawasina rocks, then olistostrome followed by the Haybi volcanic complex and associated Oman ‘exotics’, and finally by metamorphic sheets with higher-grade amphibolite facies rocks along the Semail sole (Glennie *et al.* 1974, Searle & Malpas 1980).

The corridors only reveal the upper parts of this sequence, with no olistostrome or typical Hawasina units. The missing parts of the sequence may be present at depth below the present erosion level in the corridor. In any case distal sequences will predominate further to the northeast, that is oceanward on the original Arabian margin.

The distal sub-ophiolite sequences in the Wadi Sakhin corridor match closely those in the adjacent mélange above the ophiolite (Fig. 7). Identical sequences of Upper Triassic mafic lavas, equivalent to the Haybi Complex, with limestone exotics pass up into *Halobia* limestones and radiolarites dated as Late Triassic and Early Cretaceous.

The structural style of the corridor sequences is also similar to that preserved in the mélange sheets and slabs. Similar metamorphic rocks occur in both areas.

The Wadi Sakhin corridor is particularly important in showing direct continuity of sub-ophiolite and mélange sequences (Fig. 11). The progressive structural transition has already been detailed. The similarity in lithological sequence through the corridor is illustrated by log 5 in the mélange and logs 6–10 (Fig. 7) taken progressively westwards through the corridor.

The evidence, therefore, implies that material for the mélange was mainly derived from the sub-ophiolite sequence within and below the Semail fault corridors. This important conclusion is supported by similar lithological comparisons between the Wadi Jizi corridor sequence and its overlying mélange. However, there and in the Wadi Ahin zone the exposed segment of the corridor is not now continuously open through the full thickness of the ophiolite.

Fault corridors as mélange conduits

There are three places where mélange material might have been supplied from below the ophiolite to its upper surface as it was emplaced over the Arabian margin: from the leading edge of the ophiolite slab, from behind its trailing edge and through fault corridors dissecting the slab itself. All our evidence points to the last of these possibilities.

The ophiolite rudites of the Zabyat Formation record the initiation of the Wadi Ahin and Wadi Jizi/Sakhin fault zones and the rejuvenation of the Alley zone (Robertson & Woodcock 1982). The matrix-supported rudites were deposited by mass flow off sub-marine fault scarps (Fig. 12). At this time no sub-ophiolite material was shed from the fault zones, and indeed there is no evidence to suggest that the ophiolite had yet begun to overthrust the main part of the Arabian margin.

The unordered block mélange occurs in the structurally lower part of the mélange (Fig. 12). It includes numerous metamorphic rocks and limestone 'exotics', suggesting an origin from the structurally highest part of the sub-ophiolite sequence. This material would be the first to move up widening cracks in the ophiolite and reach its upper surface. Initially local narrow gaps (tens to several hundred metres wide) would explain the small fragment size and highly mixed nature of this basal mélange. The low matrix content precludes transport over the ophiolite surface by debris flow. In Wadi Ahin, the local extent of the block mélange on one side only of the fault zone suggests a scree deposit shed from a source along the fault scarp.

Higher parts of the mélange contain relatively few

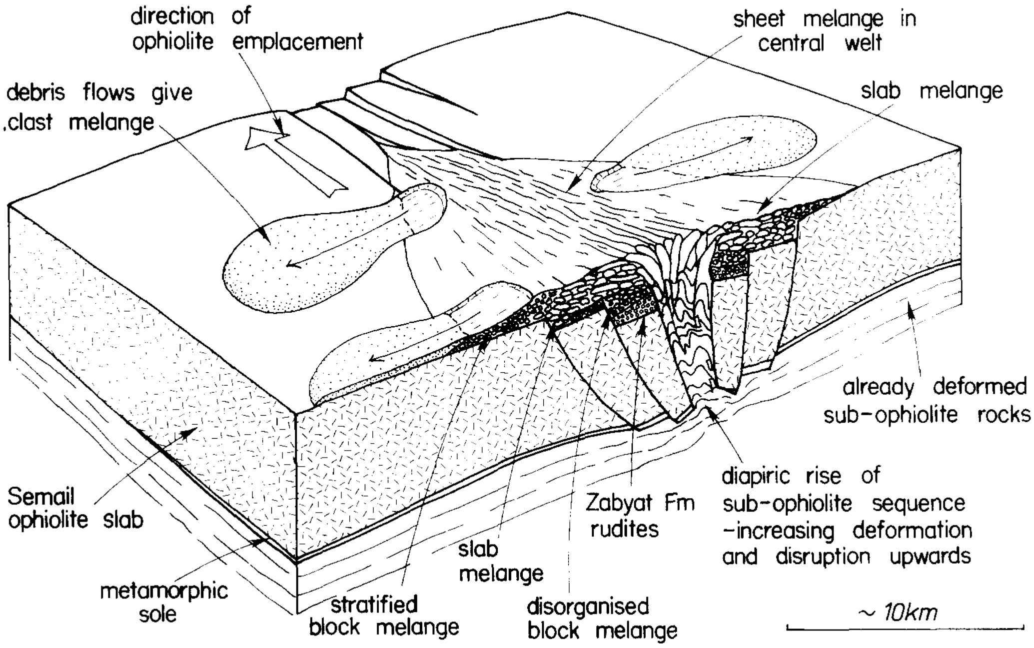

Fig. 12. Cartoon based on relationships in the Wadi Ahin area showing the postulated mechanisms of mélange supply and transport.

ultramafic Semail rocks or amphibolites from the metamorphic sole. Exceptions occur locally in Wadi Ahin and north of the Alley where substantial slabs of amphibolite and peridotite are present. The amphibolite-grade sole probably formed a strong welded slab which did not easily fragment, in contrast to the much more friable greenschist facies and unmetamorphosed lithologies beneath. The poorly exposed Semail rocks in the mélange near Wadi Ahin (Fig. 5) are probably a horst of Semail basement uplifted along the eastward extension of the Wadi Ahin corridor.

The overlying sheet, slab and stratified block mélange all contain structurally lower parts of the sub-ophiolite stack. These were emplaced as the corridors widened to give substantial conduits connecting the base and top of the ophiolite slab. Upward movement of the sub-ophiolite material was probably diapiric, driven by its lower density as compared to the ophiolite. The margins of the diapiric welt would have been shear zones against the faulted edges of the ophiolite slab. These edges must have foundered as material oozed out from beneath (Fig. 12) producing a marked slope on the ophiolite surface in towards the fault zone. This slope is now reflected in the embayments in the outcrop of the upper contact of the ophiolite near the fault zones (Fig. 1).

At depth in the fault conduit, the upwelling sub-ophiolite sequences deformed by folding and in narrow shear zones on trends parallel to the conduit walls. As the sequences moved higher up, brittle fragmentation started on all scales and began to delimit intact sheets and slabs by more finely fragmented zones (Fig. 12). By the time that the sequences emerged from the fault corridor, they had been rotated into parallelism with the bounding faults. Initially these steeply dipping fragments must have protruded above the ophiolite surface to form a local raised welt along the fault zone. Lateral transport of material occurred by gravity-spreading away from this welt, up the gently dipping ophiolite surface (Fig. 12). This was accompanied by a progressive degeneration of intact sheets into slabs and then into blocks due to the formation of matrix by abrasion and possibly hydraulic fracturing, and also by a progressive rotation of fragments from fault-parallel into parallelism with the ophiolite surface. Only a few fragments have mantling scree breccias (Naylor 1982) that would suggest transport by sliding down the free surface of the mélange pile. Many fragments were probably enclosed in the mélange mass during transport.

Lateral gravity spreading (reviewed by Elliott 1976) is only possible if the deforming mass is essentially plastic. In the mélange this plasticity must have been maintained by easy slip in the thin matrix seams between the relatively rigid fragments. The abundance of serpentinite in places was probably important in lowering plastic resistance to flow. However, the bulk plasticity of the mélange was probably still low, as material was only redistributed laterally by gravity spreading for 2 or 3 km either side of the fault zone. Even this degree of transport was only possible because high supply rates of material up the conduits maintained a high relief to the mélange welt.

The only material to be transported well beyond the fault zones is represented by the matrix-supported clast mélange. This forms a thin blanket furthest from the conduits. It formed by rapid debris-flow redeposition of material probably initiated by spasmodic slump failure of a fine-textured matrix-rich mantle to the mélange welt.

Interpretation of the Alley mélange

Interpretation of the Alley mélange is complicated by the fact that the Alley originated as a major N–S seafloor fault scarp during spreading (Smewing *et al.* 1977). By contrast, undeflected dyke trends across Wadis Ahin and Sakhin imply that these structural zones originated only during tectonic emplacement. The Alley is now connected to Wadi Jizi by arcuate steeply dipping normal faults which swing SW into the Wadi Jizi corridor (Figs. 1 and 3). Mélange can be traced from Wadi Jizi along the length of the Alley. This mélange could have reached its present position either by transport up to 15 km northwards from Wadi Jizi, or by rejuvenation of the Alley faults allowing upward protrusion of sub-ophiolite material. The second alternative would require a component of E–W extension along the Alley as well as N–S extension of the corridors. Notably, whereas the southern Alley outcrop is dominated by unmetamorphosed sheet mélange, the northern outcrops are more metamorphosed, fragmented and contain one of the few large amphibolite bodies (300 m in outcrop length) in the mélange. The northern Alley material was derived from closer to the Semail metamorphic sole than its counterpart further south. It is, thus, possible that the sole rocks were protruded first along Wadi Jizi, then slid progressively further northwards into the Alley as less metamorphosed lower sub-Semail levels came up behind to form the southern Alley exposures. Steep anastomosing serpentinite sheets which cut the Alley mélange probably represent serpentinized Semail ultramafic rocks protruded up reactivated older seafloor faults during or soon after mélange emplacement.

THE BATINAH MÉLANGE AND OPHIOLITE EMPLACEMENT

The Batinah mélange was expelled through gaps in the Semail Nappe during its emplacement over the Hawasina continental margin (Fig. 13). The initial decoupling of Semail oceanic crust and mantle took place during Cenomanian–Turonian time in an oceanic realm (95–90 Ma, Lanphere 1979, Searle & Malpas 1980). Later, during Santonian–Campanian time (80–72 Ma) the Semail Nappe impinged on the Hawasina continental margin giving rise to extensive greenschist facies metamorphism along the sole thrust. As the nappe impinged on the topographically irregular margin it must have ramped over major carbonate build-ups, the

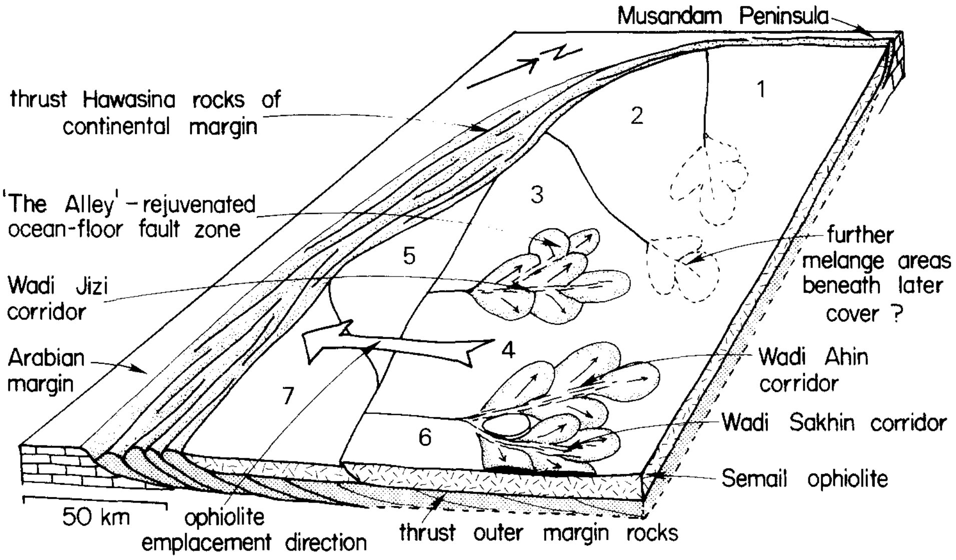

Fig. 13. Schematic view of the Semail ophiolite during emplacement and mélange generation. The main fault-bounded blocks of the ophiolite are numbered: (1) Dibba, (2) Aswad, (3) Fizh, (4) Salahi, (5) Salahi, (6) Hawasina, (7) Wuqbah.

Oman exotics, which were discontinuously distributed along the outer margin.

During its transport towards and onto the margin, the Semail ophiolite cracked into a series of slabs along the steep extensional fault zones (Fig. 13). These zones continued to widen in a N–S and less certainly an E–W direction during emplacement.

These extensional zones do not necessarily imply that the ophiolite sheet was being subjected to effective tensional stresses in all horizontal directions. It would be possible for the ophiolite to be thrust on to the margin by high E–W (or regionally NE–SW) compressive stesses yet still to split on E–W oriented tensile cracks. An analogue for this is the identation tectonics of Molnar & Tapponnier (1975).

Faulting of the ophiolite sheet first produced a highly irregular and unstable seafloor topography. Pelagic sediments and igneous rocks were redeposited off fault scarps to produce the Zabyat Formation (Robertson & Woodcock 1982). Progressively deeper levels of the ophiolite sequence were exposed with time, but no sub-ophiolite rocks were available during Zabyat Formation deposition.

Later, the faults widened sufficiently to allow the structurally highest sub-ophiolite rocks of the metamorphic sole to pass diapirically upwards in a highly jumbled state. Widening of the gaps to at least several hundred metres allowed deeper sub-ophiolite rocks to escape. By this time the Semail Nappe had been emplaced over at least the more distal parts of the Arabian margin. However it still had a large area of free sub-marine surface, partly obscured by mélange. The Semail slab cannot at this time have been totally enclosed in a accretionary prism as suggested by Welland & Mitchell (1977) and Gealey (1977).

There is no firm evidence for the precise direction of transport of mélange material on the ophiolite surface. This would be valuable information, since evidence of a slope to the ophiolite surface towards or away from the margin would respectively support or deny the possibility of gravity spreading as an emplacement mechanism. The most that can be deduced from the available data is that there was a strong component of mélange transport laterally away from the fault zones, suggesting that, whatever the direction of surface slope, its magnitude was low.

Immediately after formation of the mélange, before any pelagic deposition, the entire area was blanketed by the Batinah Sheets, forming the upper part of the Batinah Complex (Woodcock & Robertson 1982a, b). These sheets, which contrast dramatically with the Batinah mélange, record a sedimentary transition across the outer part of a Mesozoic passive margin which apparently lay to the northeast (Woodcock & Robertson 1982b). Indeed it seems likely that sliding of the Batinah Sheets effectively blocked further protrusion of mélange through the corridors. Some movement along the fault corridors probably continued during emplacement of the Batinah Sheets and may have been responsible for the partial closure of the Wadi Jizi and Wadi Ahin corridors seen at the present erosion level.

COMPARISON WITH OTHER MÉLANGES

The Batinah mélange contrasts strongly with the other mélanges in Oman (Lippard in press). Beneath the Semail Nappe there are the Hawasina mélange and the Semail mélange. The Hawasina mélange, in general, is true olistostrome mélange composed of blocks of most of the Hawasina continental margin lithologies, including limestone 'exotics' which are intercalated with Lower to Mid-Cretaceous pelagic carbonates. The olistostrome mélange underwent severe deformation during later overthrusting of the Semail ophiolite. By contrast, sedimentary mélange is virtually absent from the Batinah mélange.

The Semail mélange structurally overlying the Hawasina olistostrome contains blocks of the metamorphic rocks of the 'sole', Haybi igneous rocks, radiolarian calcilutites and cherts in a matrix of pervasively sheared serpentinite, pelite, siliceous mudstone and shale. By contrast, the Batinah mélange contains little serpentinite, and is much less pervasively deformed and metamorphosed. Material most like the Semail mélange is found in the northern Alley and lower Wadi Ahin block mélange. In part, this could be Semail mélange extruded through the Wadi Ahin corridor.

The Batinah mélange also differs strongly from the Batinah Sheets, the upper part of the Batinah Complex. These consist mostly of relatively intact, commonly gently inclined, sheets without metamorphic rocks or serpentinite.

Beyond Oman, analogues of the Batinah mélange could be anticipated wherever major ophiolite slabs have overridden deformed continental margins, though no exact analogues have yet been described. The Crabb Brook Group, overlying the Bay of Islands ophiolite, Newfoundland (Casey & Kidd 1981) shows some similarity to the Zabyat Formation plus Batinah mélange in Oman. In both areas: (a) the ophiolite is overlain by a sedimentary sequence formed during its emplacement onto a continental margin; (b) the proportion of debris exotic to the ophiolite increases up-sequence; (c) a lower unit of fine-textured sub-marine ophiolitic rudites (Zabyat Formation–Crabb Point Formation) is succeeded by a unit including much coarser sub-marine mélange (Batinah mélange/Jaws Brook Formation) and (d) some mélange material can be matched with sub-ophiolite sequences. The two areas differ in that (a) the lower rudites in Newfoundland contain clasts of sub-ophiolite lithologies, absent from the Zabyat Formation in Oman, (b) the Jaws Brook Formation contains a large proportion of structurally intact marine sediments not represented in the Batinah mélange and (c) the Crabb Brook Group includes an upper unit of shallow marine or continental sediments (Summmerhouse Brook Formation), absent in Oman until after the emplacement of the Batinah sheets. These differences may represent different relative timing of the supply and redistribution processes and the degree of ophiolite uplift rather than fundamentally different emplacement histories. A major additional event in Oman was the emplacement of the allochthonous Batinah sheets (Woodcock & Robertson 1982b), an event which punctuates what might otherwise have been a progressive shallowing sequence similar to that in the Crabb Brook Group.

The mechanism by which sedimentary material was supplied to the upper surface of the Bay of Islands ophiolite was not discussed in detail by Casey & Kidd (1981). They imply that this material must have been derived from a deeply eroding part of the ophiolite slab outside their immediate area. However this 'distant' source seems inconsistent with the highly proximal appearance of the rudites and mélange units above the ophiolite. It is a similar inconsistency in Oman which we explain by the local supply of sub-ophiolite material up fault corridors in the ophiolite. This process now needs to be considered in Newfoundland and elsewhere.

CONCLUSIONS

(1) The Batinah mélange structurally overlies the Semail ophiolite and consists mostly of deep-water sedimentary and igneous rocks, of continental margin affinity and minor Semail ophiolitic and metamorphic rocks, together ranging from Upper Triassic to Upper Cretaceous.

(2) The mélange can be subdivided into four intergradational types: sheet, slab, block and clast mélange.

(3) Matrix is restricted to small volumes produced by mutual abrasion of fragments, except for the minor clast mélange which is matrix-supported.

(4) Throughout the mélange, long intact sequences can be pieced together. These comprise Upper Triassic mafic extrusives and intercalated radiolarites and hemi-pelagic calcilutites, passing up into hemi-pelagic calcilutites and radiolarites, and then non-calcareous radiolarian cherts and Mn-rich interbeds dated as Early Cretaceous. Dolerite sills locally comprise up to 50% of outcrop.

(5) Identical sequences can be traced into corridors through the ophiolite, and crop out widely beneath the Semail Nappe, and in a similar structural position in the central Oman Mountains.

(6) The Batinah mélange was expelled through gaps in the Semail Nappe formed during its emplacement over the tectonically imbricated Hawasina continental margin.

(7) After expulsion, the mélange was redistributed over the free sub-marine Semail surface by gravity spreading. A thin mantle of degraded material was occasionally redeposited further by debris-flow.

(8) Formation of the Batinah mélange was terminated by sliding of the structurally higher Batinah Sheets from a Mesozoic passive margin located northeast of the Arabian continent.

(9) The Batinah mélange differs from other mélanges exposed in Oman, though it has at least one analogue elsewhere.

Acknowledgements—This work was funded by a N.E.R.C. research grant and the Open University research group. We thank S. Lippard for assistance in the field, G. Graham, M. Searle and J. Smewing for helpful discussions and M. Naylor for comments on the manuscript.

REFERENCES

Casey, J. F. & Kidd, W. S. F. 1981. A parallochthonous group of sedimentary rocks unconformably overlying the Bay of Islands ophiolite complex, North Arm Mountain, Newfoundland. *Can. J. Earth Sci.* **18**, 1035–1050.

Dimitrijevic, M. D. & Dimitrijevic, M. N. 1974. Internal fabric of Mesozoic bodies in the mélange around Nova Varos: a case for gravity tectonics. *Bull. Scient. Cons. Acad. RPF Yougosl.* **A19**, 70–72.

Elliott, D. 1976. The motion of thrust sheets. *J. geophys. Res.* **81**, 949–963.

Gansser, A. 1974. The ophiolitic mélange; a worldwide problem on Tethyan examples. *Eclog. geol. Helv.* **67**, 479–507.

Gealey, W. K. 1977. Ophiolite obduction and geologic evolution of the Oman mountains and adjacent areas. *Bull. geol. Soc. Am.* **88**, 1183–1191.

Glennie, K. W., Boeuf, M. G. A., Hughes Clarke, M. W., Moody-Stuart, M., Pilaar, W. F. H. & Reinhardt, B. M., 1974. Geology of the Oman Mountains. *Verh. K. Ned. geol.-mijnb. Genoot.* **31**, 1–423.

Graham, G. M. 1980. Evolution of a passive margin, and nappe emplacement in the Oman Mountains. *Proc. Int. Ophiolite Sym. Cyprus* 1979, 414–423.

Greenly, E. 1919. The geology of Anglesey. *Mem. geol. Surv. U.K.*

Hoedemaeker, P. J. 1973. Olistostromes and other delapsional deposits, and their occurrence in the region of Moratella (Prov. of Murcia, Spain). *Scripta Geol.* **19**, 1–207.

Lanphere, M. A. 1979. K-Ar ages of metamorphic rocks at the base of the Semail ophiolite, Oman. *Eos* **60**, 963.

Lippard, S. J. in press. Mélanges associated with the Semail ophiolite in the northern Oman mountains allochthon, S.W. Arabia. In: *Ophiolitic Mélanges* (edited by McCall, J.) Benchmark publications, Hutchinson & Ross, Stroudsberg, Pennsylvania.

Molnar, P. & Tapponnier, P. 1975. Cenozoic tectonics of Asia: effects of a continental collision. *Science, Wash.* **189**, 419–426.

Naylor, M. A. 1982. The Casanova Complex of the Northern Apennines: a mélange formed on a distal passive continental margin. *J. Struct. Geol.* **4**, 1–18.

Pearce, J. A., Alabaster, T., Shelton, A. W. & Searle, M. P. 1981. The Oman ophiolite as a Cretaceous arc-basin complex: evidence and implications. *Phil. Trans. R. Soc.* **A300**, 299–317.

Robertson, A. H. F. & Woodcock, N. H. in press. Zabyat Formation, Semail Nappe, Oman: sedimentation on to an emplacing ophiolite. *Sedimentology*.

Saleeby, J. B. 1979. Kaweah serpentinite mélange, southwest Sierra Nevada foothills, California. *Bull. geol. Soc. Am.* **90**, 29–46.

Searle, M. P. & Malpas, J. 1980. Structure and metamorphism of rocks beneath the Semail ophiolite of Oman and their significance in ophiolite obduction. *Trans. R. Soc. Edinb.* **71**, 247–262.

Searle, M. P., Lippard, S. J., Smewing, J. D. & Rex, D. C. 1980. Volcanic rocks beneath the Semail ophiolite nappe in the northern Oman Mountains and their tectonic significance in the Mesozoic evolution of Tethys. *J. geol. Soc. Lond.* **137**, 589–604.

Smewing, J. D., Simonian, K. O., Elboushi, I. M. & Gass, I. G. 1977. Mineralized fault zone parallel to the Oman ophiolite spreading axis. *Geology* **5**, 534–538.

Smewing, J. D. 1981. Regional setting and petrological characteristics of the Oman ophiolite in North Oman. *Ofioliti* (special issue 'Tethyan Ophiolites) **2**, 335–378.

Smith, A. G., Woodcock, N. H. & Naylor, M. A. 1979. The structural evolution of a Mesozoic continental margin, Othris Mountains, Greece. *J. geol. Soc. Lond.* **136**, 589–602.

Watson, G. S. 1966. The statistics of orientation data. *J. Geol.* **74**, 786–797.

Welland, M. J. P. & Mitchell, A. H. G. 1977. Emplacement of the Oman ophiolite: a mechanism related to subduction and collision. *Bull. geol. Soc. Am.* **88**, 1081–1088.

Woodcock, N. H. 1977. Specification of fabric shapes using an eigenvalue method. *Bull. geol. Soc. Am.* **88**, 1231–1236.

Woodcock, N. H. & Robertson, A. H. F. 1982a. Stratigraphy of the Mesozoic rocks above the Semail ophiolite, Oman. *Geol. Mag.* **119**, 67–76.

Woodcock, N. H. & Robertson, A. H. F. 1982b. The upper Batinah Complex, Oman: allochthonous sediment sheets above the Semail ophiolite. *Can. J. Earth Sci.* **19**, 1635–1656.