Folding and faulting of neoautochthonous sequence in the Al Fayah Fold Belt: Northern Oman Mountains, United Arab Emirates

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1 author:

Ali Abd-Allah
Ain Shams University

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FOLDING AND FAULTING OF NEOAUTOCHTHONOUS SEQUENCE IN THE AL FAYAH FOLD BELT: NORTHERN OMAN MOUNTAINS, UNITED ARAB EMIRATES

Abd-Allah, A. M. A.
Geology Department, Faculty of Science, Ain Shams University, Egypt

ABSTRACT

The thrust-related folds of the Al Fayah fold belt consist of three en echelon, ophiolite-cored anticlines that form a simple zigzag fold belt and overlapped by folded and faulted areas. These doubly plunging anticlines have NNE-SSW orientation and are asymmetrical towards their forelimbs. They have rounded to box hinge zones where their plunging parts terminated by conical folds. The anticlines were formed by the detachment of the Maastrichtian rocks over a blind thrust fault that lies at a depth of about 1.2 and 1.7 km in the upper portion of the ophiolite rocks. The variation in this depth is attributed to a forethrust affecting only the Bahayis anticline. The Al Fayah belt initiated in early Early Maastrichtian and amplified during the deposition of the Upper Maastrichtian rocks. During Early Paleocene, the Bahayis anticline was modified as a break-thrust fold where it was dissected by a forethrust fault. In Middle Paleocene-Middle Eocene, the three anticlines developed by rotation of their forelimbs. The anticlines resulted from S 60° E directed compression, which produced uniform shortening and homogenous strain. The strain has been accommodated by folding rather faulting. The anticlines have been formed by flexural-slip folding with local buckling inside the thick Maastrichtian beds. The folded beds have been subjected to bedding-parallel shortening prior to folding. The hinge-parallel normal and thrust faults were initiated in Early Paleocene, whereas the hinge oblique strike-slip faults are relatively younger.

INTRODUCTION

The Oman Mountains represent important regional thrust-fold belts associated with the obduction of the oceanic crust onto the Arabian margin which formed the Semail Ophiolite during the Coniacian-Early Maastrichtian time (Glennie et al. 1974; Searle et al. 1983; Searle 1988; Nolan et al. 1990; Dunne et al. 1990; Robertson et al. 1990; and others). A post-obduction (neoautochthonous) shallow-water carbonate sequence was deposited on the margins of the Oman Mountains in Early Maastrichtian-Miocene times. The neoautochthonous sequence and the underlying ophiolitic and allochthonous units were deformed by post-obduction compression to form belts of folds and thrust faults along the western front of the Oman Mountains. In the United Arab Emirates, these belts extend from south of Al Ain to the Al Fayah area (Fig. 1).

The study area includes Al Fayah folds, which lies approximately 89 km north of Al Ain City between the Dibba and Hatta shear zones (Fig. 1). In this area, the neoautochthonous Lower Maastrichtian-Eocene beds overlie unconformably the Semail Ophiolite. Considerable attention has been given to the deformation of the neoautochthonous rocks along the western margin of the Oman Mountains in the United Arab Emirates (Glennie et al. 1974; Hunting

1979; Ricateau and Riche 1980; Warrak 1986, 1987, 1996; Patton and O'Connor1990; Noweir and Eloutefi 1997; Noweir 2000; Noweir and Alsharhan 2000).

Only two structural studies were made on the study area, the first was carried out by Dunne et al. (1990) in which the correlation between the surface and subsurface structural styles was indicated in two cross sections. The second study is the descriptive study of Noweir et al. (1998) in which the structural measurements were taken only in the southern

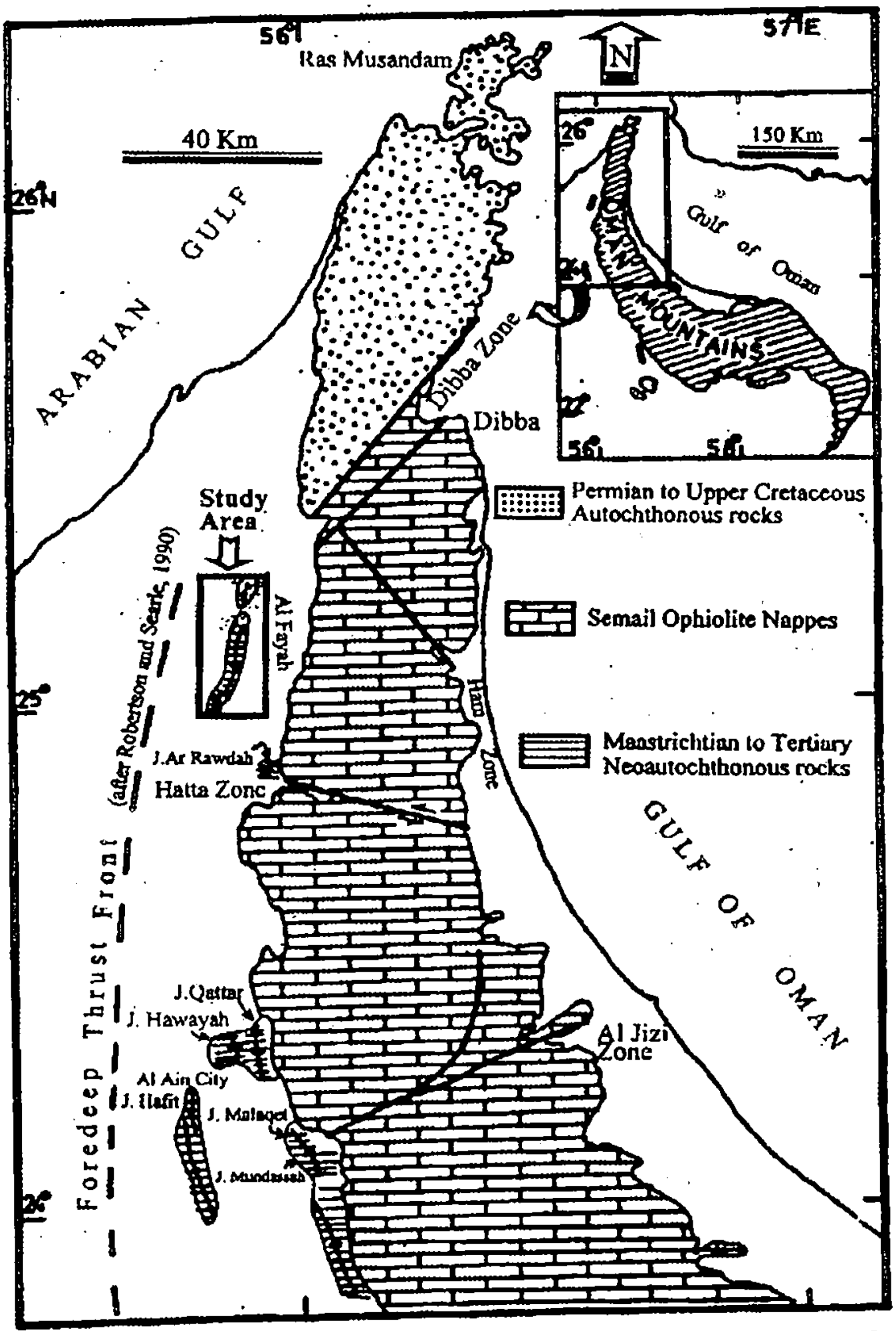

Fig. 1: Location map of the northern Oman Mountains showing the study area and the main structural elements.

part of the area. Therefore, the present study aimed at: (1) detailed field mapping of the Al Fayah folds; (2) description of the structural style of the folds and associated faults; (3) studying the folding mechanisms and model(s); (4) analysis stress and strain; and (5) indicating fold and fault propagation.

STRATIGRAPHY

The neoautochthonous sedimentary succession of the Al Fayah area ranges in age from Early Maastrichtian to Middle Eocene (Fig. 2). It overlies unconformably the Upper Cretaceous serpentinite, peridotite, and pyroxenite of the Semail Ophiolite. The Qahlah Formation is the result of the first onset of shallow marine to fluviatile (Nolan et al. 1990 and Skelton et al. 1990) clastics disconformably covered the eroded ophiolite rocks. This formation commences with a thick conglomerate bed with clasts formed of angular to rounded granules-boulders sizes derived from diverse source rocks in nearby and distant areas. The conglomerate is overlain by an interbedded section of grayish green and reddish brown conglomerates, cross-bedded sandstones, and red siltstones rich in rudistae, *Spondylus*, corals, and oysters. This faunal content indicates an Early (Hamdan 1990) or Middle (Skelton et al. 1990) Maastrichtian age. In some localities where the Qahlah Formation was not deposited, a thin conglomerate bed at the base of the Simsima Formation overlies the ophiolite. The Qahlah Formation is exposed in the southern half of the study area (Figs. 3 and 4).

The widely distributed Simsima Formation (Simsima Limestone of Glennie et al. 1974) consists of yellowish to light brown, thick bedded, moderately hard to soft grainstone and packstone beds with a few marl interbeds. The beds contain rudistae, *Acteonella, Orbitoides, Pecten, Spondylus*, algae, echinoids, corals, and other molluscs. These beds have been deposited in shallow water (Searle et al. 1983) or shallow carbonate shelf environments (Nolan et al., 1990 and Skelton et al., 1990) during the Middle (Skeleton et al. 1990) or Late (Hamdan, 1990) Maastrichtian.

Abdelghany (pres. com.) proposes a new formal unit called the Al Fayah Formation that overlies the Maastrichtian rudist/orbitoidal beds of the Simsima Formation. The Al Fayah Formation is also referred to as the Muthaymimah Formation by Nolan et al. (1990) or as the Upper Simsima Member by Noweir et al. (1998). The beds of the Al Fayah Formation are distinct from those of the Simsima Formation in being thin bedded; hard; white to reddish white, chalky limestone. These beds contain several intraformational breccia, conglomerate, and dolomite intervals. They are rich in *Orbitoides, Durania,* and foraminiferal tests indicating late Late Maastrichtian age (Abdelghany, pres. com.). This formation is exposed on the outer parts of the fold limbs (Figs. 3 and 4).

The Middle-Upper Paleocene (Abdelghany and Faris, pres. com.) marls and impure limestones lie upon the Al Fayah Formation and are separated by a 0.5 m thick bed of well rounded conglomerate. Two other conglomerate beds intervene in the middle and upper parts of the Paleocene section.

The Lower-Middle Eocene (Abdelghany and Faris, pres. com.) rocks rest unconformably on the Paleocene rocks. The Eocene rocks consist of thin bedded chalky and dolomitic limestones containing nodular limestone and conglomerate interbeds. They include

Nummulites, Alveolina, Discocyclina, and, other foraminiferal assemblages. The Paleocene-Eocene rocks constitute the outskirts of the western limbs of the southern two anticlines (Figs. 3 and 4).

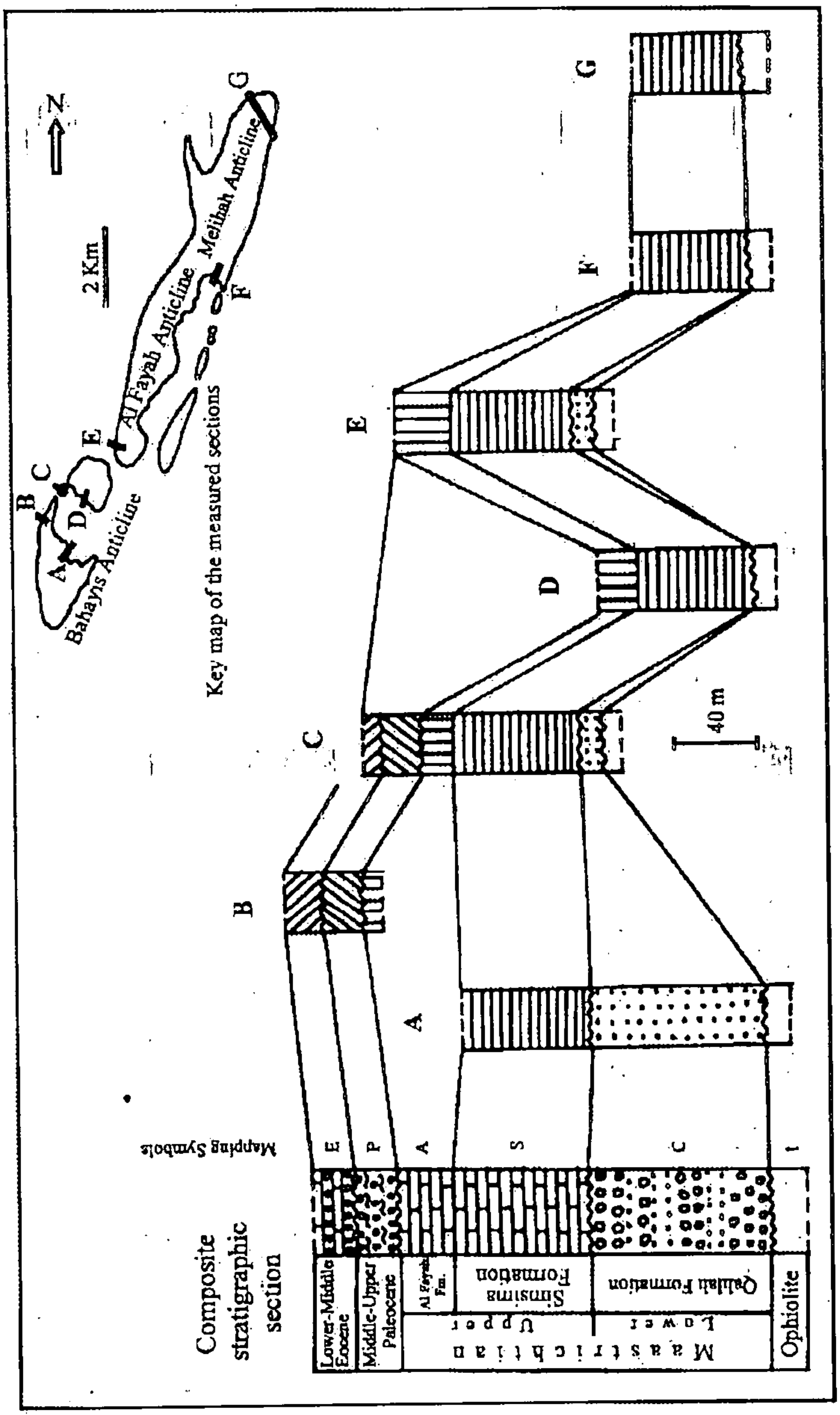

Fig. 2: Correlation of the rock units in the study area and the composite stratigraphic section.

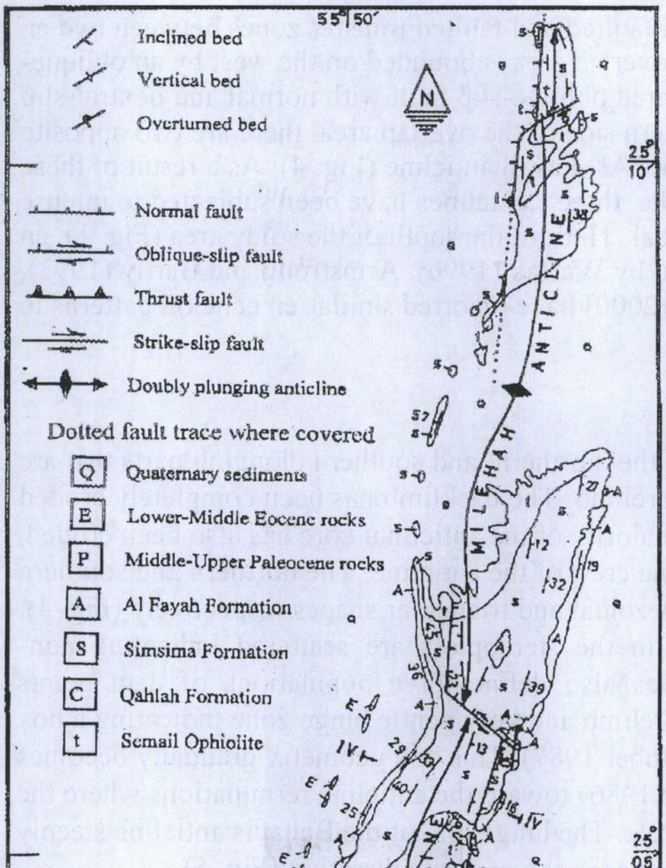

Fig. 3: Geologic map of the Al Fayah fold belt. Locations of the cross sections in figure 6 are indicated.

STRUCTURAL SETTING

The Al Fayah folds are the most known in the neoautochthonous sequence of the western margin of northern Oman Mountains (Fig. 1). These structures consist of three en echelon anticlines (Fig. 3) forming the Al Fayah fold belt. These doubly plunging anticlines are named Bahayis, Al Fayah, and Milehah. The Al Fayah anticline is right-stepped relative to the Bahayis anticline and is left-stepped relative to the Milehah anticline (Fig. 3). The crests of the anticlines were eroded to show the ophiolite cores which are overlain by the Maastrichtian-Eocene beds. The anticlines are characterized by steep to overturned forelimbs (western) and gentle backlimbs (eastern). Their hinge lines have NNE-SSW orientation and are slightly curved in the overlap areas between the anticlines.

The overlap area between the Al Fayah and Milehah anticlines is represented by an antiformal depression (Mitra and Marshak 1988; p. 233) in the hinge zones of the two anticlines and by an open syncline between the forelimbs of the two anticlines. This type of overlap is called a soft-linkage. The antiformal depression is deformed by two NNE oriented, ESE dipping normal faults that are linked by a NW oriented transfer fault. In this overlap area, the hinge lines of the two anticlines are deviated; being displaced to the east by the influences of the NW trended transfer fault. The Bahayis and Al Fayah anticlines are completely separated in the southern overlap area (Figs. 3 and 4), which is called a hard-linkage overlap. Soft- and hard-linkage terms have been used by

McClay and White (1995) to describe the unfaulted and faulted transfer zones between two en echelon faults respectively. The southern overlap area is bounded on the west by an oblique-slip, gently (42°), ESE dipping, NNE oriented oblique-slip fault with normal and dextral-slip components (rake = 30° SSW). On the eastern side of the overlap area, there are two opposite gently dipping thrust faults that affect the Al Fayah anticline (Fig. 4). As a result of these deformations, the two overlap areas of the three anticlines have been subjected to intense brittle deformation during folding. At Jabal Hafit to the south of the study area (Fig. 1), en echelon anticlines have also been described by Warrak (1996). Armstrong and Bartly (1993), Nicol (1993), and Mohajjel and Fergusson (2000) have reported similar en echelon patterns in other compressional terrains.

1- Bahayis Anticline

The Bahayis anticline consists of the northern and southern plunging parts that are connected by a prominently outcropping forelimb. The backlimb has been completely eroded or down faulted to the east (Fig. 4). The majority of the anticlinal core has also been eroded, probably due to intensive fracturing of the crest of the anticline. The northern and southern plunging parts of the anticline have trapezoidal and triangular shapes respectively (Fig. 4). Poles to bedding planes of these parts in the stereoplots are scattered indicating non-cylindrical geometry (Fig. 5). These poles also define three populations of data points representing the gentle backlimb, steep forelimb and very gentle hinge zone indicating a box geometry (as defined by Ramsay and Huber 1987). This box geometry gradually becomes conical (as defined by Webb and Lawrence 1986) toward the anticline terminations where the poles would not lie in a simple great circle. The hinge line of the Bahayis anticline steeply plunges south-southeastward and gently plunges in the opposite direction (Fig. 5).

The Maastrichtian-Eocene beds forming the central segment of the forelimb are vertical to overturned and decrease in dip due north and south. Transversely across the fold hinge line, the Qahlah and Simsima beds have steep dip that becomes progressively gentler in the overlying Paleocene and Eocene beds.

A thrust fault, a strike-slip fault, and two oblique-slip faults deform the forelimb of the Bahayis anticline (Fig. 4). The ESE dipping plane of the thrust fault dips between 26° and 43° and has a sinuous trace (Fig. 4). In the area west of Jabal Bahayis, the thrust fault has emplaced the Simsima Formation over the vertical beds of the Al Fayah Formation (cross section I in Fig. 6). To the south of this area, the trace of the fault is concealed under sand dunes. Southwest of Jabal Aqabat Al Fayah, the fault trace changes to an easterly trend and dissects the ophiolite rocks in the core of the anticline (Fig. 4). A dextral-slip fault has shifted the northern segment of the Bahayis forelimb (Fig. 4) and is associated with several small open folds around its trace. This fault is considered to be a tear fault formed to accommodate the variation in the deformation of the forelimb. Two NE oriented, oblique-slip faults with predominant normal components and subordinate dextral-slip components bound a graben block in the southwestern part of the anticline. This graben extends from the core of Bahayis anticline to its forelimb (Fig. 4). The displacement of each bounding fault gradually decreases from the core side, where the older rocks are exposed, to the forelimb side, where the younger rocks are found. This observation probably suggests that these faults have been reactivated several times during the deposition of the Maastrichtian-Eocene rocks, as shown by the fact that the older rocks are much rejuvenated compared to the younger rocks.

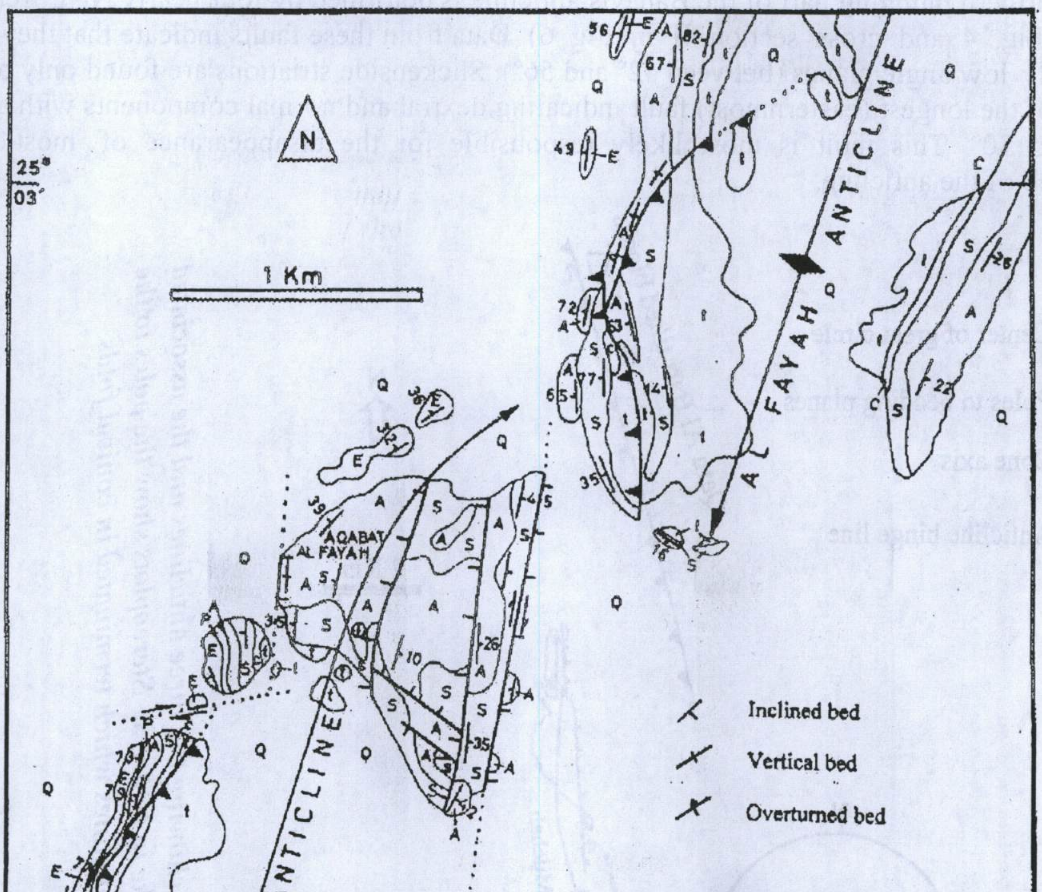

Figure 4: Detailed geologic map of the Bahayis anticline and the southern part of the Al Fayah anticline.

The northern plunging part of the Bahayis anticline is deformed by four nearly NNE trending faults (Fig. 4 and cross section II in Fig. 6). Data from these faults indicate that they have relatively low angle planes (between 42° and 56°). Slickenside striations are found only on the plane of the longest (easternmost) fault indicating dextral and normal components with a rake equal to 30°. This fault is most likely responsible for the disappearance of most of the backlimb of the anticline.

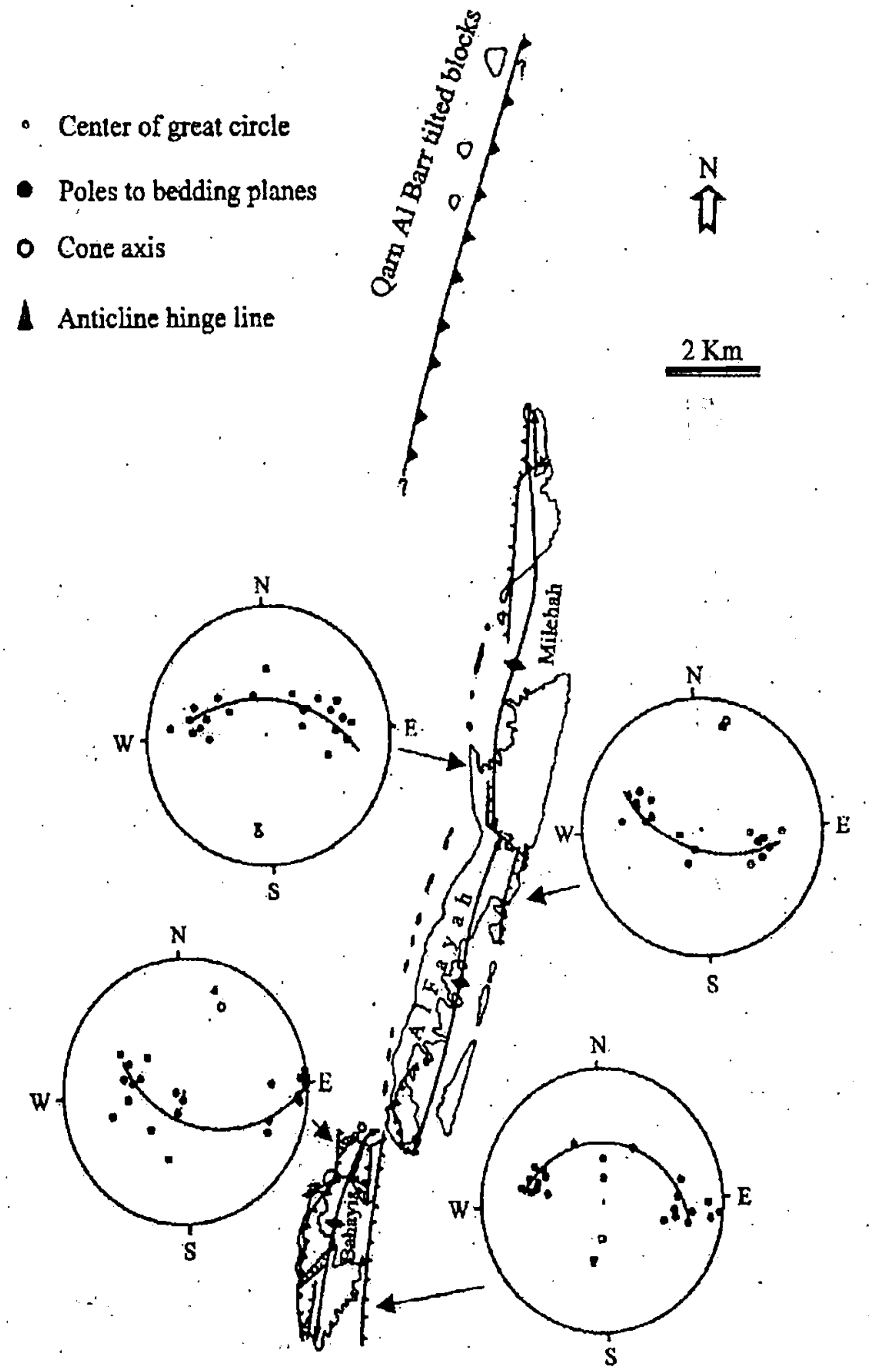

Figure 5: Structures map of the Al Fayah fold belt showing the three anticlines and the associated thrust and normal faults. Structural symbols are like in figure 3. Stereoplots show the poles to the bedding planes in the plunging parts of the anticlines which terminated in conical folds.

2- Al Fayah Anticline

The Al Fayah anticline is the most continuous fold and occupies the central part of the study area (Fig. 3). Al Fayah anticline has an eroded core bounded to the north and south by two plunging parts. It has asymmetrical limbs, the forelimb is much steeper than the

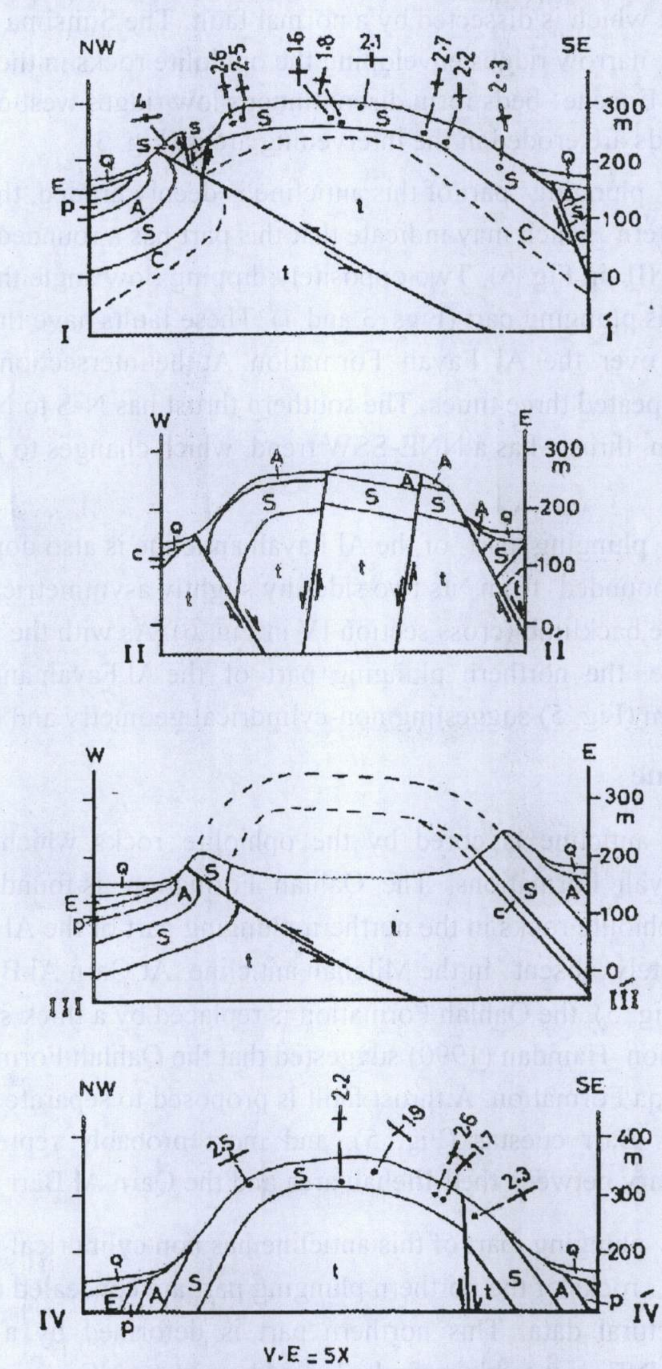

Figure 6: Cross sections crossing the anticlines of the study area showing the rounded to box fold geometry and the accompanying faults. See figure 3 for locations. The long and short axes of the deformed ellipses and the Rs amounts at each site are indicated in cross sections I and IV.

backlimb. The dip amounts of the beds forming the northern segment of the forelimb range from 23° to 42° and abruptly change to vertical and overturned in the southern segment due to the influence of two thrust faults affecting the southern segment (Fig. 3). On the other hand, the backlimb has homogeneously dipping beds (16° to 32°) except for some local changes at its northern segment which is dissected by a normal fault. The Simsima and Al Fayah beds in the two limbs form narrow ridges enveloping the ophiolite rocks in the core of the anticline. The gently dipping Eocene beds form discontinuous low ridges west of the forelimb, where the soft Paleocene beds are eroded in the intervening areas (Fig. 3).

The southern plunging part of this anticline is deeply eroded, the remaining outcrops have a rounded pattern which may indicate that this part has a rounded or box-shaped hinge zone (cross section III in Fig. 6). Two oppositely dipping, low angle thrust faults dissect the western portion of this plunging part (Figs. 3 and 4). These faults have thrusted the beds of the Simsima Formation over the Al Fayah Formation. At the intersection of the two faults, the Simsima beds are repeated three times. The southern thrust has N-S to NNW-SSE orientation whereas the northern thrust has a NNE-SSW trend, which changes to NE-SW in the core of the anticline (Fig. 4).

The northern plunging part of the Al Fayah anticline is also dominated by a rounded hinge zone that is bounded from its two sides by slightly asymmetrical limbs, the forelimb being steeper than the backlimb (cross section IV in Fig. 6). As with the two plunging parts of the Bahayis anticline, the northern plunging part of the Al Fayah anticline has a scattered bedding poles diagram (Fig. 5) suggesting non-cylindrical geometry and conical form.

3- Milehah Anticline

The Milehah anticline is cored by the ophiolite rocks, which are enveloped by the Simsima and Al Fayah Formations. The Qahlah Formation is found in several very small outcrops over the ophiolite rocks in the northern plunging part of the Al Fayah anticline. This formation is completely absent in the Milehah anticline. At Qarn Al Barr to the north of the Milehah anticline (Fig. 5), the Qahlah Formation is replaced by a thick shale and marl section of the Fiqa Formation. Hamdan (1990) suggested that the Qahlah Formation is equivalent to the upper part of Fiqa Formation. A thrust fault is proposed to separate the Milehah anticline from the Qarn Al Barr cuestas (Fig. 5), and most probably represents a sedimentary environmental boundary between the Milehah area and the Qarn Al Barr area.

The southern plunging part of this anticline has non cylindrical geometry and conical form (Fig. 5). Most rocks of the northern plunging part are concealed under the sand dunes, providing little structural data. This northern part is deformed by a zigzag fault pattern consisting of two NNE oriented long faults linked by a short NE oriented transfer fault (Fig. 3). The fault planes of the long faults are not exposed, but the outcrop pattern and bed attitudes are consistent with major normal displacements on these faults.

STRUCTURAL ANALYSIS

The structural analysis of the folds and faults of the Al Fayah fold belt is discussed below.

1- Folding Mechanisms

Only the plunging parts and the two limbs of the anticlines provide information on the geometry and mechanisms of these folds. There are sharp vertical facies changes in the folded units. The oldest units are serpentinites and pyroxenites overlain by the clastics of the Qahlah Formation which are in turn overlain by grainstone and packestone (Simsima and Al Fayah Formations); Paleocene marl; and finally the Eocene limestones. Most of the folded beds are thin, with the exception of a few thick beds in the Simsima Formation. These lithological changes yield competency differences, which controlled the formation of the anticlines by a flexural-slip folding mechanism. Bedding-parallel slickenside striations, gypsum and calcite fibers, and bedding plane veins constitute the bedding-parallel slip indicators. The magnitude of slip depends upon the dip amounts and thickness of the folded beds (Gutierrez-Alonso and Gross 1999). These slips are orthogonal to the hinge line, except for some of the slip directions that are oblique to the hinge line in some of the plunging parts and in the rotated forelimbs. The hinge-oblique slips in the plunging parts of the anticline are consistent with the non-cylindrical geometry of these parts (Price and Cosgrove 1990). Angular to box fold geometry is dominantly produced by flexural-slip folding (Erslev and Mayborn 1997). Competency contrasts between the folded units have been deduced from the drag folds (as defined by Billings 1982, p. 90). Tight drag folds resulted from the strong bedding-parallel slip (shear) in high competency contrast during flexural-slip folding.

The variable rock types of the folded units, presence of bedding-parallel slip, drag folds, and rounded to box-like hinge zones suggest the flexural-slip folding mechanism during the development of the three anticlines. The flexural-slip folding mechanism of the anticlines is supported by the associated fractures, which typically resemble the fractures formed in the anticlines folded by model 2 which was proposed by Poblet and McClay (1996). In this model, the flexural-slip fold is developed by hinge and limb rotation and accompanied by hinge-parallel and -oblique fractures.

2- Folding Processes

The development of thrust-related folds of the Al Fayah belt is controlled mainly by fold geometries, which are entirely determined by the position of the folds with respect to the thrust faults. The Al Fayah and Milehah anticlines show unaffected forelimbs, except for the southern segment of the forelimb of the Al Fayah anticline, which is dissected by two short oppositely dipping thrust faults. No thrust faults were observed in association with these forelimbs. Therefore, the Al Fayah and Milehah anticlines were formed as detachment folds (as defined by Suppe 1983; and Mitra and Namson 1989) above a blind thrust fault located in the upper part of the ophiolite rocks. Detachment folds initiate at small buckling instabilities and subsequently grow laterally with increasing layer shortening (Dubey and Cobbold 1977) where the displacement related to the blind thrust fault is accommodated by folding in the hangingwall (Jamison, 1987 and Poblet, et al. 1997). To the south of the study area at Jabal Al

Hawayah, the present author considers the Al Hawayah fold as a detachment box anticline above a blind thrust fault at a depth of 3.4 km. Mitra (1990), Groshong and Epard (1994), Epard and Groshong (1995), Poblet and McClay (1996), Rowan (1997), and others have reported detachment folds.

The Bahayis anticline is deformed by a gentle ESE dipping forethrust fault affecting the southern two thirds of its forelimb and terminating in the ophiolite rocks in the core (Fig. 4). From this description, it appears that the Bahayis anticline was formed as a fault-propagation fold (as defined by Suppe and Medwedeff 1990). However, the field evidences and structural analyses argue against the fault-propagation fold model. These evidence include (1) the forethrust fault dissects only the southern two thirds of the limb; (2) the forethrust fault formed in the Early Paleocene after the deposition of the Al Fayah Formation as discussed in another section; and (3) folding was initiated and reactivated several times before the Early Paleocene. Therefore, there is a time distinction between folding and faulting where the forethrust fault formed after folding of the Bahayis anticline. This concept is in disagreement with the idea of fault-propagation fold process in which the faulting and folding are synchronous as indicated in the studies of Jamison (1987) and Mitra (1990). Thus the field data rather support a break-thrust folding process (as defined by Fischer et al. 1992) during the formation of the Bahayis anticline. In such process, the Bahayis anticline would initially form as an unfaulted detachment fold during the deposition of the Maastrichtian Qahlah, Simsima, and Al Fayah Formations. During the Early Paleocene, the anticline was dissected by the forethrust fault. Both the folds produced by the fault-propagation and break-thrust processes are asymmetrical toward the forelimbs (Woodward 1997).

Therefore, folding in the study area seem to have taken place in three stages: (1) early detachment folding of the three anticlines during the deposition of the Maastrichtian rocks, (2) break-thrust folding which affected only the Bahayis anticline in the Early Paleocene time by a forethrust fault, and (3) fold amplification and lengthening during the Middle Paleocene-Eocene.

The depth of detachment of the three anticlines is estimated using the method described by Poblet and McClay (1996) to be 1.2 km at the southern plunging part of the Bahayis anticline and 1.7 km at the northern plunging part of the Al Fayah anticline. The variation in the depth of detachment is attributed to the forethrust fault that affects the Bahayis anticline. This fault splayed up section from the blind thrust fault and become shallower beneath the Bahayis anticline. However in the case of Al Fayah anticline, the estimated depth is interpreted to represent the depth to the blind thrust fault (Fig. 7).

The structures in the study area were formed by S 60° E directed compression (Fig. 8) from Oman Mountains side. Tectonic transport trend is inferred by using fault slip data. The resulting compression is not tangential ($\sigma 1$), it is inclined by about 22° from the horizontal. This inclination may be attributed to the rotation of the measured fracture planes during the different stages of folding.

The analysis of the four plunging parts (stereoplots in Figure 5) of the anticlines indicates that these anticlines terminate in conical folds. The shortening amounts indicated by these conical folds are estimated using the method of Nicol (1993), to be between 12% and 15.2%.

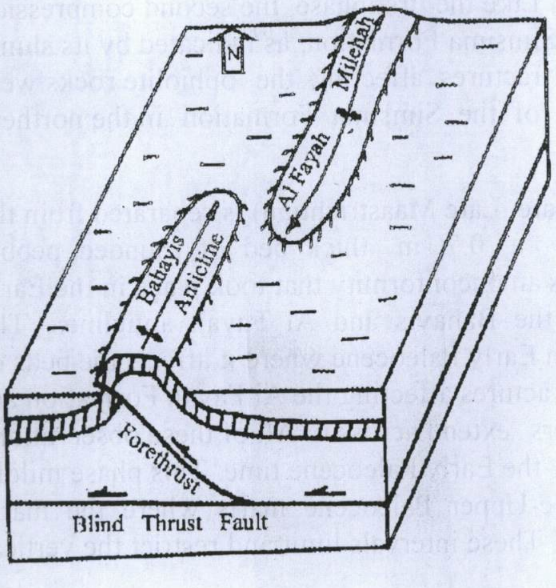

Fig. 7: Block diagram showing the three anticlines that were detached over a blind thrust fault. From this fault a shallower forethrust fault splayed to affect the Bahayis anticline.

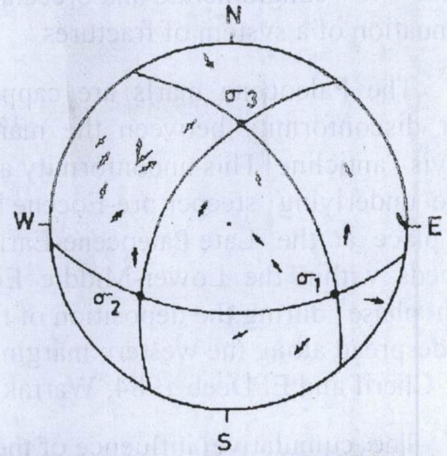

Fig. 8: Stereoplot showing the poles to twenty fault planes (points) and the fault slip vectors (long arrow and line). Arrows and lines indicate diagonal-slip and dip-slip displacements. The stress axes are estimated where the slip vectors point away from σ1 and toward σ3.

3- Time of Deformation

The Lower Maastrichtian-Tertiary neoautochthonous rocks form the Al Fayah fold belt. Deformation of this belt initiated before the deposition of the clastics of the Qahlah Formation. The thickest section of this formation filled the structurally low areas flanking the fold nuclei and show slump structures related to uplifting. The areas of Qahlah deposition occupied the present southern plunging part and the forelimb of the Bahayis anticline as well as the southern parts of the two limbs of the Al Fayah anticline (Fig. 3). Several downward filled clastic dykes of the Qahlah sediments occupy the tension fractures affecting the upper portion of the ophiolite rocks. All of these data indicate that the first compressional phase took place at the beginning of the early Early Maastrichtian before the deposition of the Qahlah Formation. This phase continued during the deposition of this formation as indicated by the slump structures associated with turbidity sedimentary structures in its sediments. The majority of the slump structures trend away from the fold hinges.

A regional folded unconformity separates the Qahlah Formation from the Simsima Formation. The unconformity is marked by a 0.6 to 3.2 m thick bed of greenish red to grayish green conglomerates. This unconformity formed in the late Early Maastrichtian and represents the second compressional phase. During this phase, several clastic dykes from the overlying Simsima sediments filled tension fractures in the upper part of the Qahlah Formation. These fractures resulted from the second folding phase. Like the first phase, the second compression phase continued during the deposition of the Simsima Formation, as indicated by its slump structures. In the second phase, some of the fractures affecting the ophiolite rocks were reactivated to dissect only the overlying beds of the Simsima Formation in the northern plunging part of the Bahayis anticline.

The top of the Al Fayah Formation (late Late Maastrichtian) is separated from the overlying Middle-Upper Paleocene marls by a 0.7 m thick bed of rounded pebble conglomerates. This conglomerates bed indicates an unconformity that took place in the Early Paleocene and exists along the forelimbs of the Bahayis and Al Fayah anticlines. The forethrust fault of the Bahayis anticline formed in Early Paleocene where it affects the beds of the Simsima and Al Fayah Formations. Some fractures affecting the Al Fayah Formation are limited to this unconformity whereas the others extend across it. All of these observations point to the third compressional phase during the Early Paleocene time. This phase mildly continued during the deposition of the Middle-Upper Paleocene marls where the marls contain two conglomerate and breccia intervals. These intervals limit and restrict the vertical continuation of a system of fractures.

The Paleocene marls are capped by a breccia and conglomerate bed representing a major disconformity between the marls and the Eocene beds along the forelimbs of the Bahayis anticline. This unconformity as well as the gentler dip of the Eocene beds, compared to the underlying steeper pre-Eocene beds are related to a fourth compressional phase which took place at the Late Paleocene-Early Eocene boundary. Several conglomerate and breccia interbeds within the Lower-Middle Eocene limestones may support the continuation of the fourth phase during the deposition of these limestones. The Paleocene/Eocene tectonic phase is widespread along the western margin of the Oman Mountains (Glennie et al. 1974; Hunting 1979; Cherif and El Deeb 1984; Warrak 1996, and others).

The cumulative influence of the four compressional phases caused the deformation of the study area by fold amplification and lengthening, forelimb rotation, and progressive decrease in the fault displacements from the cores of the anticlines into the outer parts of the anticlines.

4- Fold Development

The en echelon arrangement of the anticlines of the Al Fayah belt is related to their fold development and fold wave parameters. Each fold nucleated in the same arrangement as presently found. Folding occurred before the deposition of the Qahlah Formation in the early Early Maastrichtian (first compression phase) as indicated above. Each fold nucleus existed in the ophiolite rocks somewhat to the east of the center of each fold. Continued compression during the second compression phase (late Early Maastrichtian) and the deposition of the Simsima Formation led to amplification of the fold nuclei to form small, more or less oval shape periclines. At that stage the folds did not overlap each other (Fig. 9a). Further shortening amplified and increased the lengths of the periclines. Also, the folds started to overlap where the intervening areas and fold wavelengths decreased (Fig. 9b and c). At the end of deposition of the Al Fayah Formation (third compression phase), progressive increase in the overlap area and decrease in the wavelength of these folds led to coalescence of the Al Fayah and Milehah anticlines. Meanwhile, the Al Fayah and Bahayis anticlines remained completely separate (Fig. 9d). This is evidenced by the presence of the younger Paleocene-Eocene outcrops only in the forelimbs of the Bahayis and Al Fayah anticlines.

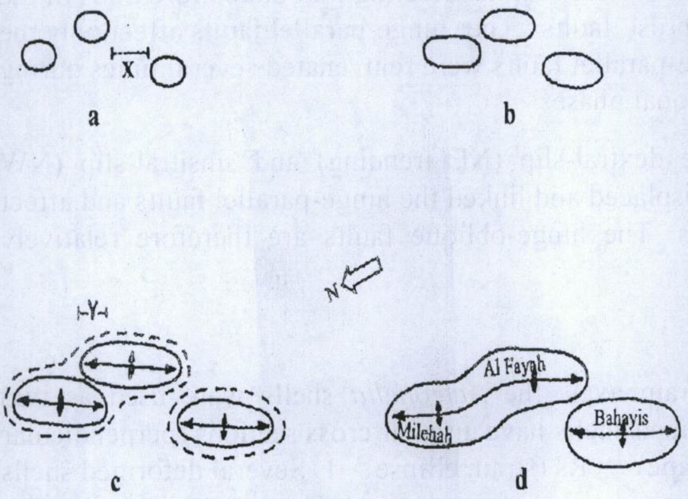

Fig.9: Development of the en echelon anticlines of the Al Fayah belt.

- *a- Amplification of the folds nuclei by shortening.*
- *b- Further shortening and formation of periclines.*
- *c- Increase in the overlap areas (Y) and decrease in the intervening areas (X).*
- *d- Coalescence of the Al Fayah and Milehah anticlines and separation the Al Fayah and Bahayis anticlines.*

Price and Cosgrove (1990, p. 265) studied the conditions at which a pair of en echelon folds interact during growth. They stated that if the offset between the two fold axial planes (intervening area) was less than one half of the wavelength of the folds, the two folds propagate in a linked way to form a larger anticline with a deflection in its hinge line. But if the offset was more than one half of the fold wavelength, the two folds propagate separately. Applying these considerations to the Al Fayah anticlines, it is clear that the left-stepped en echelon Al Fayah and Milehah anticlines have linked (Fig. 3), where the offset between them was less than one half of their wavelength. On the other hand, the offset between the right-stepped en echelon Al Fayah and Bahayis anticlines (Fig. 3) was more than one half of the wavelength and they evolved separately.

Fold-Fault Relationship

Three main fault sets affecting the folded beds that are oriented, in descending order, NNE; NE; and NW. In relation to the hinge line, the NNE set is called hinge-parallel faults whereas the NE and NW sets are referred to as hinge-oblique faults. The traces of the hinge-oblique faults form two conjugate fault sets obliquely oriented by 52° to 63° to the hinge lines. Most of the hinge-parallel faults are restricted to the steeply dipping (angular) parts of the folded beds (around the fold limbs) whereas the hinge-oblique faults affect the central parts and the forelimbs of the folds (Figs. 3 and 4). In flexural-slip folds, the hinge-parallel and -

oblique fractures may form depending on the amount of bedding-parallel shortening prior to folding (Fischer and Jackson 1999).

Based on the cross cutting relationships, analysis of the displacements along the fault traces, and the age of the affected rock units; the hinge-parallel faults were formed in the Early Paleocene after the deposition of the Al Fayah Formation as release fractures. All of these faults have predominantly normal displacements except for the thrust faults dissecting the forelimbs of the Bahayis and Al Fayah anticlines (Fig. 4). These thrust faults is related to increased strain during the limb rotation. This interpretation is also supported by the existence of several bedding-parallel normal and reverse faults affecting the rotated forelimbs of the three anticline, mostly around these thrust faults. The hinge-parallel faults affect only the Maastrichtian rocks. Most of the hinge-parallel faults were rejuvenated several times during the Middle Paleocene-Eocene compressional phases.

The hinge-oblique faults have dextral-slip (NE trending) and sinsitral-slip (NW trending) displacements. These faults displaced and linked the hinge-parallel faults and affect the Middle Paleocene- Eocene rocks. The hinge-oblique faults are therefore relatively younger than the hinge-parallel faults.

5- Strain

To determine the principal strain axes, the *Acteonella* shells were used as two dimensional strain markers. The undeformed shells have circular cross sections (perpendicular to the coil axis), where Ri (initial shape) = Rs (strain ellipse) ~1. Several deformed shells were found to have elliptical cross sections and microfractures. The deformed shells were collected from the Upper Maastrichtian Simsima Formation along the course of two cross sections (cross sections I and IV in figure 6). The shells having bedding parallel coil axes were neglected because their deformation may have been related to the weight of the overlying rock units. The azimuths and lengths of the long and short axes of the transverse section of at least five deformed shells were measured at each site, leading to a total of 102 measurements. The measured lengths of the short and long axes of the deformed shells show good linear correlation (Fig. 10) indicating homogenous deformation of initially circular shells (Ri ~ 1). After deformation, the majority of the shells have average strain ellipse that has Rs = 2.15 forming the moderate strain line (Fig. 10). This line represents the strain in the backlimbs and hinge zones areas. Several high strain shells (Rs = 3.2) form the high strain line (Fig. 10) that representing the forelimb areas.

At each site in the two cross sections, the method of Lisle (1977) was used to estimate the lengths and directions of the two axes of the deformed ellipse. The resulting data reveal that the tectonic deformation was accommodated by folding than faulting and is controlled by the structural position within the anticlines. Within the two cross sections, the rotated forelimb areas display highly strained rocks in relation to other parts of the folds. The hinge zones have moderate strain and show nearly horizontal and vertical ellipses. These ellipses mostly resulted from the subordinate buckling folding within the thick grainstone bed during the flexural-slip folding of the whole beds. The horizontal and vertical ellipses represent extension in the outer parts and shortening in the inner parts of the buckled bed respectively. The other folded parts show oblique orientation of ellipse axes relative to the bedding planes that are most likely attributed to the bedding-parallel slips during flexural-slip folding and/or to the bedding-parallel shortening prior to folding. The bedding-parallel shortening is confirmed by the existence of more fracturing and brecciation in the forelimbs compared to the backlimbs. Woodward (1997) claims that rich fractures in the forelimb postulates the bedding-parallel shortening occurred prior to folding.

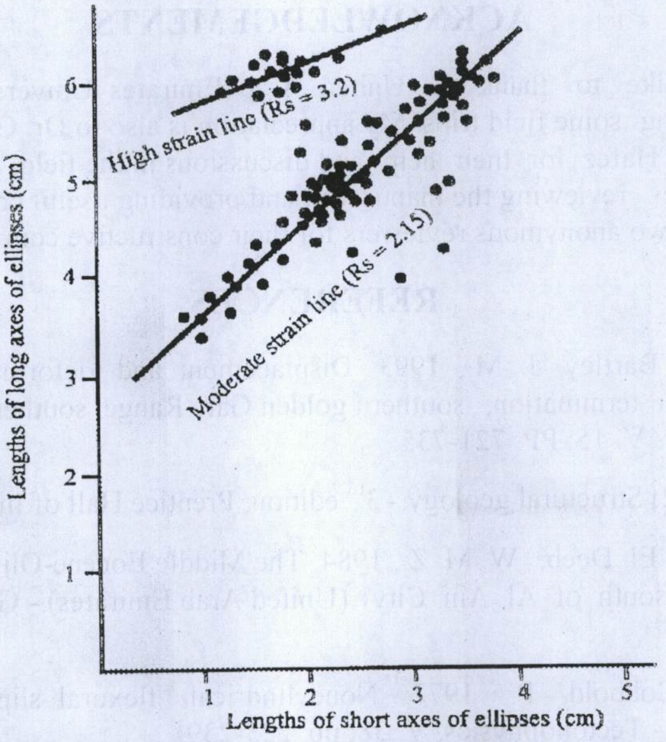

Figure 10: Relationship between the lengths of the short and long axes of the deformed ellipses showing moderate strain line (Rs = 2.15) and high strain line (Rs = 3.2).

SUMMARY AND CONCLUSIONS

The Maastrichtian-Eocene neoautochthonous rocks form three NNE oriented en echelon doubly plunging anticlines of Al Fayah fold belt. The soft linkage overlap area between the Al Fayah and Milehah anticlines is represented by a faulted antiformal depression and by an open syncline between their forelimbs. The Bahayis and Al Fayah anticlines are completely separated in the southern hard linkage overlap area. Flexural-slip folding with subordinate buckling folding within the thick bed of the Simsima Formation took place during the development of the three anticlines. Folding took place in three stages: (1) early detachment folding during the deposition of Maastrichtian rocks; (2) break-thrust folding that affected only the Bahayis anticline in the Early Paleocene; and (3) fold amplification and lengthening during the Middle Paleocene-Eocene. These anticlines formed by S 60° E directed compression from the Oman Mountains side during four compressional phases. These phases produced uniform shortening amounts ranging between 12% and 15.5%. Each anticline nucleated before the deposition of the Qahlah Formation in early Early

Maastrichtian. Progressive shortening led to coalescence of the Al Fayah and Milehah anticlines while the Al Fayah and Bahayis anticlines remained completely separate. Accumulation of strain in the forelimbs is a function of limb rotation and fold tightness. The hinge-parallel faults were initiated in Early Paleocene after the deposition of the Al Fayah Formation whereas the hinge-oblique faults are relatively younger.

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