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The generation and movement of the Semail and Hawasina nappes, Oman Mountains, United Arab Emirates

J. S. AL-SULAIMI AND W. J. PHILLIPS

Kuwait Institute for Scientific Research, P.O. Box 24885, Kuwait; and Department of Geology, University College, Aberystwyth, Wales, United Kingdom

ABSTRACT

The main characteristics of the Semail and Hawasina nappes are summarized, and the published postulated mechanisms for their generation and movement are reviewed. A new model which is consistent with recent information concerning the nature of foreland thrust belts is presented, and it is suggested that the nappes developed by gravitational spreading from an elevated zone produced when a spreading ridge reached a subduction zone.

1. INTRODUCTION

The results of recent work on the Semail ophiolite in the southern part of the U.A.E. are consistent with the interpretation that the rock association most probably formed at a constructive plate margin not long before the mass was detached and obducted onto nappes of sedimentary and volcanic rocks overlying the stable Arabian continental mass (Al-Sulaimi 1981). The relationships of the Semail ophiolite to the underlying allochthonous sedimentary and volcanic rocks, and to the autochthonous sedimentary rocks and basement were established during the survey by the Shell Oil Company (Reinhardt 1969, 1970; Glennie *et al.* 1973, 1974) although the thrust sheets had been recognized by Lees in 1928. Graham (1979) has interpreted the autochthonous stratigraphy of the Oman Mountains in terms of the evolution of a passive but thinned continental crust. The sedimentary rocks and ophiolite in the U.A.E. have been described by Allemann & Peters (1972). However, the early stages of formation and emplacement of the Semail ophiolite remain a matter of speculation and a large number of mechanisms have been postulated. The purpose of this paper is to consider the most likely emplacement mechanisms so that an attempt may be made to test the hypotheses by careful field observations. Detailed accounts of the area studied will be published separately.

2. THE HAWASINA OCEAN AND SEMAIL OPHIOLITE

The autochthonous and allochthonous sedimentary sequences of the Oman Mountains have been identified by Glennie *et al.* (1973, 1974). Since the movement of the Hawasina nappes was from the east and northeast onto the Arabian Shield, Glennie *et al.* concluded that the highest nappes had travelled the greatest distances. Their palinospastic reconstruction suggests that the Hawasina sediments were deposited in a 'half ocean' that was limited in the southwest by the Arabian continent and in the northeast by a spreading oceanic ridge at which the Semail ophiolite nappe was formed.

The Middle Permian exotic limestone blocks represent the oldest rocks to be deposited on the oceanic crust, and they are thought to have formed on submerged volcanic hills several hundred kilometres from the continental edge. The minimum width of the area of deposition of Hawasina sediments is thought to be 400 km (Glennie *et al.* 1974). The deposition of the Hawasina sediments occurred between the Middle Permian and the mid-Cretaceous; a period of about 150 m.y. The maximum known thickness of shelf-slope sediments is 1600 m and they thinned eastwards to about 500 m. Because mafic lavas are associated with Hawasina sediments of Permian, Trias and Cretaceous ages and the youngest Semail lavas are dated by middle and late Cretaceous fossils, Glennie *et al.* (1974) concluded that the oceanic ridge was volcanically active and spreading throughout this period. Since there is no evidence of thrusting during this period, it is further thought that the distance between the Arabian continental shelf area and the spreading ridge was increasing throughout this time. The situation in the interval mid-Jurassic to mid-Cretaceous is represented by Fig. 1. Thus the Hawasina ocean was interpreted as part of Tethys, which was created by the late Palaeozoic break up of Pangaea into the two continental masses of 'Gondwanaland' and 'Eurasia'.

The end of the Cenomanian is marked by a widespread unconformity throughout the continental margin. Slight backwarping of the continental edge started at the beginning of the Cretaceous and developed gently throughout the early and middle Cretaceous. In the Coniacian and Campanian, conglomerates, carbonate clastics and turbidites of the Muti Formation were deposited in an intracratonic trough on the continental margin (Fig. 2). The sedimentary material was derived from the east, indicating that the continental slope must have been warped up to sea level at this

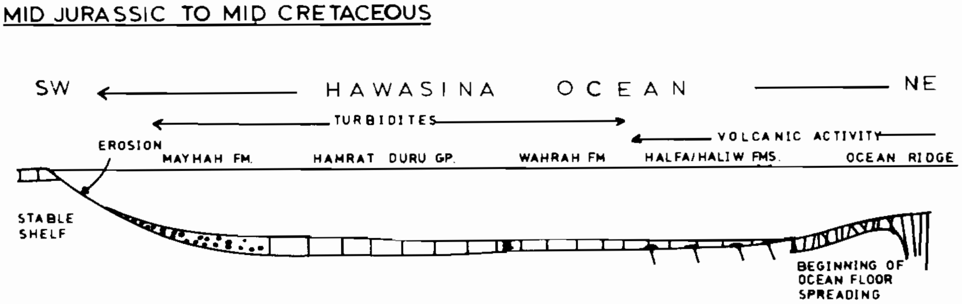

Fig. 1. Schematic representation of Hawasina deposition in the period mid-Jurassic to mid-Cretaceous (after Glennie *et al.* 1974).

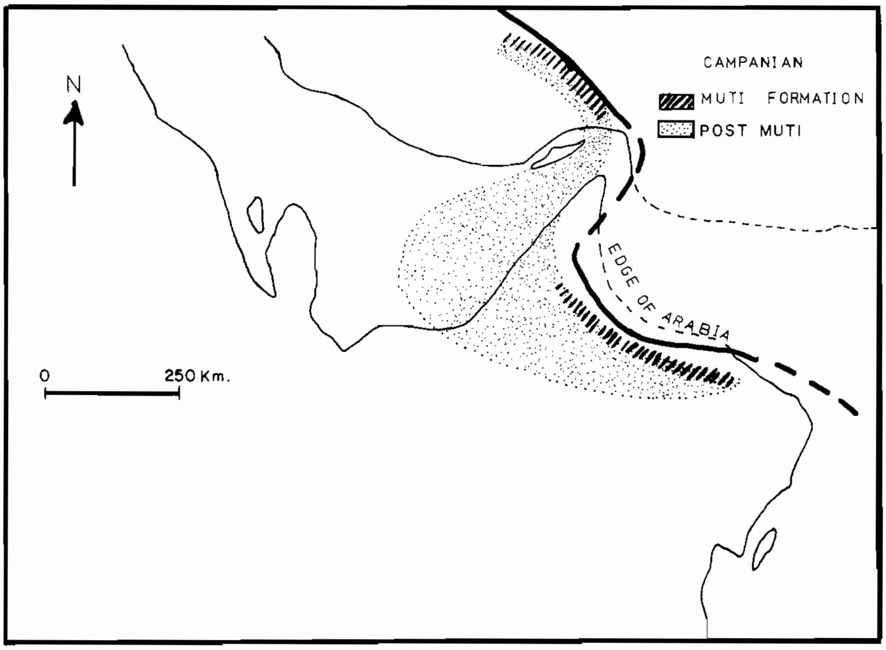

Fig. 2. Distribution of the Muti Formation 'basinal' facies, illustrating the development of the Arabian intra-marginal foredeep in the Campanian (after Glennie *et al.* 1974).

time. Muti sedimentation continued until the late Campanian when the depositional area was covered tectonically by the Hawasina and Semail nappes. The Aruma group of late Cretaceous age contains conglomerates with ophiolite debris, indicating the presence of an ophiolite nappe at a higher elevation than the intracratonic basin. The nappes are overlain unconformably by shallow marine limestones of late Maastrichtian age.

Because deformation in the Hawasina nappes consists of gentle folds and imbricate faults, Glennie *et al.* (1974) concluded that they were emplaced as gravity slides, probably down the slope along which the detritus of the Muti Formation had travelled. The Hawasina sedimentary rocks must have been detached from the oceanic crust and possibly from Permo-Triassic rocks before subduction. Wilson's (1969) interpretation of the Semail ophiolite as autochthonous and due to massive and rapid extrusion from tensile fractures cannot be accepted in view of the tectonic structures and the experimental petrological evidence concerning the depth of origin of the peridotites.

During Palaeozoic time, Iran was an extension of the Arabian platform and a part of Gondwanaland. A rift in the Arabian–Iranian platform opened in late Palaezoic or early Mesozoic times and was followed by the formation of a neo-Tethys ocean in the south. During Permian to Lower Miocene times, up to 10,000 m of predominantly carbonate sediments accumulated in Southern Iran. The closure of Tethys in Maastrichtian time was followed by reintegration of the Iranian part of Eurasia, and the Palaeocene folding of the Alpine orogeny during which time the mountains were raised 12 km above the gulf area. Much of the marine sediment within Tethys may have been lost by subduction but it is thought that the narrow zone of contact of the

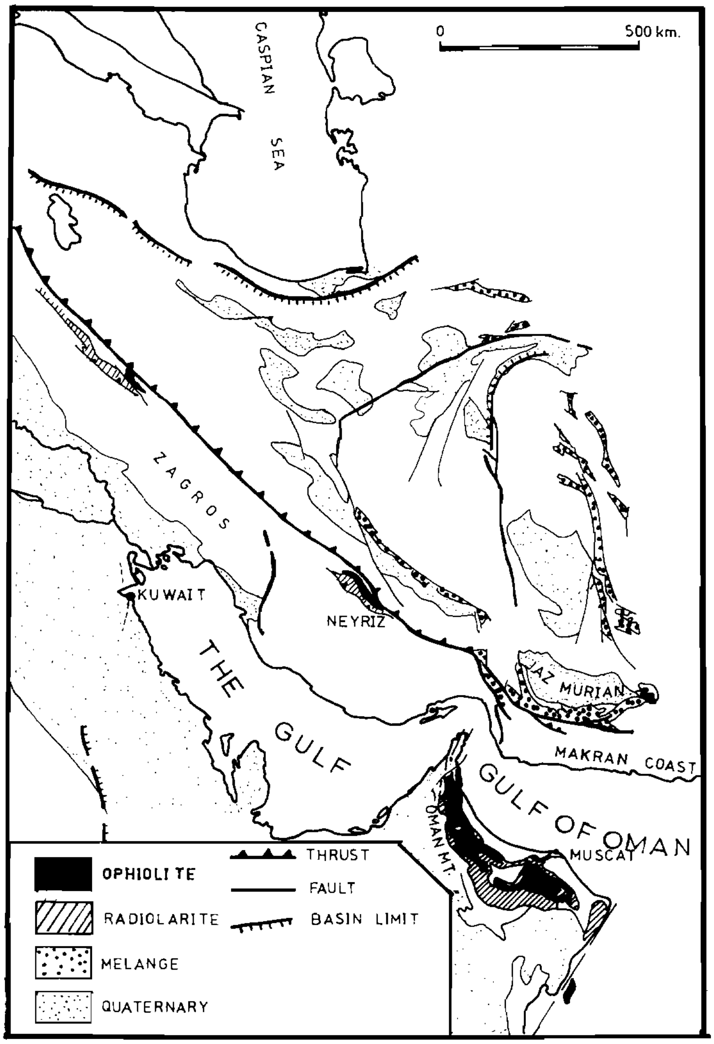

Fig. 3. Ophiolite zones and main structural trends of Iran and adjacent areas (after Stöcklin 1974).

continents is marked by the zones of ophiolites, radiolarian cherts and melanges, which in the Zagros and Oman Mountains are very similar in character and age of formation, although the Iranian ophiolites are not as complete and are more deformed than those of Oman (Fig. 3), (Stöcklin 1974; Stoneley 1974).

The features and events which have to be incorporated into an explanation of the generation of the Semail nappe are listed below:

(1) By the mid-Jurassic there was a depositional basin at least 400 km wide containing the Hawasina sediments (Glennie *et al.* 1974).

(2) Oceanic crust was forming at a spreading ridge to the northeast, so that the Hawasina rested partly on continental crust and partly on new oceanic crust.

(3) The present Hawasina nappes are approximately 100 km wide but the maximum thickness of sediments is only 1.6 km.

(4) The Hawasina sediments are not intensely deformed and unmetamorphosed except in the zone just below the Semail ophiolite nappe.

(5) The Hawasina nappes are stacked in the order: nearest depositional area at the bottom, furthest depositional area at the top.

(6) The autochthonous sediments of the Muti Formation were derived from an eastern source area indicating a reversed surface in the Campanian. This sedimentation was terminated by the emplacement of the Hawasina nappes from the east.

(7) The Semail ophiolite was formed at an accretionary plate margin, and it contains rocks which must have crystallized at a depth of at least 15 km.

(8) The ophiolite assemblage was obducted a very short time after its formation.

(9) The Hawasina and Semail nappes were obducted onto a continental margin which appears to have been passive because the absence of volcanic activity or metamorphism suggests the absence of a subduction zone.

(10) The period of nappe emplacement was relatively short and probably occurred in the Campanian within a period of 6 m.y.

(11) The Zagros fault zone marks the line of a major northeast inclined subduction zone which was initiated in the late Jurassic but was most active during the Campanian and also during the main Tertiary mountain-building period.

3. PLATE TECTONIC MODELS OF THE ZAGROS–OMAN AREA

Glennie *et al.* (1974) concluded that the Hawasina nappes had been emplaced by gravity sliding from uplifted sea floor to the northeast. It was suggested that the uplifted continental margin and oceanic crust were consumed on a southwest dipping subduction zone. With this model it is necessary to postulate the stacking of the Hawasina nappes on shallow thrusts which dip in the opposite direction to the subduction zone. However, the obduction of ophiolite when a spreading ridge arrives at a subduction zone can be explained in the manner suggested by Christensen & Salisbury (1975). The plate tectonic model of Oxburgh (1972) has a similar geometry but is supposed to develop as a result of irregularities in the continental margin. Smith (1976) points out that the continental margin of Oman appears to have been passive, with no andesitic extrusion or regional metamorphism, which would be expected over a southwest dipping subduction zone. He argued that the subduction of at least 400 km (Glennie *et al.* 1974) of oceanic crust at rates of at least 7 cm/year would almost certainly have produced andesitic magmatic activity.

Haynes & McQuillan (1974) base their plate tectonic model of the Zagros on the seismic work of Nowroozi (1972) which suggests the existence of a plate about 60 km thick dipping at 20° to the north. They postulated that a trench developed above the Zagros subduction zone before mid-Cretaceous. Southwest of this trench, sediments deposited on the oceanic crust were rafted northwards to the subduction zone. During the Maastrichtian the whole of the trench succession was uplifted and eroded to expose the thrust slices of oceanic crust. Thick Eocene and Miocene sediments were deposited before the main Tertiary orogeny accentuated the Zagros thrust zone.

Robertson & Woodcock (1979) have studied the regional tectonic setting of the Troodos massif and presented a sequence of events which is very relevant to the understanding of the Oman ophiolites. Their interpretation commences with continental rifting in mid to late Triassic times in the Eastern Mediterranean. The spreading appears to have ceased during the Jurassic but restarted in the early Cretaceous. The amount of ocean crust formed exceeded 500 km in width. Robertson & Woodcock (1979) regard this spreading line as a continuation of the spreading oceanic ridge inferred by Glennie *et al.* (1974) to the northeast of the Oman Mountains. Robertson & Woodcock suggested that in Campanian times a northward dipping subduction zone was initiated under the northern part of the Troodos ocean basin so that oceanic crust was consumed. On their palinospastic maps, Robertson & Woodcock indicate that the Troodos complex formed on a spreading ridge which by the Maastrichtian had reached a position above a northward dipping subduction zone.

Welland & Mitchell (1977) consider that sediments similar to the Hawasina were deposited to the northeast of a spreading ridge of the kind postulated by Glennie *et al.* (1974) where the oceanic crust was destroyed along the Zagros subduction zone and commenced in the Upper Jurassic. Sediments were thrust under the Iranian continental crust to form a series of nappes. The ophiolite derived from the spreading ridge was emplaced in a thrust slice below the sediments and was underthrust by a sequence of nappes of Hawasina rocks which mirrored the overlying nappe sequence. Welland & Mitchell (1977) do not explain how the Semail ophiolite nappe was initiated or the mechanism of its obduction onto the Arabian continental margin.

Stoneley (1974, 1981) offers an explanation of the Zagros thrust in terms of a subduction zone but favours an explanation involving a diapiric emplacement of peridotite. He regards this supposed peridotitic diapir as a result of an aborted attempt to form a new spreading ridge on the margin of the continent. The basic and ultrabasic rocks slipped off the diapir to form gravity nappes. According to Stoneley, the Zagros thrust zone developed after the Maastrichtian. In Makran, Tertiary flysch deposits lie between the Gulf of Oman and a strong thrust zone with melanges to the north (Fig. 3). Stoneley (1974) places the 'Southern Tethys suture' at the foot of the northern continental slope of the Gulf of Oman. He suggests that although the Arabian continent has collided with Iran along the Zagros line, the Oman part of the continental mass has not collided with the northern continent of Iran. The line of suture is thought to continue below the Gulf of Oman and is probably offset by transform faults, particularly along the Oman line.

A number of authors have suggested the presence of northward dipping subduction zone immediately northeast of the Oman Mountains. Gealey (1977) proposed that the ophiolite nappe formed from the over-riding plate on which an island arc had developed. Searle *et al.* (1980) have studied in detail a group of volcanic rocks up to 700 m thick forming the major component of the Haybi complex, which occurs as a discrete thrust slice beneath the Semail ophiolite nappe. The lower lavas are dominantly alkaline and the upper lavas tholeiitic. Searle *et al.* (1980) suggest that part of the Haybi volcanics were erupted as within-plate magmas of Triassic age that formed as ocean island volcanoes close to the site of initial rifting of the ocean basin.

Graham (1979) has also postulated a northeast dipping subduction zone with an open ocean on its northeast side. He suggested that the continental crust was subducted to the northeast and the Hawasina sediments were under thrust as a series of nappes. After an unknown period of continental under-thrusting, isostatic rebound enabled the gravity spreading mechanism to take over as the driving force of emplacement of the allochthonous units. Several other authors have postulated that the obduction of ophiolite nappes involved subduction of continental crust (Coleman 1971; Dewey & Bird 1973; Dewey & Kidd 1977; Oxburgh 1972). Since the amount of continental crust that can be subducted is limited, it is necessary to postulate that the subduction zone changes its dip direction or is displaced away from the continent in order to release the bouyant mass. Elliot (1976) has pointed out that the major objection to these hypotheses is that a continent passing under oceanic crust has not been found; in all cases the subduction zones near continents dip beneath the continents.

Pearce (1979) has made a geochemical study of basaltic lavas and suggested that the lavas from Cyprus and Oman exhibit characteristics which appear to be transitional between island arc tholeiite and mid-oceanic ridge basalt types. He believes that a back-arc basic complex developed in the Cyprus–Turkey–Oman area in the Upper Cretaceous. One analogy is with ophiolite assemblages formed in back-arc basins such as the Lau Basin and the Marian Trough (Hawkins 1979). These basins contain shallow water sediments on a floor of tholeiitic basalt which is topographically very irregular. These areas are also characterized by high heat flow and irregular magnetic anomalies. Usually there is a narrow sedimentary trough near the arc and abundant off-arc volcanism. Some spreading may occur in the back-arc basin but the basins tend to be narrow and short lived, existing for between 5 and 15 m.y. However, O'Hara & Mathews (1981) have drawn attention to the difficulties involved in trying to determine the origin of magmas from geochemical data which in any case is not very distinctive.

Smith (1976) has suggested that the available data on Oman could be explained if it is postulated that there was originally a continent off Oman in the northeast. The Hawasina sediments were scraped off a slab sinking to the northeast under the postulated continent. Eventually, the Oman continent collided with the postulated continent and the Hawasina nappes and ophiolite nappes were abducted, presumably by a push from the rear, onto the northern, higher continent and transferred by gliding to the southwest on to the Oman continent. The postulated continent then moved off to the northeast leaving behind it the Gulf of Oman.

4. THE INITIATION AND MOVEMENTS OF NAPPES

The main mechanisms that have been proposed to explain movement of nappes are (1) gravity sliding down a gentle slope, (2) push from the rear and (3) gravitational spreading of a mass due to increased elevation.

The highly coherent masses of relatively undeformed rock forming large nappes led early workers to conclude that they had slipped down a slope under the influence of gravity, because it was calculated that the force required to move such masses from the rear would far exceed the strength of the rocks. Furthermore, it was argued by Lees (1952) and others that foreland folds and thrusts in partly lithified sediments could only have formed as a result of the contraction of the basement. It was realized that sliding friction on large planes would make thrusting very difficult (Smoluchowski 1909), but this problem appeared to be solved by Hubbert & Rubey (1959) when they demonstrated that friction could be greatly reduced by high pore fluid pressure. Within deltas, large masses have moved by gravity sliding and have left listric normal faults at the rear of the sheets (Mandl & Crans 1981).

Detailed cross sections of the Rockies foreland thrust belt, particularly in Canada, have shown that the thrust planes generally dip towards the hinterland (Bally *et al.* 1966; Price & Mountjoy 1970). Moreover, reflection seismic sections indicate that the Precambrian crystalline basement in this region is remarkably smooth, planar and undeformed, so that shortening of the order of 200 km is restricted to the cover rocks above the thrusts. To explain this situation Price & Mountjoy (1970) resorted to the theory of 'gravity spreading' in which a mass tends to move sideways from an uplifted area due to the difference in elevation between the uplifted mountain area and the craton. Elliot (1976) has demonstrated that the average basal shear stress of a thrust sheet is equal to the down-surface slope stress, and the nappe always moves in the direction of the surface slope even if the basal plane dips in the opposite direction. This is true whether the movement is by viscous sliding in a basal zone or by frictional sliding reduced by fluid pressure. An important restriction is that the depth to the thrust plane is such that the mean normal stress is much greater than the shear strength of the rocks. Smith (1981) has proposed that in orogenic belts above subduction zones the intrusion of magmas might increase the elevation and aid gravitational spreading of nappes onto the foreland craton.

5. THE FORMATION OF THE SEMAIL AND HAWASINA NAPPES

Thermal convection in the mantle provides the driving mechanism for plate movement as matter is transferred from the rising asthenosphere plume to the diverging lithospheric plates (e.g. Oxburgh & Turcotte 1968; Turcotte 1980). If a rising plume formed a spreading plate margin to the northeast of the Oman mountains during the Trias to the end Cretaceous, as the new oceanic crust cooled, thickened and slipped away from the elevated ridge due to gravitational forces, tension stresses would be concentrated along the ridges (Jacoby 1980).

To the northeast of the spreading ridge, the cooled oceanic crust became gravitationally unstable and descended into the mantle along a northward dipping subduction zone. The subduction zone presumably formed within the oceanic crust some distance from the northern continent. The gravitational body force on the descending lithosphere slab would play a dominant role in causing the motion of the plate on the surface. Consequently the maximum rate of descent would occur when older and colder oceanic crust was descending. The model proposed here for the formation of the Semail and Hawasina nappes suppose that the northern half of the ocean has been reduced in width due to the consumption of the oceanic plate along the northward dipping subduction zone. It is likely that a trench developed at the edge of the over-riding plate, and that frictional drag and heating on the subduction zone produced a zone of compression and relative uplift above the subduction zone, along which an orogenic zone and/or volcanic arc developed (Fig. 4A). If continental crust was present on the over-riding plate, additional elevation may have occurred due to the buoyancy of the less dense material.

The elevation of an orogenic zone and/or volcanic arc is supposed to result in the displacement of a nappe on a gently dipping thrust plane extending upwards onto the foreland due to gravitational spreading (Fig. 4A). The nappe therefore moves over a gently rising basement which is relatively undisturbed. However, some shortening of the basement is supposed to occur due to reverse faulting on earlier normal faults and

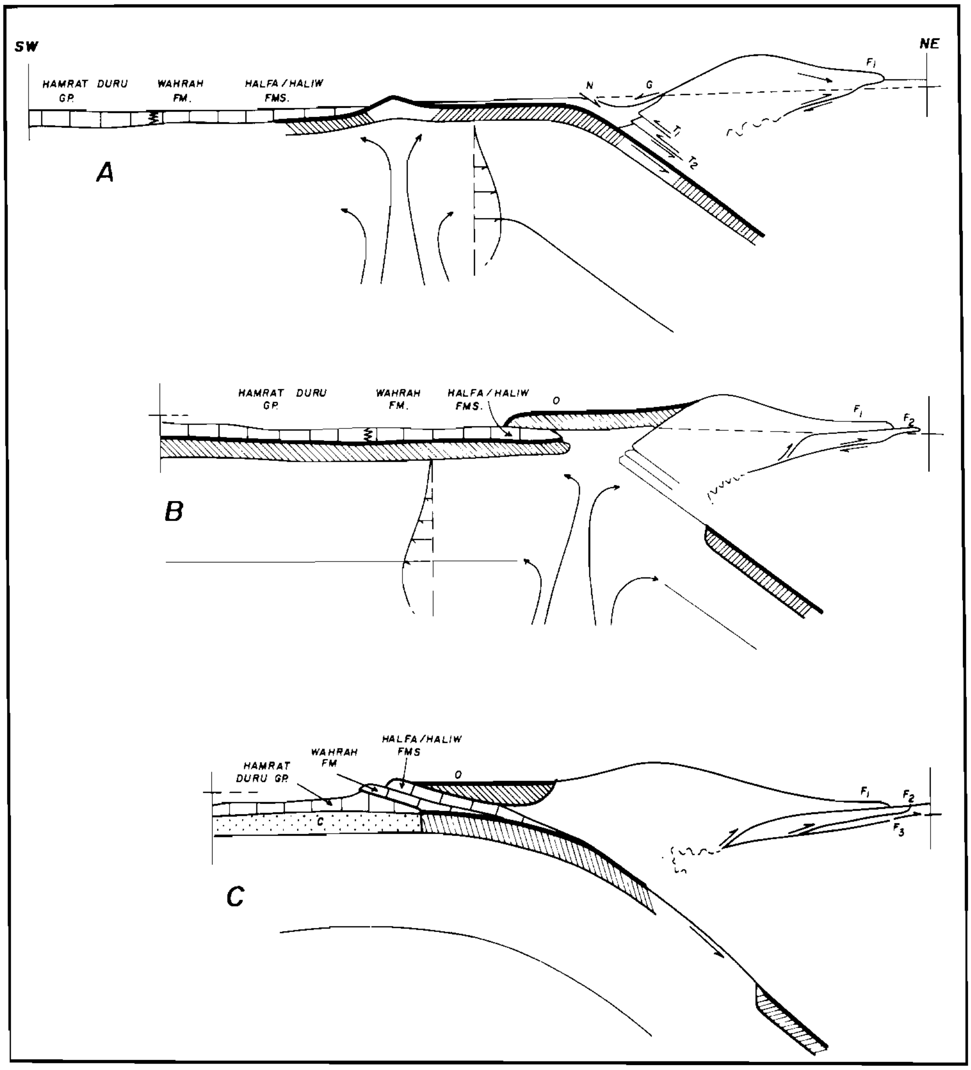

Fig. 4. Diagrammatic sections A. before, B. during and C. after the collision of a spreading ridge with a subduction zone. Symbols—$F_{1,2,3}$, sequence of foreland thrusts; $T_{1,2}$ sequence of thrusts on trench side; N, normal faults due to bending; G, gravity slide into trench; O, Semail ophiolite nappe; c, continental crust.

some basement must be consumed below the orogenic zone (Winslow 1981). Subsequent thrusts are expected to develop below the first thrust sheet and extend outwards so that the stacked thrust slices develop in a piggy-back sequence.

On the trench side of an elevated orogenic zone, nappes and melanges would form by gravitational sliding (Rigo de Righi & Cortesini 1964). Thrust slices due to gravitational spreading are likely to be present on the trench side of the elevated zone and the basal thrust is likely to be the subduction zone itself where similar displacement occur due to the drag of the down-going plate.

Normal faults or gravitational slides with melanges would develop in the sediments at the margins of the trench. On the ocean side of the trench, normal faulting may be accentuated by the tensional stresses above the region where the oceanic plate curves down into the subduction zone.

The presence of a trench above a subduction zone would hinder the seaward movement of nappes developed in the elevated zone of the over-riding plate. However, if the subduction rate exceeded the plate spreading rate so that the northern half of the ocean was consumed faster than it formed, a situation might be reached in which the elevated accretionary margin arrived at the subduction zone. The most important consequences of this situation would be that the trench would be replaced by an elevated area due to the hot rising plume from the asthenosphere (Fig. 4B). A second important consequence is that the upper part of the descending plate becomes detached along the spreading line because the body force on the down-going slab would be ineffective across the spreading line.

The presence of sheared, depleted harzburgite below the cumulate rocks within the ophiolite suggests that the oceanic plate consists of upper rigid layers extending to a depth of about 10 km, overlying a ductile zone of harzburgite. The rate of horizontal ductile flow within the mantle must increase from near zero below the cumulate rocks to a maximum before decreasing to zero again within the convection cell (Fig. 4A).

It is conceivable that subduction would continue at a reduced rate equivalent to the difference between the original northeast rate of subduction and southwest rate of spreading from the ridge. This would be more appropriately regarded as the rate at which the Eurasian and Arabian continental masses continued to move towards each other.

If when a spreading ridge reaches a subduction zone, the rising plume causes the trailing edge to collide with the over-riding plate of the subduction zone, thrust faults may develop within the upper part of the oceanic plate. The first thrust plane is likely to develop within the ductile zone of the hot harzburgite due to gravity spreading from the elevated zone (Fig. 4B). The first thrust would extend outwards through the harzburgite and would eventually step up through the cumulate rocks and overlying gabbros, dykes and lavas. This ophiolite nappe would suffer shortening so that the hotter layered rocks might be folded while the cool brittle cover rocks would be faulted. The ophiolite nappe would move by gravitational spreading onto the sediments resting on ocean crust as this moves towards the subduction zone (Fig. 4C). Since the ophiolite rocks would be at a relatively high temperature, the increased water pressures above the sedimentary rocks would greatly reduce friction and aid the displacement of nappes away from the elevated zone. Stable isotope data indicates that most serpentinization of ophiolite peridotites occurs after emplacement onto continental crust (Coleman 1977).

If the elevation and subduction was maintained, subsequent nappes successively composed of rise, slope and shelf sedimentary rocks detached from the more rigid oceanic crust would develop below the ophiolite nappe (Fig. 4C). The arrival of the stacked nappes would cause rapid loading and depression, whereas the area behind the nappe would tend to rise because of off-loading. Gretner (1981) has suggested that this isostatic response produces a moving bulge with an outward slope which tends to make thrust faulting a self-prepetuating process. However, it seems more likely that nappes develop and move as a result of gravitational spreading from an elevated area so that as the elevation is reduced, thrusting decreases and eventually stops. The stacked nappes rest in depressions bounded by listric reversed faults and the hot elevated area would eventually subside due to the collapse of the underlying plume. The temporary re-establishment of subduction may have further reduced the elevation and eventually produced a new trench zone so that deep sedimentation occurred again to the northeast of the stacked nappes which had been left isolated on the passive continental margin.

The main structures and events associated with the development of the Semail and Hawasina nappes have been explained as consequences of local plate motions which were determined by convection in the upper mantle. The oscillatory nature of geological events, such as episodes of orogenic deformation, indicates that the convection cells are not stable in position or activity. This oscillation may be due in part to the nature of the convection system. Initially the hot rising plume is likely to be the dominant feature, but as the lithospere plate extends and cools it is more likely to be involved in subduction. If the body forces of the descending plate increase the subduction rate in excess of the spreading rate, the convection cell will contract. Several authors have indicated that when a spreading line meets a subduction zone, very special circumstances arise. The model proposed here depends only on the elevation that may occur during collision of a spreading zone with an over-riding plate, which need not contain continental crust. The situation would not necessarily result in the generation of an ophiolite nappe but if there was still sufficient hot matter in the asthenosphere plume at the time of collision for significant elevation to occur, the conditions could give rise to a piggy-back stack of nappes with an ophiolite slice at the top.

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حركة وتكوين كتل الحواسينا والسماعيل في جبال عمان

جواد صادق السيلمي
معهد الكويت للابحاث العلمية
ص . ب ٢٤٨٨٥
الكويت

وليم جون فيلبس
قسم الجيولوجيا بجامعة
ويلز ، ابريستويث ، ويلز ،
المملكة المتحدة .

خلاصة

ان البحث المقدم يعطي نبذة موجزة عن اهم الخصائص المميزة لوحدات الصخور الرسوبية (حواسينا) وصخور الافيوليت (سماعيل افيوليت) التي تكونت على شكل كتل صفائحية (nappes) . ولقد تمت مراجعة النظريات التي سبق نشرها حول تكوين هذه الكتل وتحركاتها ، كما يقدم البحث تفسيرا جديدا لعملية تكوين هذه الكتل الصفائحية وانتقالها من موقع تكوينها الى مكانها الحالي .