STRUCTURAL EVOLUTION OF DJEBEL DEBADIB
ANTICLINE: A CLUE TO THE REGIONAL
TECTONIC STYLE OF THE TUNISIAN ATLAS

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Abstract. Djebel Debadib is a northeast trending anticline in the Tunisian Atlas, near El Kef, Tunisia. The core of the anticline consists of a deformed Triassic, gypsum-matrix breccia containing clasts of supratidal dolomite, terrigenous clastic rocks, and ophites (metabasites). Locally, low-grade metasedimentary rocks, occurring as clasts in the evaporite, may represent fragments of basement rock plucked from salt subcrop during deep-seated flowage. The multiply deformed Triassic rocks are juxtaposed against Cretaceous or younger rocks, and Jurassic and Neocomian strata are not present in outcrop. These characteristics have been cited in many studies to suggest a history of diapirism to explain both the internal structure of the Triassic rocks and the contact relations with the younger rocks. A previously unreported unconformity, developed on the Triassic rocks and overlain by Aptian-Albian strata, indicates that an important period of piercement occurred during the Early Cretaceous for the Djebel Debadib diapir. From the mid-Cretaceous to the late Eocene the continental margin of northern Tunisia was a regional basin in

which a thick sequence of carbonate rocks was deposited. Beginning in late Oligocene time, sandy clastic sediments accumulated on the older carbonate rocks above a regional unconformity, and during the middle Miocene Atlas orogeny, numerous northeast-southwest folds deformed the rocks of the Tunisian trough including the diapiric Triassic masses. These folds, commonly boxlike in geometry, were extensively faulted during the late Miocene and Pliocene. A four phase tectonic model is recognized for the Tunisian Atlas: (1) early Mesozoic rifting of the North African continental margin, (2) diapiric emplacement of the Late Triassic-Liassic(?) evaporites into overlying strata beginning in the early Cretaceous, (3) folding of the cover strata in response to regional compression culminating in the middle Miocene Atlas orogeny, (4) the development of transversal grabens during late orogenic normal faulting (latest Miocene to Recent). A major regional décollement is not considered necessary to account for the shortening of the sedimentary cover during the middle Miocene deformation. Rather, the principal driving mechanism of regional crustal shortening was the reactivation of early Mesozoic normal faults as reverse faults that displaced basement rocks. This model implies that the small amount of shortening recorded in the Tunisian Atlas involved active shortening and structural thickening of

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Fig. 1. Generalized tectonic map of Tunisia. The approximate position of the area covered in Plate 1 is indicated. Symbols: 1, high-angle reverse fault; 2, transverse graben; 3, fault, nonspecific; 4, anticlinal fold axis; 5, exposures of Triassic rocks, e.g., "zone of diapirs." Modified from Buroillet et al. [1978] and Perthuisot [1978].

basement and the concurrent deformation of the sedimentary cover.

INTRODUCTION

The North African Maghreb orogenic belt in Tunisia consists of the Tellian and Tunisian Atlas ranges and is bounded on the east and south by relatively undeformed cratonic platforms: the Pelagian block and the Saharan shield, respectively (Figure 1). An important tectonostratigraphic element in both the Tellian and the Tunisian Atlas is elongate masses of complexly deformed Triassic rocks consisting chiefly of evaporite and

supratidal dolomite with subordinate terrigenous clastic rocks and metabasites (ophites). Numerous workers [e.g., Castany, 1951a, 1952; Buroillet and Dumestre, 1952; Perthuisot, 1972, 1978, 1981] have suggested a diapiric origin for these features in light of their chaotic internal structure and common association with faults. Although substantial evidence [e.g., Perthuisot, 1978, 1981] indicates that diapirism played a major role in the evolution of these structures, our geologic mapping near El Kef, Tunisia, documents the importance of Neogene box folds as an additional structural element. This article describes the

Djebel Debadib anticline, a well-exposed, diapir-cored box fold near El Kef, Tunisia (Figure 1) and its developmental history involving Mesozoic diapirism, Cenozoic crustal shortening, and late orogenic normal faulting. We also integrate our detailed structural studies at El Kef into a tectonic model for the region.

REGIONAL TECTONIC FRAMEWORK

The structure of the western Tunisian trough in the vicinity of El Kef is characterized by broad, relatively flat synclines, cored by a thick succession of Cretaceous through Paleogene limestones and marls alternating with narrow-crested anticlines whose cores mostly consist of complexly deformed Triassic rocks (Plate 1). These folds, which generally trend northeast, have been locally modified by small-scale thrusts and normal faults. Tortochaux [1968], among others, has argued that the Triassic-cored folds of eastern Algeria and Tunisia are the product of early diapirism and superimposed compressional orogenic stresses. This structural zone is commonly referred to as the "zone of diapirs" [e.g., Burollet et al., 1978; Perthuisot, 1981]. The role of diapirism in the early development of the anticlines is supported by several observations: (1) the disrupted character of the Triassic strata, (2) the common absence of Jurassic and pre-Aptian Cretaceous rocks in contact with Triassic strata, (3) widespread faulting along the flanks of the Triassic-cored structures, (4) local vestiges of diapir-induced folds (i.e., rim synclines), (5) scarce exotic blocks of "basement" (this report, Table 1), (6) stratigraphic thinning of mid-Cretaceous and younger units over the Triassic-cored structures (documented at Djebel ech Cheid by Perthuisot, [1972, 1978]), and (7) complex mesoscopic structural features in the Triassic rocks indicating a multiply deformed history.

During the Neogene, the Atlas orogeny, a major compressional orogenic event, affected broad areas in northern Tunisia. In the Tellian province, deep-water Numidian Flysch was thrust a minimum of 15 km onto a partly contemporaneous shelf sequence [Carr and Miller, 1979]. In the Tunisian Atlas, the Mesozoic and Paleogene carbonate platform rocks were buckled, and presumably, in part, were translated on the low-viscosity, evaporite-rich Triassic substratum

[Burollet, 1973]. However, an aspect of this article is to reevaluate the role of Triassic evaporites in the tectonic evolution of the region. We argue that reactivation of basement normal faults may be the key mechanism controlling the structural style of the Tunisian Atlas during the Atlas orogeny rather than a regional décollement localized in the Triassic evaporites.

STRATIGRAPHIC SUBDIVISIONS AND RELATIONS

Three stratigraphic sequences are recognized in the study area: (1) a complexly deformed Late Triassic-Liassic(?) evaporite-bearing assemblage, (2) a Cretaceous-Paleogene basinal sequence, and (3) late Paleogene-Neogene marginal marine to nonmarine clastic sediments (molasse deposits). The stratigraphy of these rocks is summarized in Figure 2 and is briefly described below.

Late Triassic rocks

The Triassic rocks are chiefly a gypsum-matrix breccia containing a diverse array of clasts ranging in size from centimeter granules to coherent, stratified slabs hundreds of meters long. Common rock types include laminated to massive dolomite, carnegue (porous to cellular carbonate rock), dolomite breccia, fine-grained terrigenous clastic rocks, massive to thinly laminated impure gypsum, and metabasites (so-called ophites) (Table 1).

Salaï and Bajanić [1972] attempted to apply the tripartite Germanic lithostratigraphic subdivision to the Triassic rocks exposed in the core of Djebel Debadib anticline. However, the intense dismemberment of the strata make such a stratigraphic classification impossible to apply broadly to the Triassic rocks.

Despite the apparent impossibility of establishing meaningful lithostratigraphic subdivisions, the lithologic character of the Triassic-Liassic rocks is useful in the determination of original depositional environment. The following features taken together strongly suggest a coastal sabkha-type depositional environment: (1) the association of abundant gypsum and laminated dolomite, (2) widespread occurrence of shallow-water, small-scale sedimentary structures in the associated terrigenous clastic rocks, (3) scarce

TABLE 1. Lithotypes in Triassic Assemblage, Djebel Debadib Anticline, Tunisia

Lithology	Characteristics and Special Features
gypsum	white to varicolored; massive to delicately banded with clay impurities; commonly recrystallized as a fibrous tectonite; smoky quartz bipyramids are locally common as well as dolomite porphyroblasts
dolomite	gray to black, yellow; commonly laminated (relict algal structure)
cargneule	vuggy, cellular massive carbonate
dolomite breccia	massive breccia consisting of angular clasts of fine-grained, gray dolomite in a sugary, tan calcareous matrix, veinlets of white sparry calcite and crystal-lined vugs are ubiquitous
mudstone to siltstone	varicolored but commonly pale green or lavender; silty to clay-rich varieties locally calcareous and/or gypsiferous; sedimentary structures include burrows, halite casts, slump structures, ripple drift laminations, oscillatory ripples
sandstone	commonly white to tan or lavender; small-scale cross stratification is typical
ophite	aphanitic to microporphyritic basalt to dolerite, scarce mafic tuff; intensely statically altered, typical mineral assemblage: chlorite-actinolite-albite-epidote/clinozoisite-sericite-alkali-feldspar-carbonate-leucoxene-hematite $\pm$ biotite $\pm$ quartz [Kurtz, 1979]; coarse-grained veinlets of hematite are common
gray phyllite	relict fragmental texture of subrounded clasts in a chiefly pelitic matrix; mineral assemblage: white mica-quartz-chlorite-olive green biotite-sodic-plagioclase-carbonate-opaque oxides; unusual inclusion within gypsum-matrix breccia, possibly a metamorphosed late Paleozoic metasedimentary rocks
limestone (pink to orangish yellow)	fine-grained, sugary texture, slabby character, unusual inclusion within gypsum-matrix breccia, possibly recrystallized Jurassic carbonate rock

Plate 1. Geologic map and cross section of El Kef and Ouargha areas. Modified from Burolet and Sainfield [1956] and Sainfield [1951].

EXPLANATION Lithologic Units

QUATERNARY--surfacial deposits	
Qa	Alluvium (Holocene)
Qoa	Older alluvium and colluvium
TERTIARY--MESOZOIC ROCKS	
Upper Segui Formation -- Pliocene (?)	
Lower Segui Formation -- Upper Miocene	
Hakima Formation -- Lower Miocene	
Fortuna Formation (?) -- Oligocene	
Metaoui Formation and Souar Shale -- Eocene	
El Haria Formation -- Paleocene/Cretaceous	
Abiod Formation	
Upper Aleg Formation	
Lower Aleg Formation	
Bahoul Formation	
Fahdene Formation & black marls (Albian)	
Sedimentary breccia, glauconitic dolomite, reefal dolomitic limestone -- Aptian	
Liassic- Triassic undifferentiated, black = ophite masses	

Symbols

--- where approximate, dotted where inferred or covered	Contact, dashed where approximate, dotted where inferred or covered
--- where approximate, dashed where inferred or covered	Unconformity, dashed where approximate
Low-angle fault	Fault, ball and bar on downthrown side, dashed where approximate, dotted where inferred or covered
Strike and dip of bedding, inclined (left); completed (center); and overturned (right)	
Strike of bedding from aerial photographs	
Foliation in gypsum tectonite	
Macroscopic fold axis showing direction of plunge; syncline (above), anticline (below)	
Locality referred to in text

Plate 2. Detailed geologic map of the Djebel Debadib anticline based on field studies of A. W. Snoker, S. Schamel, and R. M. Karasek and modifications of Burollet and Sainfeld [1956] and Sainfeld [1951].

Plate 3. Stereograms summarizing bedding (Triassic and Cretaceous rocks) and foliation (Triassic rocks) in the Djebel Debadib anticline. Subarea 1 includes the part of the anticline northeast of the Oued er Rmel and subarea 2 includes the part of the anticline southwest of the Oued er Rmel but also includes data collected along the river.

Fig. 2. Diagrammatic stratigraphic column summarizing stratigraphic nomenclature of Mesozoic and Tertiary rocks of the Jebel Debadib anticline and surrounding area. Derived principally from Burollet [1956].

"chicken wire" texture in massive gypsiferous dolomite, (4) halite pseudomorphs in lavender siltstone, (5) fine interlamination of gypsum and dolomite, and (6) interlamination of

mudstone/sandstone with gypsiferous dolomite.

The association of evaporite-dolomite-basalt is commonly considered an assemblage characteristic of an extensional tectonic regime [e.g., Wilson, 1975]. Detailed geochemical studies on the metabasitic rocks (ophites) found in the Triassic of northern Tunisia [Kurtz, 1979] support a model of basaltic magma genesis during intracontinental rifting. Brown and Van Houten [1979] have argued for the initiation of extensive continental rifting along the length of northwestern Africa during Late Triassic time. This rifting environment was probably a manifestation of a broad transtensional zone that developed during the early stages of the opening of the Tethys ocean [e.g., Laubscher and Bernoulli, 1977; Bernoulli and Lemoine, 1980; Kelts, 1981].

Pre-Aptian-Albian Unconformity

An important aspect of this study has been the recognition and detailed investigation of the contact relationships between the Triassic rocks and the younger adjacent rocks. The absence of regionally extensive Jurassic and Lower Cretaceous rocks in the study area indicates that the contact between the Triassic and younger strata must be a fault; an unconformity; some combination of these relations, e.g., a faulted unconformity; or intrusive (related to diapiric emplacement). Previous studies of these contacts have commonly concluded that the boundaries are either intrusive or faulted. Contacts between Triassic rocks and younger rocks on the *Carte Géologique de la Tunisie* [Castany, 1951b] are uniformly shown as "faults" (contacts anormaux) throughout northern Tunisia.

However, during our mapping of Djebel Debadib anticline, we discovered one locality where stratigraphic and structural relations clearly indicate an unconformable contact between disrupted Triassic rocks and overlying Cretaceous (Aptian?) rocks, as well as numerous other localities where such an interpretation is likely. The best site for observing the unconformable relationship between Triassic rocks and the Cretaceous strata is a small ravine south-southwest of Koudiat Nab el Azreg (Locality A, Plate 2). At this locality, Triassic gypsum-matrix breccia is unconformably overlain

Fig. 3. Detailed stratigraphic column at locality A (Plate 2).

by subhorizontal beds of pelletal dolomite and a sedimentary breccia (Figure 3). The breccia is stratified and consists chiefly of dolomitic clasts, up to 4 m long, in a marl matrix. The breccia is overlain by several meters of dolomitic strata including a distinctive sandy, glauconitic dolomite. This sequence in turn grades upward into a fissile, organic-rich black marl, which Buroillet and Sainfeld [1956] dated as upper Albian based on the presence of the foraminifera *Thalmanninella* sp.

In other places above the breccia a ridge-forming, dolomitic limestone is

locally developed. Its lenticular nature and fossiliferous character suggest a reefal accumulation. Buroillet and Sainfeld [1956] assigned an Aptian age to this unit based on its stratigraphic position and macrofossil determinations. This unit appears to be a lateral equivalent to the dolomitic sequence exposed in the ravine at locality A (Plate 2 and Figure 3). These relationships indicate that the unconformity developed between Late Triassic and Aptian time. Several thousand meters of Jurassic limestone and Lower Cretaceous marls and sands penetrated by the diapir are nowhere

exposed near Jebel Debadib anticline. The succession is known principally from exposures along the southern margin of the zone of diapirs [e.g., Rakus, 1973].

Late Cretaceous to Eocene Sequence

The rocks that surround the Triassic core of Jebel Debadib anticline and overlie the pre-Aptian unconformity are chiefly Upper Cretaceous to Eocene basinal facies carbonate rocks. This thick carbonate sequence can be divided into distinct lithostratigraphic units including (oldest to youngest): Fahdene Formation, Bahloul Formation, Aleg Formation, Abiod Formation, El Haria Formation, Metlaoui Formation, and Souar Shale (Figure 2). The rocks consist mostly of a monotonous variation from chalky limestone to marl, although a massive lower Eocene nummulitic limestone (Metlaoui Formation) is a prominent ridge former in the eastern part of the area.

As previously noted, Aptian-Albian rocks form the base of the Cretaceous-lower Tertiary carbonate sequence. These rocks apparently were deposited directly on disrupted Triassic rocks (chiefly gypsum-matrix breccia) in the region encompassing the existing Jebel Debadib anticline. The surface upon which the Aptian-Albian carbonate rocks accumulated was the extruded and subsequently eroded top of a pre-Aptian diapiric structure. This diapiric structure may have remained intermittently active after the early Cretaceous, although contact relations indicate only modest post-Aptian diapirism prior to Neogene folding. In contrast, Perthuisot [1978] has documented stratigraphic thickness and facies variations in Upper Cretaceous to lower Tertiary strata across Jebel ech Cheid and has suggested that this Triassic-cored structure, located near Teboursouk approximately 60 km northeast of El Kef, experienced a continuous diapiric history from the late Mesozoic into the mid-Tertiary.

Oligocene(?) to Pliocene Units

The mid-Cretaceous to Eocene marine carbonate rocks are unconformably overlain successively by upper Oligocene paralic to nonmarine, lower Miocene marine, and upper Miocene and Pliocene nonmarine sedimentary rocks [Buroillet, 1967; Van Houten, 1980]. This transition in depositional environments corresponds to the tectonic

transition from a continental margin setting in the Paleogene to a collisional zone during the middle Miocene Atlas orogeny, i.e., "Maghrebian deformation" of Alvarez et al. [1974].

In the Jebel Debadib area, stratigraphic correlation of middle and upper Tertiary rocks is uncertain, but our tentative correlations are that the upper Oligocene(?)–lower Miocene rocks are an equivalent of the Fortuna Formation [Buroillet, 1956, 1967; Van Houten, 1980], the remaining lower Miocene rocks are equivalent to Hakima Formation; and the upper Miocene and Pliocene rocks are Segui Formation [Buroillet, 1956; Buroillet, 1967]. A sedimentary breccia, i.e., debris flow deposit, forms the base of strata equivalent to the Fortuna Formation, and this deposit is overlain by a heterogeneous suite of rocks including light gray marl with interbedded crystalline, vuggy limestone, clean, fine-grained quartz sandstone, and varicolored shale and siltstone. The Hakima Formation is quite variable but chiefly consists of siltstone, silty gypsiferous claystone with lenses of conglomerate, and sandstone. The sandstone is commonly structureless, but locally contains large-scale, festoon cross-bedding. At a few localities, the sandstone contains abundant marine fauna. The Segui Formation consists principally of sandstone, siltstone, and silty claystone, with minor intercalated lenses of conglomerate which forms lenses up to 2 m thick. Near the base of the unit, west of Koudiat Zag et Tir, is a 1- to 4-m-thick bed of massive gypsum. The Segui Formation in our study area is devoid of fossils; it probably was deposited in a continental depositional environment, likely fluvial in part. Unconformably above the upper Miocene section of the Segui Formation is a Pliocene(?) unit of marl and marly limestone. We have informally included this unit with the Segui Formation. Within the upper Miocene part of the Segui Formation there may be one or more angular unconformities. At Zag et Tir, we observed unconformities with 15°–25° angular relations with bedding and stacked in a radial fashion indicating the continued growth of Zag et Tir during the late Neogene.

MACROSCOPIC STRUCTURE

The Jebel Debadib anticline is an elongate, northeast plunging fold having a

relatively simple geometry but a multiphase evolution. In the core of the anticline is a disrupted Triassic succession, consisting chiefly of gypsum-matrix breccia. This incompetent core is surrounded by Cretaceous-Eocene marls and limestones which form the competent carapace of the fold. On the northwest flank of the anticline is a tight syncline-anticline couplet that passes into a system of large folds characterized by broad, rather flat synclines and narrow-crested anticlines. The southeast flank of Djebel Debadib anticline is characterized by conspicuous normal faulting, especially in the area broadly surrounding Koudiat Tarja (Plates 1 and 2). Further to the southeast, the Cretaceous-Eocene carbonate rocks are folded into a broad syncline.

The overall geometry of the Djebel Debadib anticline is that of a boxlike fold with steep flanks and a relatively flat crest (Plate 1). On the northwest flank, Cretaceous strata are commonly subvertical to overturned, and locally small-scale reverse faults are present. In a few localities near the northeast nose of the anticline and along the northwest margin, Cretaceous rocks have been overturned and the Triassic rocks form an overhanging rim. The overturned strata suggest that the gypsiferous Triassic assemblage flowed ductilely upward during folding and subsequently spread away from the crestal zone of the fold.

Furthermore, during this deformational phase the following distinctive flank structures developed: (1) the tight syncline-anticline couplet on the northwest and (2) the complexly faulted terrane on the southeast. Both of these features appear to be manifestations of subsurface flow of evaporite away from the flanks of the anticline coupled with the upward movement of the core and consequent gravitational collapse of the southeast limb of the anticline.

MESOSCOPIC STRUCTURAL FEATURES IN THE TRIASSIC ROCKS

The Triassic succession records a polyphase deformational history complicated by evidence of widespread solution collapse. A great variety of mesoscopic structures are characteristic of the Triassic rocks and can be broadly classified into the following groups: (1) tight to near isoclinal folds and

associated transposition of stratigraphic layering, (2) syndiapiric solution breccia characterized by a heterogeneous suite of lithic clasts in a foliated matrix, (3) late solution breccia characterized by a heterogeneous suite of lithic clasts in a nonfoliated matrix, and (4) postdiapiric, disharmonic folds, probably related to Cenozoic folding.

Early tight to near isoclinal folds (Figure 4a) are common in the gypsum matrix, actually a low-rank metamorphic tectonite. Foliation parallel to the axial surfaces of the folds is characteristic. These early folds probably developed during diapiric ascent.

Brecciation is a ubiquitous feature within the diapir (Figure 4b). Some brecciation is clearly nontectonic and is probably a collapse breccia produced by synemplacement and postemplacement solution [Middleton, 1961; Stanton, 1966]. On the other hand, some brecciation is clearly tectonic as indicated by association with folds, and is probably related to diapiric ascent and eventual surface piercement of the Triassic rocks during the Early Cretaceous. Early stages of tectonic brecciation and dismemberment may be related to transposition of bedding near the hinge zones of folds or extensive boudinage of competent dolomite layers in ductile evaporite on the limbs of folds (Figure 4c). Breccias formed via these processes have a gypsum tectonite matrix, and lithic clasts are monolithologic to polymictic depending on strain history and local stratigraphic variations.

Clasts of folded gypsum tectonite in gypsum-matrix breccia (Figure 4d) suggest that a continuum existed from penetrative plastic deformation of the evaporite during the early deformational history to brittle failure in later stages. This deformational continuum may reflect the diapiric ascent of the Triassic rocks from their maximum burial level (at least 2000 m and perhaps as much as 4000 m below the surface), where crystal-plastic deformational processes of the evaporite prevailed, to an upper level or near-surface environment, where brittle failure dominated.

Solution breccias commonly contain a heterogeneous suite of lithic clasts in either a foliated or nonfoliated gypsum matrix. To a first approximation, the fabric of the gypsum matrix probably depends on the deformational history during the solution phenomenon. According

Fig. 4. Mesoscopic deformational features in the Triassic sequence of Jebel Debadib anticline. (a) Near isoclinal folds in gypsum tectonite, (b) gypsum-matrix breccia with dolomite clasts, (c) extreme boudinage of competent black dolomite in gypsum-matrix breccia, and (d) clast of folded gypsum tectonite in gypsum-matrix breccia.

to this hypothesis, solution breccias formed synchronous with diapiric rise are characterized by a foliated gypsum matrix, and postemplacement solution breccias are characterized by a nonfoliated gypsum matrix.

Disharmonic folds, another common structure where original stratification is preserved, principally reflect the strength contrast between dolomite and gypsum/anhydrite. The younger disharmonic fold phase is probably related to the development of the northeast-southwest trending Djebel Debadib anticline. These structures fold foliation in gypsum tectonite and are not associated with the development of a penetrative fabric.

Stereogram summaries of bedding and foliation in the Triassic rocks and bedding in the Cretaceous-Paleogene rocks indicate a rough parallelism with the northeast-southwest trend of the anticline (Plate 3); however bedding in the diapiric Triassic succession clearly show more scatter. These data therefore suggest either overprinting of earlier orientations by the younger deformation or that both the pre-Aptian and the late Cenozoic structures share a common orientation despite contrasting structural styles.

DEVELOPMENTAL HISTORY OF THE DJEBEL DEBADIB ANTICLINE

The following critical relations must be incorporated into the developmental model of the Djebel Debadib anticline: (1) the Jurassic and Neocomian section is absent at the present level of exposure; (2) an unconformity is present between upper Lower Cretaceous rocks and Triassic rocks in the region of the anticline; (3) a sedimentary breccia rests directly above this unconformity; (4) Aptian reefal limestones and Albian(?) glauconitic horizons indicate shoals in the present axial region of the anticline during late Early Cretaceous time; (5) the highly incompetent, gypsum-rich Triassic assemblage is polyphase-deformed and extensively brecciated; (6) scarce "exotic" fragments, e.g., gray phyllite, recrystallized limestone occur in the Triassic gypsum-matrix breccia; (7) the Cretaceous-Paleogene section above the pre-Aptian unconformity is well bedded, not dismembered, and is folded into broad synclines and narrow to boxlike anticlines; and (8) the Cretaceous-Paleogene section is cut by numerous

normal faults locally near the Triassic-cored anticline.

We have therefore developed an evolutionary model for the Djebel Debadib anticline with the above observations as constraints, the important stages are summarized in Figure 5.

The shallow marine Triassic sequence was deposited on a continental margin thinned and extended by normal faults during the opening of the Tethys ocean [Bernoulli and Lemoine, 1980]. Above this evaporite-bearing, coastal sabkha sequence was deposited at least 2000 m and perhaps as much as 4000 m of Jurassic and Neocomian strata as the continental margin subsided. Piercement by the Triassic evaporites through the overlying strata was initiated during the early Cretaceous (Figure 5a). The triggering mechanisms are uncertain but differential overburden loading related to the buried basement fault blocks [Jenyon, 1985] was probably instrumental in localizing the rise of the diapirs. The inclusion of a low-grade metamorphic rock in the gypsum breccia suggests that rock fragments below the Triassic sequence were locally incorporated into the rising evaporite intrusion. The "plucking" of rock fragments from the salt subcrop is apparently a common phenomenon in some salt piercement structures [Harrison, 1930; Wilson, 1975].

During the period of diapiric upwelling, the evaporitic rocks were penetratively deformed into a variety of tight to near isoclinal folds. Brecciation related to transposition of layering and extreme boudinage occurred in the limbs of the folds. As the diapir intruded higher in the crust, the style of deformation evolved from quasi-plastic flow to brittle failure. Extensive brecciation and dismemberment of all the lithologic units occurred at that stage (Figure 5b). The role of temperature during the diapiric ascent is difficult to assess, but Gussow [1968] has argued that heat is a critical, and often overlooked, factor in the emplacement of salt dome intrusions. The extensive recrystallization and crystallographic-preferred orientation of the gypsum tectonite, the development of synkinematic to postkinematic dolomite porphyroblasts, the lower greenschist facies metamorphic mineral assemblages in the ophite inclusions, and the recrystallization of limestone inclusions (Table 1) suggest that elevated thermal conditions were

Fig. 5. Structural evolution model for Jebel Debadib anticline (modified from Karasek [1977]). (a) Initial upwelling of evaporitic-rich Triassic strata (including salt) after burial by Jurassic and Neocomian(?) strata, (b) formation of unconformity and cap rock breccia after piercing of the Jurassic and Neocomian(?) section, (c) inferred configuration of salt dome in Aptian-Albian time following the development of the breccia unit above the unconformity, and (d) the present configuration of the Jebel Debadib anticline after middle Miocene folding and late normal faulting.

important during at least part of the diapiric evolutionary history.

Following the piercing of the Jurassic and Neocomian strata (Figure 5c)

in pre-Aptian time, solution phenomena probably became widespread over the top of the diapir with the extensive development of solution collapse breccia. Much of the gypsum and calcareous-matrix breccia that forms the core of Jebel Debadib anticline has characteristics of cap rock, i.e., residual deposit commonly formed above salt domes. The widespread lead-zinc mineralization [Sainfeld, 1951; Buroillet and Sainfeld, 1956; Rouvier et al., 1985] associated with the Triassic rocks is also reminiscent of local mineral occurrences described from Gulf Coast salt dome cap rock [Hanna and Wolf, 1934; Price and Kyle, 1983]. Therefore, it is possible that salt is present at depth in Jebel Debadib anticline beneath a carapace of breccia. Such relations are well documented through well data from evaporitic diapirs in other geologic settings [e.g., Brinkmann and Logters, 1968].

The origin of the sedimentary breccia unit immediately above the unconformity is enigmatic, but the deposit probably represents local stripping and redeposition of the uplifted carapace above the actively rising diapir. The breccia, in part, may be a debris flow derived from nearby elevated portions of the diapir.

Following the solution and erosion of the evaporite dome and the unconformable deposition of the breccia over the Triassic rocks, a sea transgressed the area in the Aptian. Organic (reefal) buildups developed in shallow water over the dome on stable substrata probably in part provided by the larger blocks in the sedimentary breccia unit. The region then subsided and a thick mid-Cretaceous to Eocene carbonate sequence developed. Modest intermittent diapirism probably occurred throughout the late Mesozoic and Tertiary in response to sedimentary loading.

An important time of tectonic transition began in the mid-Tertiary. The middle Eocene to upper Eocene Souar Shale is the last manifestation of the long-lived, stable continental margin basin history that characterized the Tunisian trough throughout the Mesozoic and early Tertiary. Beginning approximately during the late Oligocene and extending into the early Miocene, uplift, erosion, and tilting resulted in formation of an angular unconformity. Sands were deposited on top of the unconformity. The influx of terrigenous sediment probably

was related to the initial subduction of the northern shelf margin. In the middle Miocene, regional compression (Atlas orogeny) resulted in the development of numerous northeast-southwest trending folds [Alvarez et al., 1974]. These folds appear to reflect the response of the sedimentary cover to regional shortening of the basement (Figure 5d). The box-fold shape of Djebel Debadib anticline resulted from the reactivation of an incompetent diapiric core overlain by a thick competent sedimentary sequence. Late orogenic normal faulting partially fragmented the anticline and is probably related both to the subsurface redistribution of evaporite and regional extension after Neogene folding.

Continental deposits of late Miocene to Pliocene age were deposited in small basins. There are several unconformities in this section suggesting the continuous rise of the evaporite core of Djebel Debadib subsequent to Neogene regional compression.

REGIONAL IMPLICATIONS

The tectonostratigraphic history of Djebel Debadib anticline and the surrounding region provides clear evidence of at least four regional tectonic events critical in the evolution of the Tunisian Atlas: (1) early Mesozoic rifting suggested by the Late Triassic-Liassic(?) association of the following rock types: evaporite, supratidal carbonate, terrigenous clastic rocks, and basalt; (2) pre-Aptian diapirism indicated by the highly deformed Triassic-Liassic assemblage and the unconformity between the Triassic rocks and overlying Aptian-Albian strata; (3) Neogene compression indicated by numerous folds, including Djebel Debadib anticline, that trend northeast-southwest; and (4) late orogenic normal faulting manifested by the local faulting of earlier formed features. Given these tectonic events, we have devised a developmental model for the Tunisian Atlas which is summarized as a series of diagrammatic sketches depicting the important tectonic phases in this history (Figure 6).

The first phase of our tectonic evolution involves the formation of a rifted continental margin along the northwest margin of Africa during the early development of the Tethys ocean [Laubscher and Bernoulli, 1977; Bernoulli and Lemoine, 1980]. Thinning of the

continental margin crust resulted in formation of normal faults in crystalline basement rocks (probably Hercynian age). The rock-stratigraphic manifestation of this rifting event was widespread evaporite-supratidal carbonate deposition and the local intrusion and/or extrusion of basaltic and silicic igneous rocks [Bajanik, 1971; Kurtz, 1979]. These rocks principally accumulated in a series of basins localized on downthrown fault blocks (Figure 6). A thick Early Jurassic to Neocomian marine carbonate sequence was deposited above the evaporite-rich Triassic rocks as the continental margin continued to subside during the mid-Mesozoic [Salaj, 1978]. Diapirism of the Triassic evaporites probably began during the Neocomian. In the southwestern part of the "zone of diapirs," i.e., near El Kef, Tunisia, piercement occurred in the Early Cretaceous, although at other localities, farther to the northeast, piercement may have been much later [Perthuisot, 1981]. Nevertheless, an extensive period of intermittent diapirism of the Triassic evaporite-rich sequence characterized the Tunisian Atlas from early Cretaceous to early Miocene time (Figure 6).

The middle and late Tertiary period was a time of complex tectonism in northern Tunisia, i.e., Atlas orogeny, when rocks of the Tellian Atlas were thrust southeastward onto the northern margin of the Tunisian Atlas [Glacon and Rouvier, 1972]. The rocks involved in the Tellian nappes were principally the Numidian Flysch of Oligocene-Miocene age [Carr and Miller, 1979] in Tunisia but also include pre-Triassic crystalline rocks in northern Algeria, i.e., Kabyle complex; Bossière and Peucat [1985]. In the Tunisian Atlas the Atlas orogeny was chiefly manifested by the development of numerous folds in Mesozoic to Paleogene carbonate rocks of the Tunisian trough. The folds generally trend northeast-southwest, and the cores of many of the anticlines are occupied by chaotic Triassic evaporite-rich assemblages. The evolution of these folds was no doubt complex, but we believe that the reactivation of basement normal faults as high-angle thrusts or reverse faults was the critical shortening process in the Tunisian Atlas. The folds in the cover rocks are therefore chiefly a passive response to basement shortening at depth.

A sole décollement is not implied as a fundamental structural element in the Tunisian Atlas because a distinct

DEVELOPMENTAL MODEL FOR THE TUNISIAN ATLAS

Fig. 6. Developmental model for the Tunisian Atlas.

imbricated fold and thrust belt does not exist. On the other hand, it seems inescapable that the cover strata did not locally glide on the evaporite-rich Triassic rocks situated immediately above basement rocks [Burollet, 1973].

An instructive analogue to the Tunisian Atlas is the tectonic model derived by Jackson et al. [1981] to interpret the

current seismicity in the Zagros fold belt of Iran. The seismic activity of the Zagros is distributed across the whole width of the belt and appears to reflect slip along reverse faults. This seismicity is explained by the reactivation of older normal faults as high-angle thrusts. The Zagros therefore reflects the development of a fold belt on

a template of distended continental crust subsequently shortened during continental collision [Bird et al., 1975]. Furthermore, the presence of salt at the base of the Paleozoic sedimentary cover above basement is analogous to the stratigraphic framework of the Tunisian trough. The role of décollement glide cannot be precluded in the shortening history of the simply folded belt of the Zagros [Falcon, 1969], but as in Tunisia, the manifestation of this décollement is apparently local rather than regional. The presence of the salt horizon may also account for the lack of surface breaks in the Zagros fold belt, for the basement faults do not propagate upward through the salt [Jackson et al., 1981]. A similar argument may also be a reasonable explanation for the virtual absence of thrust faults in the Tunisian Atlas.

Superimposed on the Atlas compressional structures are numerous transverse grabens (Figure 1). The age of these faults is probably latest Miocene to Recent, and they may be related to transtensional rifting [Jongsma et al., 1985; Reuther and Eisbacher, 1985] during the later stages of collision between the North African continental margin and the Corsica-Sardinia microplate [Alvarez et al., 1974; Cohen et al., 1980]. Minor post-Messinian folding and reverse faulting followed the extensional regime and continues to the present [Kamoun and Hfaiedh, 1985].

An important element of our tectonic model for the Tunisian Atlas is the reactivation of early Mesozoic normal faults as high-angle reverse faults during the Neogene Atlas orogeny. This aspect of the model is an application of the concept of "inversion tectonics," a tectonic style that has recently been postulated for parts of various compressional orogens that experienced an early history of crustal extension [e.g., Winslow, 1981; Cohen, 1982; Ziegler, 1987]. A problem associated with the inversion tectonics model is the nature of the mechanisms responsible for transmission of stresses across the foreland to account for basement fault reactivation during lateral compression. Ziegler [1987] has argued that the reactivation of ancient wrench faults may be critical in the deformation history of the European foreland. In our two-dimensional, cartooned developmental model we have not incorporated the role of strike-slip tectonics in the Tunisian foreland, although a complex wrench fault system has been recognized by Boccaletti et al. [1984]. If this fault system or

earlier elements of it existed during the lateral compression associated with the middle Miocene Atlas orogeny, these faults must have played an important role in accommodating the basement shortening that we infer for the Tunisian Atlas.

In summary, the application of the inversion tectonics concept to the Tunisian Atlas will need considerable testing before it is widely accepted; the critical tests are obvious: seismic reflection profiling coupled with selected deep boreholes. The ongoing geophysical studies of the European Geotraverse [Galson and Mueller, 1986] offer an excellent opportunity to further explore the application of the inversion concept and the role of basement deformation in the evolution of the Tunisian Atlas. As Falcon [1969] emphasized in his review of the structure of the Zagros Mountains, advances in the understanding of the deep structure of complex mountain belts commonly begin with a geological model which in turn can only be thoroughly evaluated by geophysical surveys and drilling.

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