Late Cretaceous–Eocene Reactivations of the Hatta Shear Zone, Northern Oman Mountains

Ali M. A. Abd-Allah, Waheed A. Hashem and Osman Abdelghany

***Abstract*—**The NW-trending Hatta Shear Zone was formed in the Late Cretaceous during the emplacement of the Tethyan rocks and oceanic crust on the eastern margin of the Arabian plate. The western end of this shear zone is draped over by the Campanian-Lower Eocene carbonate rocks. These rocks were thrusted and folded later during the Tertiary Alpine deformation event. The folds are represented by two large plunging, asymmetrical NW-oriented anticlines that are interveined with a middle box-shape syncline, in addition to, four small NE and E-W trending folds. The syncline is characterized by a 3-segmented z-shape, as separated by the two bends; one of them is occupied by NE-oriented folds while the other is occupied by E-W oriented folds. The origin of this syncline may be controlled by the displacement over NW-trending, NE-dipping en echelon thrust faults bounding it. The estimated E-W regional compressive stress that initially accompanied the Cretaceous rock emplacement was locally adopted in later stages to NE-SW orientation. This deformation took place synchronous to deposition in three stages. It is commenced during the Campanian-Late Maastrichtian and renewed in Early Paleocene and in post Early Eocene times. This NE-SW compression produced El Rawdah structures, which reflect shortening values between 14% and 29.4%. The rock mechanical properties and bed thicknesses controlled the folding mechanisms. Whereas, buckling developed open folds in the thick and relatively brittle beds of the Campanian to Maastrichtian rocks, while flexural slip folding mechanism produced tight folds in the thin and ductile beds of the Maastrichtian to Early Eocene rocks.

***Keywords*—** Cretaceous-Eocene deformations, Jabal El Rawdah, Hatta shear zone, Northern Oman Mountains.

I. Introduction

The most significant event in the geologic history of the Arabian plate is represented by the Late Cretaceous emplacement of the Tethyan rocks and Semail Nappes onto the eastern passive continental margin of the Arabian platform that ultimately resulted in the formation of the Oman Mountains [1]-[16]. These nappes were stratigraphically classified into different units, namely, the Sumeini Group, the Hawasina Group, the Haybi Complex and the Semail Ophiolite [2]. In the late stage of this event, several foredeep basins were developed on the northwestern flank of the Northern Oman Mountains [11]. These basins hosted onlapping deposition of an Upper Cretaceous-Tertiary sedimentary sequence that accumulated mostly under shallow marine conditions [17]-[19]. This unconformably overlying sequence was later deformed by thrust faults and related folds in the Late Cretaceous and again in the Tertiary times [14], [20], [21].

A. Objectives of the Present Study

All of the Tertiary thrust-related folds along the western margin of the Northern Oman Mountains have either NNW trend, as Jabals Hafit, Malaqet, Mundassah, to N-S trends, as Al Fayiah Mountain Range, (Fig. 1). This is in contrast to Jabal El Rawdah folds at the northwestern end of Hatta shear zone, which have an anomalous NW-SE trend. This contrast prompted its selection for investigation in the present study. This contribution aims to throw light on the structural setting, development, and the relative age of faulting and folding in the area. The tectonic relationship between El Rawdah folds and the N-S to NNW trending folds is also considered.

B. Location of the Study Area and Previous Work

The study area is located northwest Hatta city, at the border between the United Arab Emirates and Oman. It is about 87 km north of Al-Ain city and 45 Km southeast Dubai Emirate (Fig. 1). The stratigraphy, sedimentation and tectonic setting of Jabal El Rawdah have been studied by many researchers, among them are [6], [14], [23]-[27]. They concluded that the main structures of El Rawdah area are faulted NW oriented anticline - syncline fold pair.

II. Stratigraphy

The rocks of Jabal El Rawdah area form two main groups separated by a regional non conformity. The older group is the allochthonous rock units which contain the Sumeini Group and the Semail Ophiolite. The younger group is the unconformably overlying neoautochthonous Campanian-Lower Eocene units. These latter units include, from the oldest to the youngest, the Qahlah, Simsima, and Muthaymimah Formations (Fig. 2). The lithostratigraphic and biostratigraphic descriptions of these rock units are briefly discussed in the following text.

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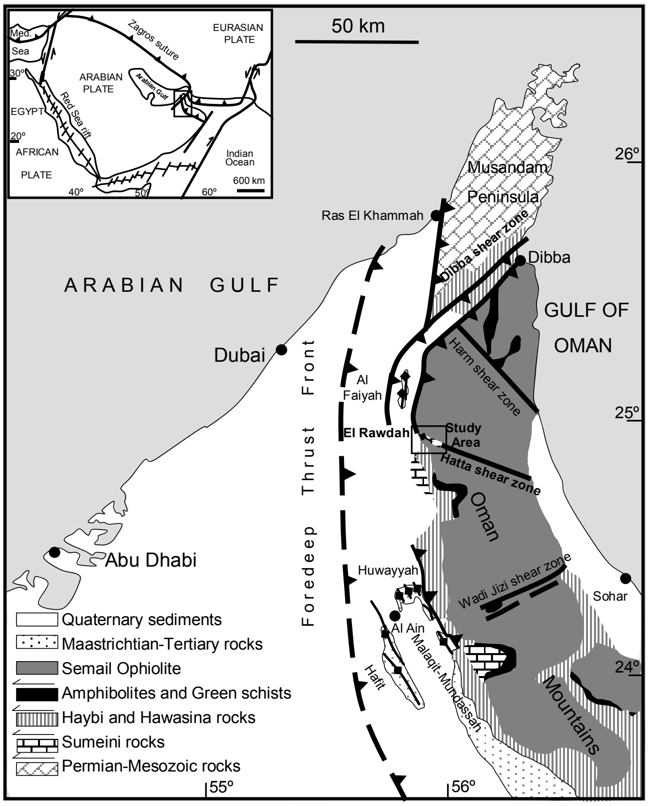

Fig. 1. Location map of the Northern Oman Mountains showing the trend of the neoautochthonous folds in the western margin of the mountains and the location of El Rawdah area. The structures and outcrops of the Oman Mountains are compiled from [1],[2], [10], [13]-[15].The tectonic framework in the inset map is after [22].

A. Allochthonous Units

The Steeply dipping beds of the Sumeini Group form the Masfut-El Rawdah ridge, which is bordered to the NE and SW by the Semail Ophiolite (Fig. 3). This group is composed of subvertical sheets of low-grade carbonate metasediments that were thrusted into their present configuration during the Late Cretaceous obduction event [2]. The greenschist rocks of this unit are locally exposed in the south of the southeastern segment of El Rawdah syncline. They are interpreted as a quartzose unit within the Sumeini Group that was sheared and partly recrystallized during emplacement [14]. The Sumeini succession in the Oman Mountains belongs to the shallow marine carbonate platform of the Hawasina basin [28]. The Triassic-Middle Cretaceous sediments of this basin were thrusted over the Tethyan continental margin of the Arabian plate in Late Cretaceous times [10],[29]-[30].

The Upper Cretaceous Semail Ophiolite is represented by gabbro and serpentinite that are outcropping in the core of El Rawdah anticlines and extensively exposed around the study area (Fig. 3). The ophiolite extends southeastward to the Jabal Quimah tectonic window. The contacts between the Semail Ophiolite and the other allochthonous units are mostly thrust controlled.

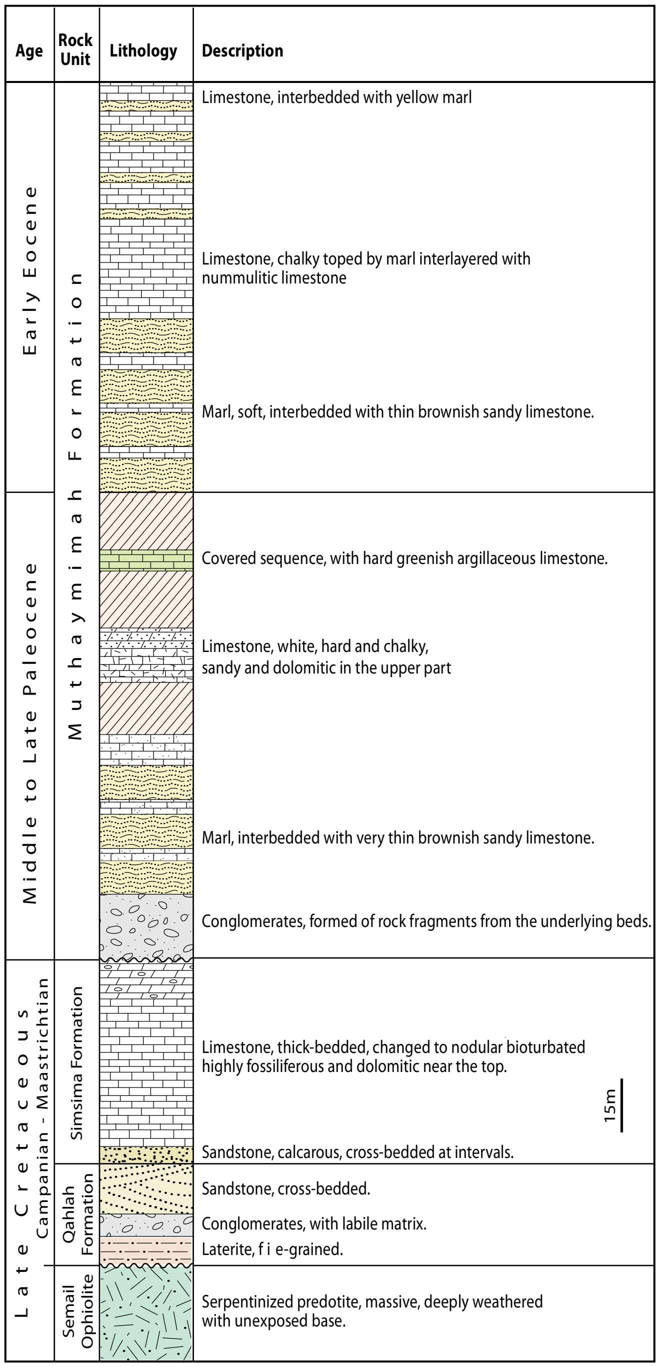

Fig. 2. Composite stratigraphic section of the deformed units in El Rawdah area.

B. Neoautochthonous Units

1. Qahlah Formation (Late Campanian)

The Qahlah Formation was proposed by [2]. In the study area, this formation lies unconformably upon the Semail Ophiolite rocks in the core of El Rawdah south anticline and is exposed along the flanks of the southeastern segment of El Rawdah syncline (Fig. 3). The Qahlah Formation consists of three non-fossiliferous sections. The lower section is composed of fine grained laterite (11m thick), the middle one consists of conglomerates (clast-supported ophiolitic boulders with variable matrix, 7m thick), and the upper section is a varicolored and cross-bedded sandstone (17m thick) (Fig. 2). Along the western margin of the Northern Oman Mountains, the Qahlah Formation shows considerable variations in its thickness and lithology. It attains 80m thickness in Jabal Buhays (El Faiyah Mountain Range) and about 55m thick in Jabal Huwayyah [26]. These two locations lie at about 19km to the northwest and 66 km to the south of the study area, respectively (Fig. 1). However, the greatest thickness (140m) is found at its type section near Qalhat area on the southeastern side of the Oman Mountains [12]. These considerable changes are attributed to the irregularity in the post-obduction paleotopography and to the sediment supply variations [31], [32].

The age of the Qahlah Formation has been designated as Late Campanian- early Late Maastrichtian, according to the Loftusia rich levels found in its upper part in different locations in the western margin, particularly in its type section and at Jabal Huwayyah [33]. Other researchers have suggested an Early to Middle Maastrichtian age based on Loftusia species, rudists and corals [2], [20], [31]. The upper part of the Qahlah Formation at Jabal Huwayyah was assigned to the Early Maastrichtian age based on its content of larger foraminifera, whereas its lower clastic part as Late Campanian [26]. The Qahlah Formation at Jabal El Rawdah area can be correlated with this clastic and non-fossiliferous lower part of the same formation at Jabal Huwayyah. Consequently, it can be assigned to the Late Campanian age in the study area. This correlation is also supported by the estimated Late Campanian/ Maastrichtian age of the overlying carbonate beds of the Simsima Formation in El Rawdah area [25], [27].

2. *Simsima Formation (Late Campanian–Maastrichtian)*

The Simsima Formation was first described by [2]. Reference [12] designated Jabal El Faiyah section (19 km northwest of Jabal El Rawdah) as an alternative surface type-section for this formation due to the inaccessibility of the subsurface type section. The Simsima Formation is subdivided in the eastern side of the United Arab Emirates into lower and upper members [19].

In El Rawdah area, the Simsima Formation rests conformably on the Qahlah Formation (Fig. 2) and can be divided into two units. The lower unit consists of thick calcareous sandstone (8m thick) which is cross-bedded at intervals. The sandstone were formed by reworking from the underlying Qahlah sediments and the Ophiolite rocks. The upper unit (53 thick) is represented by bioturbated limestone beds rich in orbitoids and rudists. The last unit is equivalent to the two members, which were described by [19]. Like the Qahlah Formation, the thickness of the Simsima Formation is variable within the study area.

Along the western margin of the Northern Oman Mountains, the Simsima Formation is assigned to the Middle [20] or Late [34] Maastrichtian. However, in El Rawdah study area, the age of the Simsima Formation is assigned to the Late Campanian-Maastrichtian based on the larger foraminifera [25]. The possible overlap in ages between the Qahlah and lower member of the Simsima Formations is attributed to the interfingering relationship between the two units on the western side of the Northern Oman Mountains that is, in turn, reflects the contemporaneous deposition of both of these formations [26].

3. *Muthaymimah Formation (Middle Paleocene-Early Eocene)*

The Muthaymimah Formation was originally described by [12] from the northwestern side of Sayh Muthaymimah, southeast of Buraymi, Oman. The outcrops of the Muthaymimah Formation in the El Rawdah area are located mainly in the trough of El Rawdah syncline (Fig. 3). This formation unconformably overlies the Simsima Formation and is subdivided into two informal units. The lower unit consists of soft marl interbedded with thin, brownish, sandy limestone of Middle to Late Paleocene age (150m thick). The upper unit is composed of chalky limestone followed by sandy, dolomitic limestone, and is topped by marl interlayered with nummulitic limestone of Early Eocene age (130m thick). The age of these units is based on the planktonic foraminifera and calcareous nannofossils [35].

The planktonic foraminifera indicate that the beds of the Muthaymimah Formation were deposited in an open deep marine environment. According to [12], this formation was deposited in a relatively deep marine debris flow environment, and accumulated along the eastern steep slope of the basin that existed along the NW flank of the northern part of the Oman Mountains.

4. *Depositional environment*

The studied rock units in the El Rawdah area contain two unconformities. The older one exists between the ophiolite and Qahlah units and has pre-Campanian (to Campanian) age. The younger one is found between the Simsima and Muthaymimah Formations and has Early Paleocene age. These unconformities are related to two regional deformation events that are associated with the change in the sedimentary environment. The fine lateritized sedimentary rocks at the base of the Qahlah Formation and on the pre-Campanian unconformity point to subaerial weathering in a warm, humid climate while the overlying conglomerates and sandstones were deposited in a shallow marine beach to fluvial environment [23], [31], [32]. The lower calcareous sandstone unit of the Simsima Formation was deposited in a marginal marine environment whereas its upper limestone unit was deposited in a highly agitated, foreshore to shallow shoreface zone [23]. The latter environment changed upward over the Early Paleocene unconformity to the open deep marine conditions in which limestone and marl beds of the Muthaymimah Formation were deposited. The absence of transitional shallow marine sediments over this unconformity demonstrates that the uplift was followed by a rapid subsidence during the deposition of the Muthaymimah beds.

III. Structural Setting

The NW trending Hatta zone is a sinistral strike-slip shear zone that affects mainly the Semail Ophiolite and the

Hawasina and Haybi complexes [2]. The Masfut-El Rawdah ridge represents the northwestern part of this zone with Jabal El Rawdah located at its northwestern end (Figs. 1 & 3). The geological structures of El Rawdah area are divided into the Masfut-El Rawdah ridge (showing syn- and post-obduction deformations) and El Rawdah structures (showing post-obduction deformation only). The exposed thrust segments in the study area have high-angle planes, but we have no data about their deeper segments. Southward at Al Ain area, the seismic sections show a thin-skinned structural model, in which a nearly flat thrust plane ascents upward to have a nearly vertical attitude. Thus, the term "thrust" is used here to refer to the high angle reverse fault.

A. Masfut-El Rawdah Ridge

Masfut-El Rawdah ridge consists of thrust assembled Sumeini Group sandwiched between the gabbro and serpentinite rocks of the Semail Ophiolite on either side of the ridge. The Sumeini Group consists mainly of sheared and thrusted carbonate metasediments with generally low grade of metamorphism. Some primary sedimentary structures are preserved.

The two sides of the ridge are limited by two opposite dipping high angle thrust faults (68º to 81º dip amount). The bedding planes of the intervening metasediments show a sub-vertical dip with localized steep northeast and southwest dips. These metasediments contain several small drag and sheared folds as well as bedding plane slickensides, all indicating sinistral shearing associated with a reverse-slip movement. The contact between the Sumeini rocks in the ridge and ophiolite rocks in the cores of folds is a NE trending thrust fault (Figs. 3 & 4).

The westward continuation of the sinistral and dextral Hatta and Dibba shear zones, respectively, has been proposed based on the magnetic map of the western margin of the Oman Mountains [36], [37].

B. El Rawdah Structure

El Rawdah structure is represented by three NW to WNW-oriented large plunging asymmetric alternative folds, and four small folds. The northern folds are dissected by two thrust faults. The folds were named as in the accompanied map and cross-sections (Figs. 3 & 4).

1. El Rawdah north anticline

The El Rawdah north anticline is a doubly plunging asymmetric and NE-verging fold. It is defined by the beds of the Simsima Formation while those of the Muthaymimah Formation are partially exposed in the outer parts of its limbs. The dip angle increases to vertical or is even locally overturned as the thrust fault is approached. The northwest-plunging nose of this anticline has conical geometry with cone axis plunging N58ºW (Fig. 5a). This fold is associated with two oppositely dipping thrust faults (Fig. 3), so that the southwestern fault has a dip angle between 66º and 81ºNE and the northeastern fault has a dip between 46º and 61ºSW.

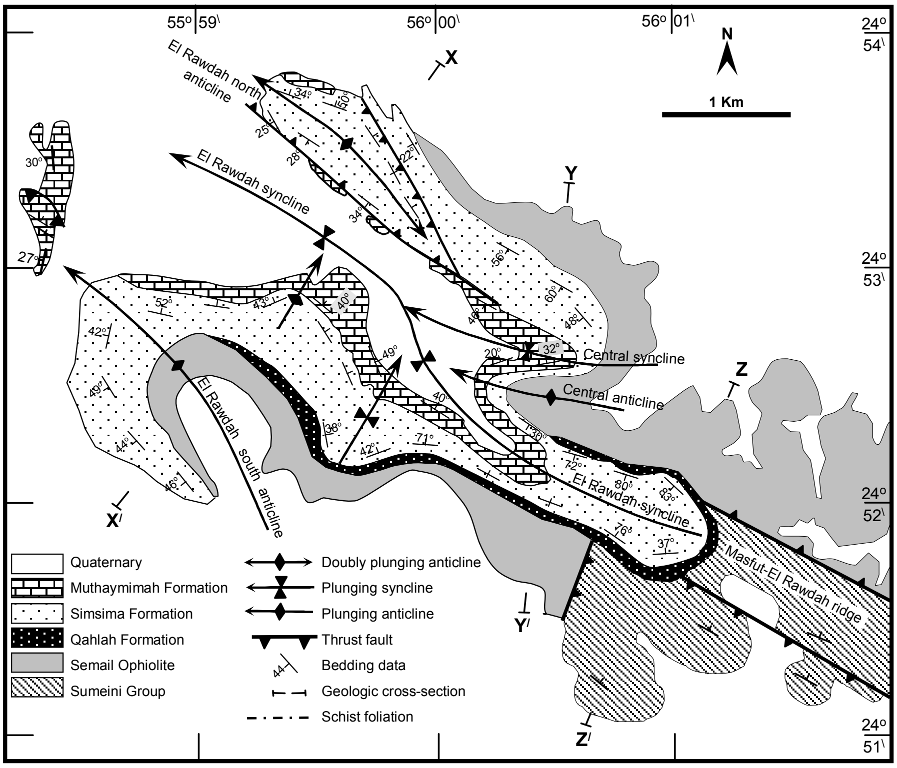

Fig. 3. Geologic map showing the geometry of the folds and faults as well as the aerial distribution of the deformed units in El Rawdah area.

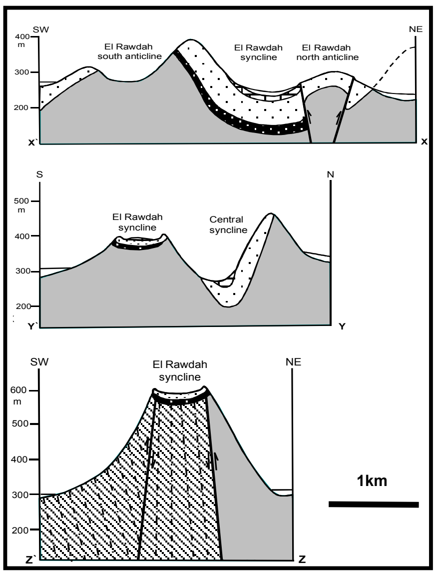

Fig. 4. Geologic cross sections of El Rawdah structures indicating the main structural styles. See figure 3 for symbols and locations (vertical exaggeration = 4).

2. El Rawdah syncline

El Rawdah syncline is a NW plunging asymmetric open fold. It is characterized by a sinuous z-shaped trend that can be divided into three segments are occupying the low lying area between El Rawdah north and south anticlines (Fig. 3). The terminal segments trend in NW, while the middle one trends in NNW. The middle segment merges mostly with the hinge line of the central syncline in the area south El Rawdah north anticline (Fig. 3). El Rawdah syncline has a boxfold geometry that is well exhibited in its southeastern segment. Steep to vertical beds exist at its outer flanks whereas nearly horizontal beds form its hinge zone (Figs. 4 and 5b).

3. El Rawdah south anticline

This anticline is nearly symmetrical and northward plunging (Fig. 5c). The northeastern flank of the El Rawdah south anticline contains small NE trending folds which plunge toward El Rawdah syncline (Fig. 3). The fold includes the Semail Ophiolite at its core and affects the beds of the Qahlah, Simsima and Muthaymimah Formations.

4. Central syncline and anticline

The dip of the Simsima beds in the northern flank of the central syncline increases as the contact between these beds and the underlying ophiolite is approached. The beds of the Muthaymimah Formation in the trough of the syncline have lower dip angles. The closure of this syncline has conical geometry with west-plunging cone axis (Fig. 5d). The flanks of the E-W trending central anticline are short and are defined by beds of the Simsima and Muthaymimah Formations. The closure of this anticline also has conical geometry with cone axis plunging towards N76ºW (Fig. 5e).

I. STRUCTURAL ANALYSIS

A. Stress and Strain Estimations

The thrust-related folds in the western margin of the Oman Mountains trends parallel to the outer peripheral frontal edge of these mountains. Accordingly, in Al Ain area, these folds affect the Upper Cretaceous-Miocene rocks and trends in NNW, whereas at El Faiyah Mountains, these folds have the N to NNE (Fig. 1). These marginal folds resulted from the Tertiary compressive stresses that propagated from the frontal margin of the Northern Oman Mountains [21], [38]. Accordingly, in the study area, El Rawdah folds have the same NW trend as the Masfut-El Rawdah ridge (Fig. 3). This trend is completely different from the N to NNE trend of the marginal folds in the neighboring pre-mentioned areas (Fig. 1). The compressive stresses responsible therefore have similar orientation to those that attended obduction in this area. These compressive stresses operated during the Tertiary to deform the neoautochthonous Cretaceous to Early Eocene rocks.

The slip data for faults with variable net slips and the data for the bedding plane slickensides are used together in stress estimations, where the orientation of the principal stress axes are determined as in [39]. The slip vectors of the thrust faults (Fig. 5f) and the bedding planes (Fig. 5g) are mainly aligned parallel to the $\sigma 1$ trend. This revealed that the orientation of this compressive stress is subhorizontal with a N40º-47ºE - S40º-47ºW trend. This estimated trend is nearly perpendicular to the S 60º E compressive trend that produced the structures of El Faiyah range in the western margin (trend after [21]). This would reflect a local change in the regional stress orientation in this northwestern end of the Hatta shear zone.

On the other hand, the %shortening related to folding in the study area is estimated in the plunging parts (fold noses) of these folds to exclude the shortening related to the thrust faults and the bedding parallel shortening. This estimation is done by using of the plunging conical parts of each fold as described by [41]. According to this author, the cone geometries and their curvature reflect divergence of bedding poles along a small circle provides a measure of the curvature and shortening of the plunging part. The shortening values of the large El Rawdah south and north anticlines are 14% and 29.4%, respectively (Figs. 5c & a), while, the shortening values of the small central syncline and anticline are 17% and 21%, respectively (Figs. 5d & e). The drag related to the two thrust faults bounding the El Rawdah north anticline increased the dip angles of its folded beds and consequently its shortening value, while the unfaulted larger El Rawdah south anticline has a relatively lower value.

B. Structural Evolution

The folds in the western margin of the Northern Oman Mountains are controlled by thrust faults either from one side, like the southern folds of El Faiyah range and the Malaqet-Mundassah folds, or from two sides such as the Hafit anticline. These folds have the same trend as the strike of the bounding thrust faults and the western front of the Oman Mountains. These bounding faults propagated upward from nearly horizontal blind thrust faults to dissect the Upper Cretaceous-Miocene section. These blind thrust faults lie at about 1.2 km depth in El Faiyah range [21] or at about 3 km depth in Al Ain area [38].

The previous structural model suggested for the formation of El Rawdah structures indicates that these structures were developed over an E-W striking lateral ramp oriented sub-parallel to the transport direction of the obducted nappe [24]. This development took place in post-Middle Eocene time [5], [6].

The Northern Oman Mountains are dissected by several NE and NW trending shear zones (Fig. 1). These zones were formed by the reactivation of pre-existing fractures during the Late Cretaceous emplacement of the allochthonous nappes [14]. The dextral and sinistral senses of shearing along these NE and NW zones, respectively, are related to the Early Cretaceous E-W compression and consequent shortening (Fig. 6a). The E-W shortening direction was locally rotated in the study area to have a NE-SW orientation during syn- and post-obduction deformations (Fig. 6a). The present study revealed that this shortening is produced by a N 40º-47º E - S 40º-47º W oriented compressive stress. This stress, in turn, reactivated some of the orthogonally striking shear faults as thrust faults, like those bounding Masfut-El Rawdah ridge, and developed new thrust faults like that on the northeastern flank of El Rawdah syncline (Fig. 6a). The similarity in the structural

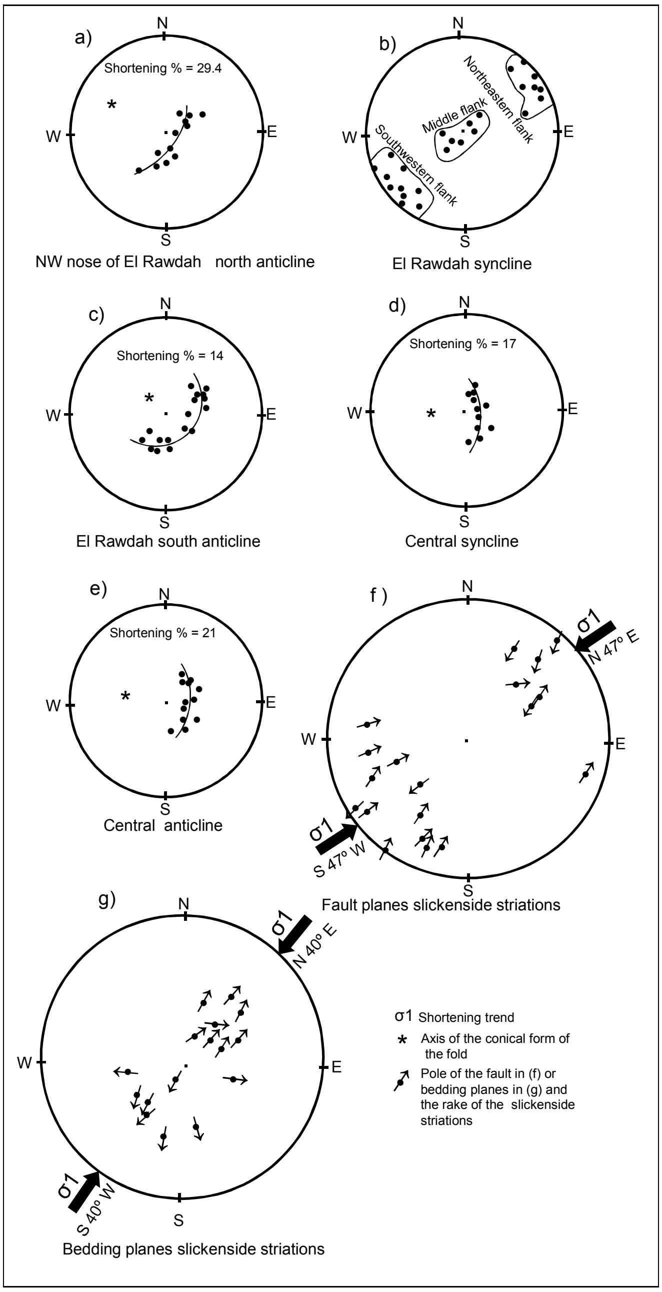

Fig. 5. Stereographic plots showing the conical forms of the noses of the anticlines and synclines (a, c, d, and e) and the box geometry of El Rawdah syncline (b). The estimated shortening trend is indicated by using the fault slip data (f) and the bedding plane slickensides (g). The method of [40] is used for estimating the shortening trend whereas the method of [41] is used for the shortening% estimation.

trend between El Rawdah structures and Masfut-El Rawdah ridge indicates that this NE-SW compressive stress that produced the ridge is also responsible for the later formation of El Rawdah structures. Whereas the reverse displacements of the beds on the thrust faults, led to the development of the large fold pairs parallel to their accompanied thrust faults (Fig. 6b). The anticlines were developed on the hanging wall of the thrusts, and the synclines were developed on their footwalls (Fig. 6b).

The NE-dipping fault bounding Masfut-El Rawdah ridge and the NW trending fault affecting El Rawdah syncline have a right-stepped en echelon arrangement. The displacements of the beds over these arranged thrust faults are responsible for the origin of the Z-shape in the large folds, particularly El Rawdah syncline (Fig. 3). The terminal segments of each Z shaped fold have the NW trend parallel to the nearby thrust fault, where, the unfaulted area between these thrusts is occupied by the NNW trending middle fold segment (Figs. 3 & 6b). The three segments of El Rawdah syncline form the full Z-shape while the exposed part of the El Rawdah south anticline shows partially two segments (Fig. 6c). These three segments of the southwestern limb of El Rawdah syncline are separated by two bends (Figs. 6c). Each bend represents an inflection area at which the dip direction changes from one segment to the other segment. This change in dip direction forms two NE trending folds which plunge toward the synclinal trough. The plunged anticlines exist at the concave bends whereas the plunged synclines occupy the convex bends. On the other northeastern limb of El Rawdah syncline, two E-W trending central syncline and anticline were developed .These alternative folds were formed to solve the space problem in the relay area between the pre-mentioned en echelon thrust faults (Fig. 3). The continuous amplification of these folds led to the merge of the hinge lines of El Rawdah syncline and the Central synclines. In later time a NNW-trending thrust fault is developed on the northeastern limb of El Rawdah syncline. The reverse drag of the beds over this fault created El Rawdah north anticline.

C. *Folding Mechanisms*

The folded beds in El Rawdah area show contrasting competence from the hard, non-stratified gabbro and serpentinite rocks of the Semail Ophiolite to the less competent overlying clastic and carbonate beds. Amongst these sedimentary rocks, there are also variations in the mechanical properties (e.g. thickness and bedding plane contact properties). The Qahlah and most of the Simsima formations are mainly dominated by brittle beds while the overlying sequence is characterized by ductile limestone and marl beds. The thick beds at the base of the Qahlah Formation show poorly developed bedding plane contacts, but change to be well-defined planes among its upper part. In some areas, the fractures affecting the Ophiolite rocks continue upwards to affect the lower part of the Qahlah Formation.

The slickenside striations are found in the topmost beds of the Simsima Formation as well as being found frequently within the Muthaymimah beds. The trend of these striations is orthogonal to the hinge lines of the folds except for a few of them, which trended obliquely to these lines (Fig. 5g). The presence of the hinge-oblique striations is consistent with the non cylindrical geometry of the plunging parts of the folds [42]. Also, small drag folds are observed only among the Muthaymimah beds. Accordingly, the thin and ductile beds of both the upper part of the Simsima Formation and all of the Muthaymimah Formation were deformed by flexural-slip folding. The presence of the slickenside striations in the most curved portions of the studied folds is consistent with flexural-slip folding as indicated by [43]. The flexural-slip mechanism was suggested by [21], [38] for the folding in the El Faiyah range and Malaqet-Mundassah folds, respectively. On the other hand, a buckling mechanism is proposed for the folding of the older beds of Qahlah and Simsima Formations. These beds show almost parallel bedding planes and are not dissected by extension fractures related to outer-arc extension. The absence of these fractures is interpreted by [44] to indicate significant layer parallel shortening. This shortening is mostly represented in the studied folds by axial plane-parallel stylolites.

D. Time of Deformations

The development of El-Rawdah structure began after the emplacement of the Ophiolite nappes and continued during the deposition of the Campanian-Lower Eocene rocks. This took place in different stages as indicated from the different types of the unconformities found between the studied rock units and their variable bed thicknesses and sedimentary structures. Whereas, this rock sequence contains two unconformity surfaces. The older one (Campanian age) exists between the Semail Ophiolite and Qahlah rock units. The younger one (Early Paleocene) is found between the Simsima and Muthaymimah Formations. These unconformities are related to two Alpine deformation events and associated with changes in the sedimentary environment.

The Qahlah Formation is exposed only along the northeastern flank of El Rawdah south anticline and extends to both flanks of the southeastern segment of El Rawdah syncline (Fig. 3). The thickness of this formation increases from the nose of this anticline (few meters thick or absent) and from the southeastern end of this syncline (18m thick) toward the middle segment of El Rawdah syncline (47 m thick). During deposition, the beds of this formation were subjected to gravitational sliding. The regional variation in the thickness of the Qahlah Formation was attributed to the topographic control. But locally in the study area, this thickness variation and gravitational structures may be due to the fact that El Rawdah south and north anticlines began their development before and during the deposition of this formation. Hence, the intervening El Rawdah syncline received thick sediments of this formation. The Qahlah Formation has a sharp contact that is irregular and wavy, in places, with the overlying Simsima Formation. Generally the beds of the later formation are thick with some thin limestone interbeds (around 1 m thick each). Some of these limestone beds contain tectonic stylolite surfaces; the majorities of these surfaces are more or less parallel to the fold hinge lines and cut vertically through the bedding planes. Some of the sandstone beds show northward slumped laminations. These slumping movements created several extension fractures which are oriented perpendicular to the Simsima beds. The thickness of the Simsima Formation increases towards the north. Whereas it changes from 18m in the southeastern end of El Rawdah syncline, and from 41m in the El Rawdah south anticline, to about 61 m in the area of El Rawdah north anticline. The thickness variation and the slumping structures might be explained as that El Rawdah south anticline being actively folded during the deposition of this formation, so that the El Rawdah north anticline was a

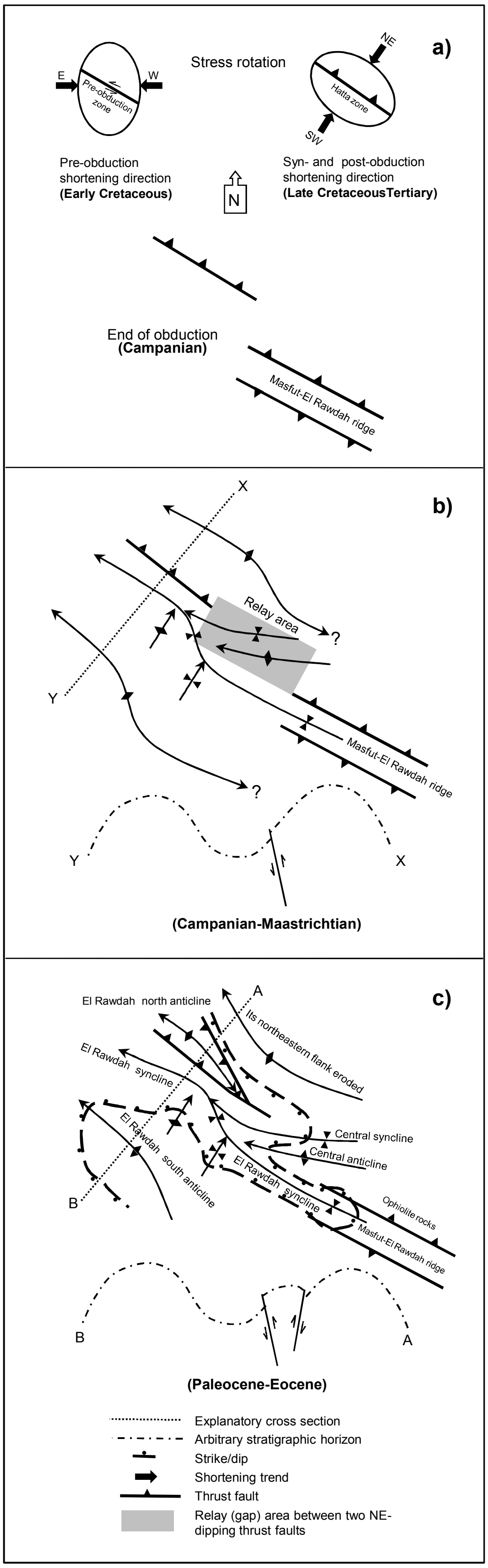

Fig. 6. Structural model and sequence of the structural development in the northwestern end of Hatta shear zone.

low area. Consequently, the first stage of deformation may be commenced in the Campanian time by creating the main thrust faults and continued mildly during the Maastrichtian by folding during the deposition of the Qahlah Formation and the lower part of the Simsima Formation (Fig. 6b).

The thinly bedded limestone and marl beds of the Muthaymimah Formation lie unconformably over the Simsima Formation in the trough of El Rawdah syncline. This unconformity is represented by a thick conglomerate bed and is marked by the disappearance of the Lower Paleocene rocks. The initiation of the northeastern thrust fault bounding the El Rawdah north anticline was coeval with this Early Paleocene unconformity. The thrusting and the consequent amplification of El Rawdah north anticline uplifted the northeastern part of the study area after the deposition of the Simsima Formation and before the deposition of this Muthaymimah Formation (Fig. 6c). This may account for the deposition of the Muthaymimah Formation at the margins of this anticline (Fig. 3). Hence, the second phase is Early Paleocene in age and is responsible for this unconformity and the NE-trending thrust fault that, in turn, developed El Rawdah north anticline.

The last phase of deformation is dated as post Early Eocene. This phase resulted in the folding of the Muthaymimah beds which has an angular contact with the underlying steep beds of the Simsima beds. This event is also reported along the western margin of the North Oman Mountains by [2], [21], [38], [45]-[47].

So, it can be concluded that the deformation in this area is syn-depositional. This finding is matched with that provided by [48] on the deformation of the southern part of the northern Oman Mountains (e.g. Jabals Hafit and Malaqet & Mundassah). He proved that the deformation of the neoautochthonous rocks in this region was developed synchronous thier deposition. The Campanian, Early Paleocene, and post-Early Eocene compressional events in the study area may be equivalent to the Syrian Arc deformations in the north Arabian and African plates (e.g. [49]-[53]).

II. Summary and Conclusions

The Masfut-El Rawdah ridge in the northwestern part of the Hatta shear zone is a strip of the Sumeini succession bordered on both sides by the Semail Ophiolite. The crest of this ridge is covered by the Campanian-Lower Eocene sedimentary carbonates and clastics that area affected by El Rawdah folds. Whereas the thrust-related folds along the western margin of the Northern Oman Mountains have the same orientation as the frontal edge of these mountains. The folds of El Rawdah have the same NW trend as the Masfut-El Rawdah ridge. The E-W shortening preceding obduction was followed locally by NE-SW shortening during the obduction and the later deformations. This NE-SW compressive stress produced shortening values between 14% and 29.4% in the Campanian-Tertiary time.

The El Rawdah structures have three large NW trending folds and four small E-W and NE oriented folds. The NW trending folds and thrust faults were formed by a N40º-47ºE - S40º-47ºW compressive stress. The NW-trending thrust faults and the large folds began their evolution during Campanian-Maastrichtian time. This fault describes a with other NE-dipping thrust fault. This displacements of the beds on the right-stepped en echelon arranged thrust faults formed the Z-shape of the related large folds, particularly El Rawdah syncline. The three segments of the Z-shaped this syncline are separated by two bends, each one lie between two consecutive segments. These bends are represented by NE and E-W oriented small folds. The central anticline and syncline formed at the SW-dipping flank of El Rawdah syncline in the relay area between the two en echelon thrust faults. The northeastern flank of El Rawdah syncline was dissected by the NNW-oriented thrust fault in Early Paleocene age to develop El Rawdah north anticline.

The folded units are characterized by vertical heterogeneity in their thicknesses and mechanical properties. The slickenside striations and drag folds are observed among the topmost beds of the Simsima Formation and all beds of the Muthaymimah Formation. Accordingly, the thin and ductile beds of these formations were deformed by flexural-slip folding. On the other hand, a buckling mechanism is proposed for the folding of the beds of the Qahlah Formation and most parts of the Simsima Formation. The deformations of El Rawdah structures were syn-depositional and took place in three shortening events. The first commenced by thrusting in the Campanian time and continued mildly by folding in the Maastrichtian, during the deposition of the Qahlah and Simsima Formations. The second affected the area during the Early Paleocene by thrusting in the northern part and amplifying folds before the deposition of the Muthaymimah Formation. While, the third shortening event was post the Early Eocene and led to the folding of the beds of the Muthaymimah Formation.

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