

Neogene deformation in northern Tunisia: Origin of the eastern Atlas by microplate–continental margin collision

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ABSTRACT

Detailed structural analysis in the southern Hédil region, northern Tunisia, suggests that the area is characterized by normal faulted, southeast-vergent and upright, box- to close-style folds. Fold nappes and imbricate thrust sheets postulated previously are absent in the Hédil, although thrust sheets do occur farther north in the Mogods and Kroumerie regions.

A two-stage tectonic model is proposed: (1) middle Miocene progressive deformation involving initial buckle folding and later shear faulting in the Hédil, and southeast-directed thrusting in the Mogods and Kroumerie; and (2) postdeformation extensional faulting parallel to regional fold trends, bimodal (basalt-rhyolite) volcanism, and molasse deposition. Minor, post-Messinian southeast-vergent thrust faulting followed this extensional regime and continues to the present. Maximum principal compressive stress (σ_1), horizontal and striking S38°E, is inferred for the middle Miocene deformation.

The middle Miocene fold and thrust structures are related to the collision of the counterclockwise-rotating Corsica-Sardinia-Petit Kabylie plate with the Tunisian continental margin. Following this collision, in the Tortonian, the development of a sphenochasm spreading system to the west of the present-day Straits of Sardinia produced the extensional regime that prevailed in northern Tunisia. As spreading continued, the Petit Kabylie rotated clockwise away from Sardinia. Movement ceased when the Petit Kabylie collided with the Algerian continental margin.

INTRODUCTION

The Atlas in northern Tunisia is a northeast-trending mountain range that is found in the Mogods, Kroumerie, and Hédil regions (Fig. 1). Major southeast-directed imbricate thrusting and folding occurred during the middle Miocene in the Mogods (Biely and Rouvier, 1970; Carr and Miller, 1979) and Kroumerie regions (Glaçon and Rouvier, 1972; Rouvier, 1977). Previous studies in the Hédil have produced similar fold-thrust tectonic models (Caire and others, 1971).

The study area (Fig. 1), within the southern Hédil, is divided by earlier workers (Caire and others, 1971) into two zones: (1) a northern, structurally higher domain termed the “Unité de Hédil” and (2) a southern, structurally lower domain termed the “Unité des Écailles.” The former is suggested to be a nappe riding on Triassic evaporites which was emplaced from the northwest (Castany, 1953; Kujawski, 1969; Biely and Rouvier, 1970; Caire and others, 1971; Biely and others, 1974), although the magnitude of displacement is uncertain. The Unité des Écailles is a zone of imbricate thrust sheets soled by Cretaceous-Tertiary shales, also vergent to the southeast (Castany, 1953; Kujawski, 1969; Biely and Rouvier, 1970; Caire and others, 1971; Biely and others, 1974). A third, structurally highest domain, termed the Numidian flysch complex, is found 20 km farther north (Glaçon and Rouvier, 1967; Caire and others, 1971).

However, the proximity of the Hédil to the “Zone of Diapirs” to the south (Fig. 1) has been used by some authors to suggest that many of the folds within the Hédil may be due to diapiric intrusions of Triassic evaporites at depth (Kujawski, 1969). Alternatively, the seemingly random orientations of some units within the southern Hédil have led other workers to explain Hédil structures by gravity tectonics (DeJong, 1975). The roles of these different deformational mechanisms in the over-all structural evolution of the Hédil region is thus not clear.

The structural data that we obtained during detailed (1:12,500) mapping indicate that proposed deformational mechanisms (imbricate thrusting, diapirism, and gravity gliding) do not explain the developmental history of the southern Hédil. Our data suggest a reinterpretation of this portion of the Tunisian Atlas, according to a plate-tectonics model, modified substantially from that of Alvarez and others (1974), which relates the structural geometries and history to a microplate–continental margin collision.

STRATIGRAPHY

Triassic

The Triassic rocks are the most complex units in the Hédil and have posed numerous problems due to their highly discontinuous lithologies, variable outcrop setting and structural relations, and equivocal faunal age determinations. Triassic lithologies include:

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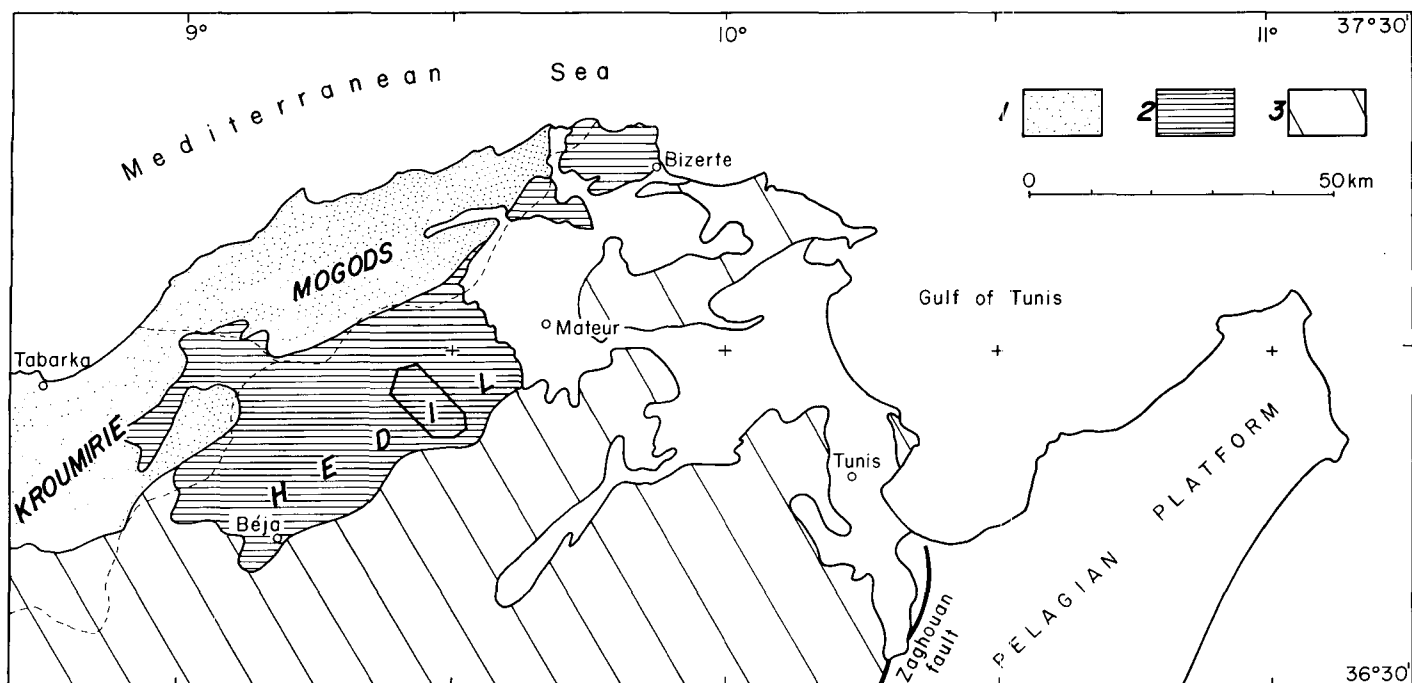


Figure 1. Index map of northern Tunisia. 1 = Numidian flysch nappe; 2 = "Imbricate Thrust Zone"; 3 = "Zone of Diapirs." Study area within the southern Hédil is outlined.

(1) chaotic, brilliantly colored, variegated marls, locally containing smoky, bipyramidal quartz; (2) dolomite altered to *cargneule*; (3) dolomite breccias; (4) gypsum breccias; and (5) *ophite*. Dolomite and gypsum breccias predominate, yet no unequivocal stratigraphic or structural relations exist with respect to the other lithologies.

The Triassic rocks in northern Tunisia are in two outcrop settings: (1) southwest-trending massifs aligned parallel to major faults and (2) isolated areas which exhibit no apparent continuity (Kujawski, 1969). In the northern Hédil, the structures containing the Triassic appear to be diapiric (Kujawski, 1969), yet farther south, in the present study area, it is represented as a major fault-bounded unit. The Triassic units in the study area are about 600 m thick. Kujawski (1969) observed that the Triassic ranges from 1 to 4 km thick near Bazina, 3 km north of the study area.

Elsewhere in northern Tunisia, Pervinquièrre (1903) and Burollet (1956) suggest a Late Triassic age for units containing *Alectryonia sp.*, *Ostrea sp.*, *Avicula sp.*, and *Equisetites sp.* Bolze and Crampon (1964) propose, however, that dolomite and gypsum breccias occur conformably between the Abiod and Metlaoui Formations (Late Cretaceous and early Eocene in age, respectively), completely replacing the El Haria Formation (Cretaceous-Tertiary transition) and locally the Metlaoui Formation, and are therefore Paleocene in age.

Three schools of thought thus exist on the nature of relations between Triassic and the younger rock units described below: (1) the Triassic has been diapirically emplaced into younger units (Sainfeld, 1952; Kujawski, 1969); (2) the Triassic represents a rootless sheet at the base of thrust units (Solignac, 1927; Jauzein and Rouvier, 1968); and (3) evaporite units considered as Triassic are actually Paleocene in age (Bolze and Crampon, 1964; Crampon and Sigal, 1967).

The exact nature of the relationship between Triassic units and the Atlas trough is at present unclear. Van Houten and Brown (1977) suggest that Triassic units represent the oldest sediments

deposited in the vicinity of the developing Atlas trough, formed during intracontinental rifting in Late Triassic time. Alternatively, the evaporites may have been deposited on a stable shelf prior to this rifting event.

Tellian Sequence

Late Cretaceous to early Eocene limestones, marls, and shales (Fig. 2), termed the Tellian sequence, comprise the dominant rock types in northern Tunisia. In the study area, this sequence is composed of three formations: the Abiod, El Haria, and Metlaoui, representing a trend from lower to upper slope depositional environments (Carr and Miller, 1979). Three additional formations, the Aleg marl (Campanian), Souar shale (late Eocene), and Fortuna sandstone (Oligocene) are present elsewhere in Tunisia.

Abiod Formation. This unit of Campanian to Maestrichtian age, regionally contains three unnamed members: (1) a lower, white to cream-colored limestone unit; (2) an intermediate unit of alternating gray to brown marls and marly limestones; and (3) an upper, light gray to cream-colored massive limestone unit. The formation crops out within two large, southwest-trending anticlines in the northern part of the study area, Djebel Tiour el Lil-Anntra and Djebel el Hara-Hassane. The Abiod has a minimum exposed thickness of 300 m; the base of the intermediate member is not exposed but is known elsewhere and in the subsurface (Kujawski, 1969).

El Haria Formation. Upper Cretaceous to Paleocene (Kujawski, 1969) gray to black shales and marls underlie major valleys throughout northern Tunisia as well as the present study area (for example, Henchir en Nemra). Extremely fissile, the more than 300-m-thick sequence is poorly indurated and weathers to a gray to black soil.

Metlaoui Formation. This lower Eocene, thin- to medium-bedded unit grades from tan to gray marls and marly limestones at

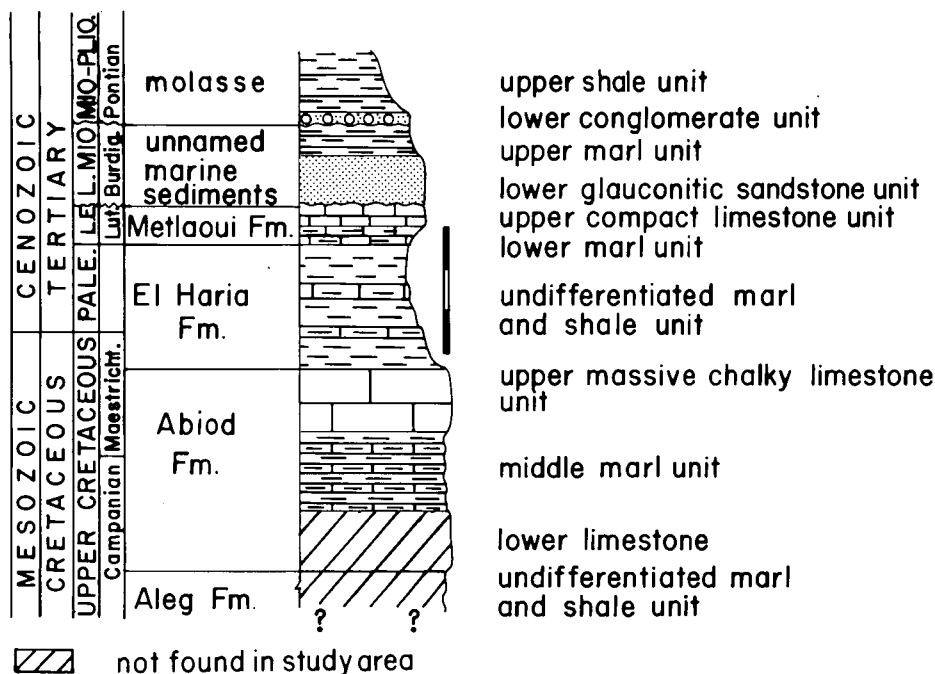


Figure 2. Generalized stratigraphic column of units within the southern Hédil; see text for discussion. Thicknesses are maximum measured or calculated; divisions on vertical rule are per 100 m.

its base, representing the transition from the El Haria Formation, to a medium- to thick-bedded limestone unit. The latter exhibits three main facies (Burolet, 1975), two of which are seen in the study area: a nummulitic facies southeast of Djebel Tahent (Fig. 3, loc. 1); toward the north, a transitional facies also containing *Globigernia*. Calculations yield a minimum thickness of 80 m for the Metlaoui Formation. North of Oued Begrat (Fig. 3) the Metlaoui Formation rests above Triassic evaporites, in apparent structural concordance. Previous workers (Caire and others, 1971) suggest that this contact is structural and that the Metlaoui limestone represents an independent thrust sheet above the Triassic units. Although the structural evidence along the contact is equivocal, it is difficult to envision an alternative means of deriving such a juxtaposition.

Lower Miocene Units

Disconformably overlying the Telliian sequence (Fig. 2), a unit of glauconitic sandstone about 120 m thick containing bryozoa, echinoderms (*Clypeaster*), and pectinids (Kujawski, 1969) is found. The orange to olive-green unit is poorly (CaCO_3) cemented and contains well-rounded, coarse quartz clasts. The sandstone grades upward into a unit of indistinctly bedded tan marls, about 60 m thick. These clastic units are in part contemporaneous with the Numidian flysch complex (Burolet, 1975; Carr and Miller, 1979). Kujawski (1969) suggested that the units are of early Miocene age and rest with angular unconformity on older units. Although bedding is rarely distinct, where present in the study area (Hennchir en Nemra), there is no evidence of angular discordance with older units. Moreover, Carr and Miller (1979) report that these units are in normal stratigraphic sequence above the Souar shale in the Mogods region to the north. The time span covered by the disconformity is from late Eocene to Oligocene, and the southern Hédil was thus probably emergent during this time.

Miocene-Pliocene Molasse

The youngest rocks exposed are continental units and include coarse conglomerates and gray, black, and red sandy shales (Fig. 2).

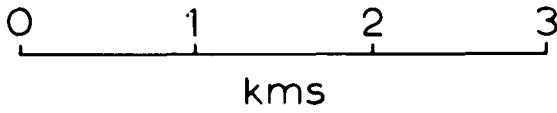
The conglomerate contains a Messinian fauna (Kujawski, 1969, p. 182–188). At the Semène mine (Fig. 3, loc. 10), the lower conglomerate and upper shale units attain thicknesses of 30 and 150 m, respectively. These units are in fault contact with both the Abiod Formation to the south and the Triassic breccias to the north. DeJong (1975) proposed, however, that these Triassic units are intrusive into younger units, on the basis of suggested variable attitudes of the contact. Throughout the study area, the contact dips consistently northwest with moderate to steep inclination, yet nowhere along it are younger units overturned. In the absence of this overturning — which would be likely with such later piercement structures — we conclude that Triassic rocks are not intrusive into younger units.

STRUCTURES

Box Folds

Upper Cretaceous and younger rock units are folded into three major southwest-trending anticlines, northwest to southeast, the Djebel Tiour el Lil-Antra (Fig. 3, locs. 7 and 8), Djebel el Hara-Hassane (Fig. 3, locs. 4 and 9) and Kef el Kattous—Ae Soula (Fig. 3, locs. 3 and 11) anticlines. These structures lie within the structurally lowest “Nummulitic Eocene Nappe” of Caire and others (1971). The folds plunge gently both to the northeast and southwest and are characterized by southeast-vergent and upright, box to close fold styles. The two northern anticlines are separated by a broad, flat-troughed syncline, the Hennchir en Nemra syncline (Fig. 3, locs. 5 and 6). Regionally, large-scale anticlinal culminations and depressions result in basinal configurations for the intervening synclines.

The overturning of units on both limbs of the Djebel Tiour el Lil-Antra anticline and on the northwest limb of the Kef el Kattous—Ae Soula anticline is demonstrated in pre-fault restorations (Fig. 5) of structural cross sections (Fig. 4). These overturned limbs are separated from upright units by sub-vertical normal faults with as much as 700 m of displacement. Stereonet diagrams of poles to bedding (S_0) for each of these folds show similarity in attitudes for derived fold axes (π) (Fig. 6). A change in direction of



EXPLANATION

MESOZOIC	TRIASSIC		\overline{R}_{db}	unnamed Triassic rocks	
			\overline{R}_g	dolomite breccia	
			\overline{R}_m	greenstone marls	
	CRETACEOUS	Upper	Campan, Maestrict	Ka_c	chalky limestone
				Ka_m	marly limestone
				Ka_u	limestone, undifferentiated
		Paleocene		KT_{eh}	El Haria Fm. undifferentiated
			Lower Eocene	L. Lutetian	Tm_n
	Tm_u	marly limestone undifferentiated			
	TERTIARY	Lower Miocene	Burdigal.	Tlm_m	unnamed L. Miocene rocks marl
Tlm_g				glaucouitic sandstone	
Mio-Pliocene		Pontian	Tmp_m	unnamed Mio-Pliocene rocks marl	
			Tmp_c	conglomerate	
QUATERNARY			Qal	alluvium	

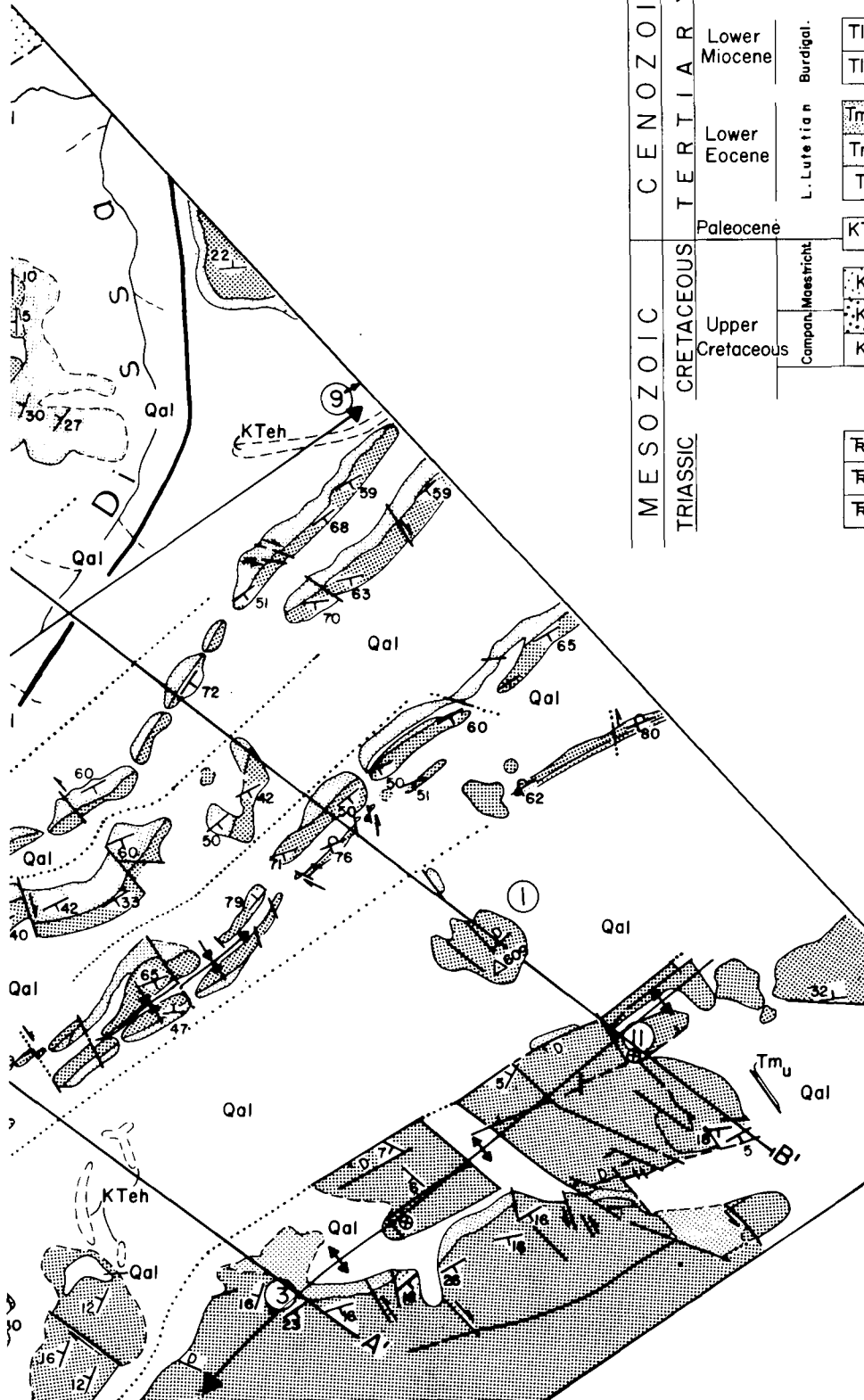


Figure 3. Geological map of study area in southern Hédil. Circled numbers refer to locations mentioned in text: 1 = Djebel Tahent; 2 = Ae es Sottara; 3 = Kef el Kattous; 4 = Djebel el Hara; 5 = Hennchir en Nemra; 6 = Hennchir Gandouza; 7 = Djebel Tiour el Lil; 8 = Djebel Antra; 9 = Djebel Hassane; 10 = Semène; 11 = Ae Soula.

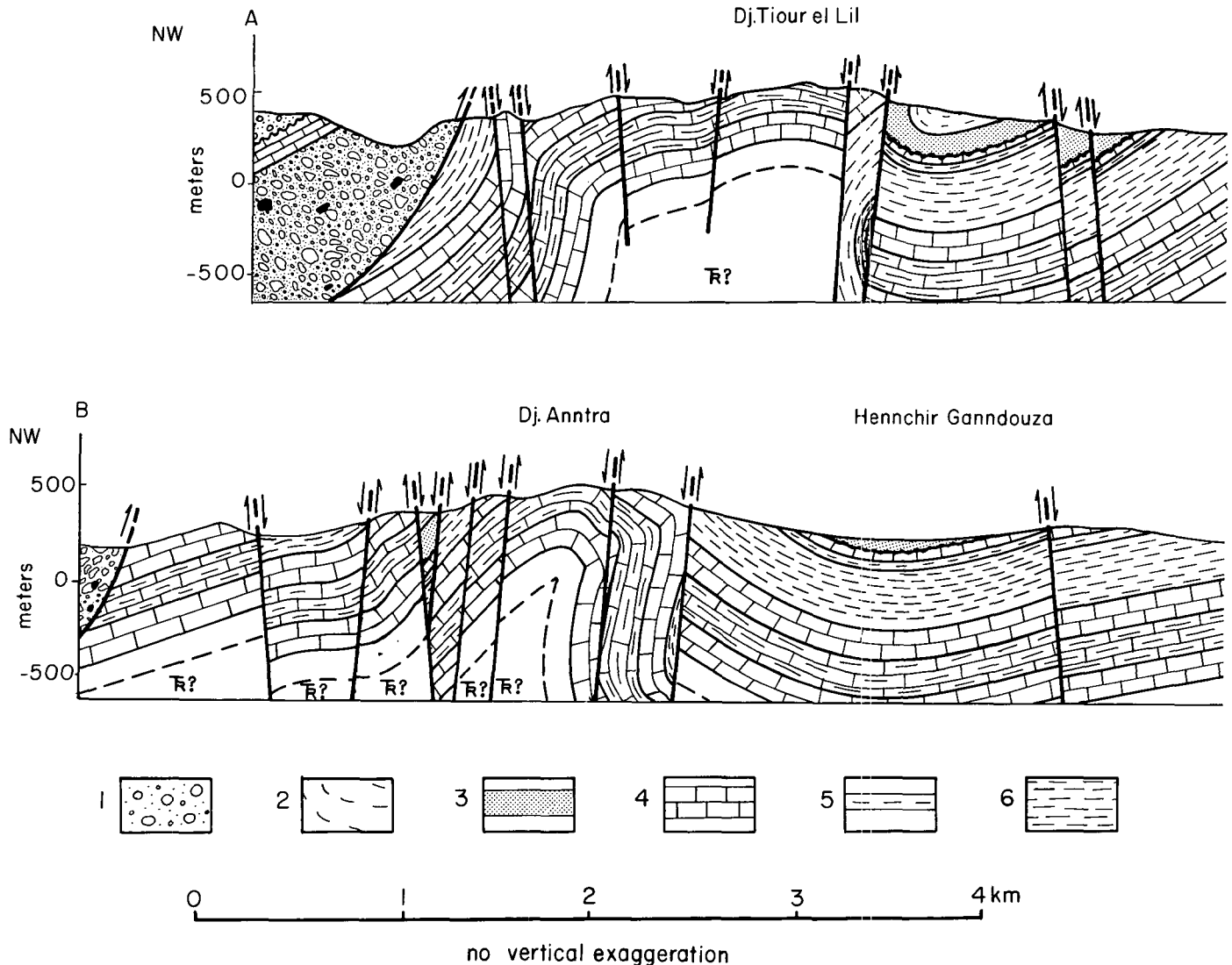


Figure 4. Structural cross sections from Figure 3. A-A' = section between Djebel Tiour el Lil-Kef el Kattous; B-B' = section between Djebel Antra-Tahent. Legend (refer to Fig. 3 for abbreviations): 1 = Tmp_c ; 2 = Tmp_m ; 3 = Tlm_u ; 4 = Tm_n ; 5 = Tm_m ; 6 = KT_{eh} ; 7 = Ka_c ; 8 = Ka_m ; 9 = Ka_u ; 10 = Aleg Fm.; 11 = Tr_{db} containing Tr_u /inferred Triassic at depth.

plunge, reflecting a northwest-southeast-trending culmination of the folds, is seen along a line between Djebel Tiour el Lil and Kef el Kattous (Fig. 3). Northeast of this line, folds plunge northeast (Fig. 6, A through D); the same folds plunge southwest on the southwest of this culmination (Fig. 6E). Fold trends strike within 12° of one another and plunge within 10° of the horizontal.

Faults

Three fault sets cut the folds: (1) longitudinal and (2) transverse faults, respectively striking parallel and orthogonal to regional structural grain, and (3) conjugate, oblique faults with transverse faults as their acute bisector. The longitudinal and transverse sets represent sub-vertical normal faults with mean attitudes of $N64^\circ E$,

90° and $N40^\circ W$, $80^\circ SW$, respectively (Fig. 7A). They thus represent two approximately orthogonal symmetry planes of the major folds. Magnitudes of displacement along these sets generally range from 100 to 500 m. The oblique set represents mutually crosscutting, conjugate shear faults with mean attitudes of $N54^\circ W$, 90° (right-lateral) and $N12^\circ W$, 90° (left-lateral) (Fig. 7B). Magnitudes of offset are as much as 100 m. Longitudinal faults cut both transverse and oblique faults.

A plot of slickenside lineation rake against fault strike (Fig. 7C) demonstrates a relationship between fault attitude and nature of movement. The means of two high-rake ($>30^\circ$) slickenside clusters strike about $N41^\circ W$ and $N45^\circ E$. These attitudes correspond closely with transverse and longitudinal fault sets, respectively, as shown in Figure 7A. The 19° disparity between the determined strikes for

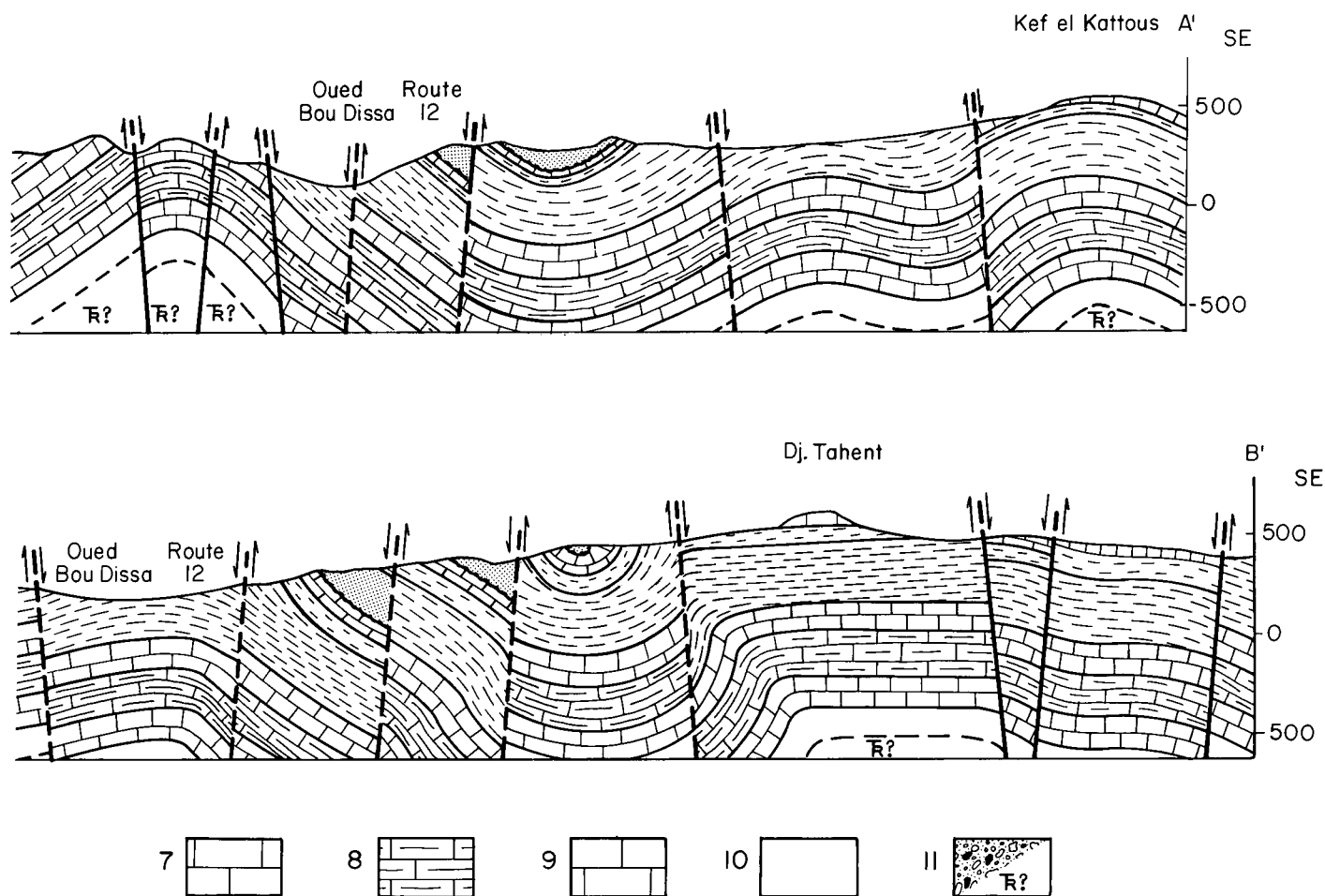


Figure 4. (Continued).

longitudinal faults is perhaps due to a data measurement bias in that some of the faults plotted in Figure 7A had no measurable slickenlines and could not be plotted in Figure 7C.

Intermediate between the two high-rake peaks of Figure 7C are two low-rake ($\leq 30^\circ$) valleys, the means of which are about $N08^\circ W$ and $N68^\circ W$. These attitudes correspond to those for conjugate shear faults (Fig. 7B). The 14° difference between right-shears in Figures 8B and 8C also probably relates to data measurement bias.

The acute angle between the shears in Figure 7B is 42° ; in Figure 7C, it is 60° . This suggests that a value closer to that expected from brittle shear failure (Friedman, 1964, p. 471; Billings, 1972, p. 162) is obtained where both fault and slickeline attitudes are measured. The trend of the acute bisector for the shears in Figure 7B is $S33^\circ E$ as compared with $S38^\circ E$ in Figure 7C.

“Unité de Hédil”

Triassic dolomite and gypsum breccias, resting with fault contact on younger units immediately south of Oued Begrat (Fig. 3), evidence a minor, late thrusting episode. A foliation subparallel to the fault is present in the gypsum breccias; it is manifest as a schistosity and/or compositional layering. A streaking lineation, defined by the

alignment of gypsum crystals which generally plunge downdip of the schistosity, is also locally present. The fault contact has variable trace due to erosion but generally trends northeast with moderate to steep northwest dip.

DISCUSSION

Dynamics of Deformation

Restored (pre-normal fault) structure sections (Fig. 5) illustrate fold form prior to longitudinal faulting (assuming no volume change). The geometries of these constructions strongly suggest that Triassic evaporites, underlying the section at depth, acted as a detachment horizon during fold genesis. This is particularly evident in the cases of the Djebel Tiour el Lil-Anntra and Kef el Kattous–Ae Soula anticlines where an inverted tear-drop shape at depth, manifest at the surface by large-scale box folds, is inferred. We suggest that during detachment at the level of Triassic evaporites, buckling of the Tellian cover sequence occurred. As folding progressed, evaporitic material flowed into anticlinal cores, causing constriction and overturning of units at depth (see Djebel Tiour el Lil, Fig. 5A). This arrested further folding during deformation.

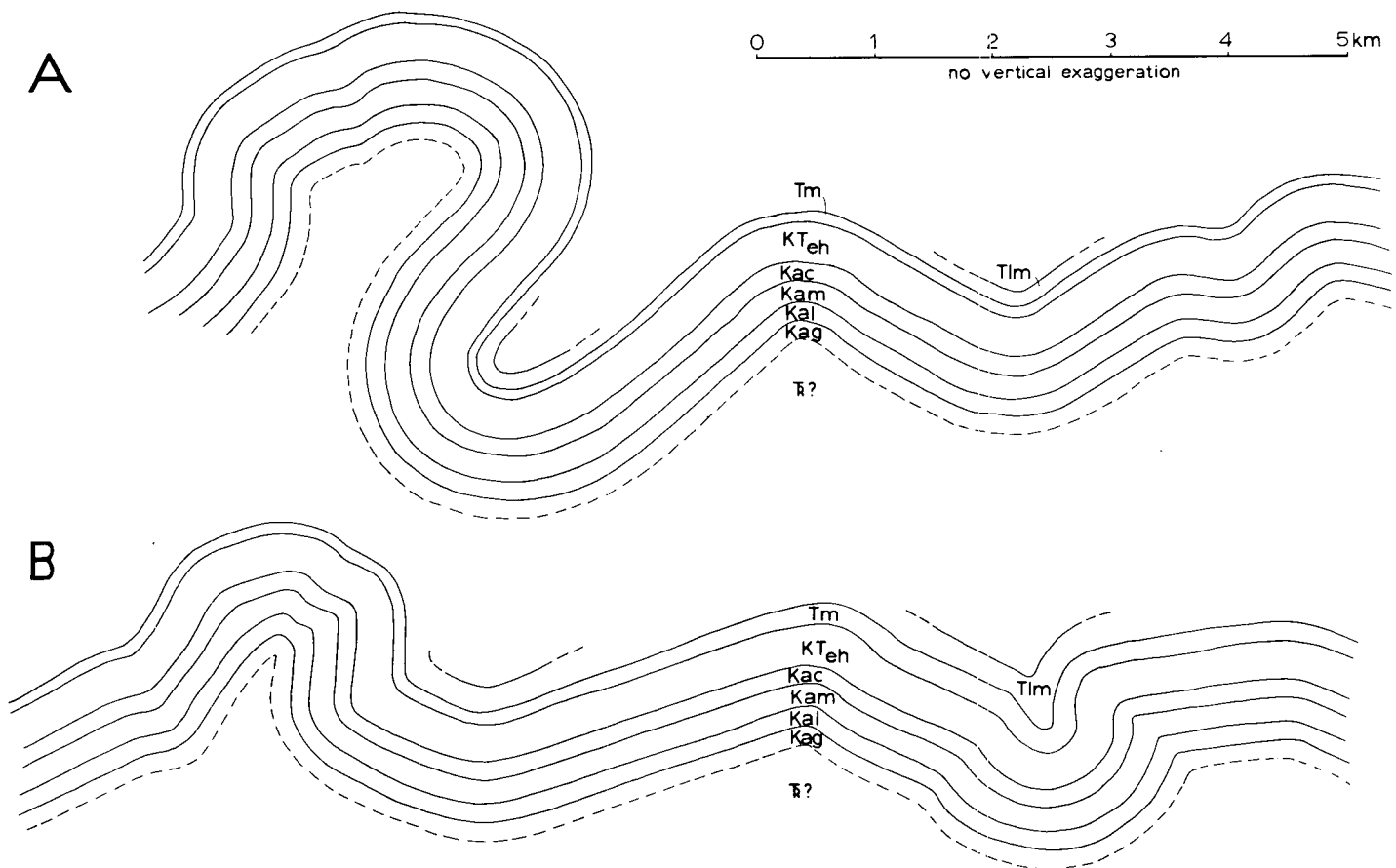


Figure 5. Restored sections of structure sections from Figure 3. Units on either side of longitudinal faults have been physically restored to their pre-fault positions assuming no volume change. A. Section between Djebel Tiour el Lil-Kef el Kattous; B. Section between Djebel Antra-Ae Soula. Note intimate relations between fold development, degree of overturning on some limbs, and inferred Triassic evaporite cores.

Continued stress activated an alternative deformation mechanism (conjugate shear faults) once applied stress could no longer be relieved by buckle folding. This was probably achieved by a 90° rotation of the σ_2 and σ_3 axes about σ_1 (Cohen and Schamel, 1979), perhaps through loading (Tapponnier and Molnar, 1976). Because (1) the acute bisector of oblique shears is orthogonal to fold trends, (2) the shears cut the folds, (3) the determined acute angle is of the order expected for brittle shear failure, and (4) folds verge to the southeast, we suggest that folds and shear faults represent continuous, progressive deformation in response to a horizontal maximum principal compressive stress (σ_1) directed S38°E. The transverse normal faults which bisect the conjugate shears are interpreted as extensional faults related to the same stress that produced the shears' faults and folds (Friedman, 1964, p. 471). The transverse faults strike parallel to the inferred σ_1 . Longitudinal faults postdate the earlier structures and are interpreted as relaxational faults. Similar fault-fold relations are described elsewhere by Melton (1929), Bonham (1957), Friedman (1964), and Billings (1972).

Solignac (1927), Kujawski (1969), and Caire and others (1971) interpreted the southern Hédil as imbricate thrust slices of the Telliian sequence (Fig. 8B). The *apparently random* orientations of

Metlaoui limestone in the area led DeJong (1975), however, to suggest gravity gliding of this lower Eocene formation on the El Haria shale (Fig. 8A) as an explanation of the area's structures. Our analysis has shown, however, that neither of these mechanisms is required to explain the structure of this part of the Atlas. The southern Hédil may thus be a more external portion of the Atlas than previously recognized.

Timing of Deformation

Because progressive deformation (folding and shear faulting) in the "Unité des Écailles" affects units as young as early Miocene, this deformative phase must have postdated the Burdigalian (post 15 m.y. B.P.; Van Eysinga, 1975). Younger thrusting in the structurally overlying "Unité de Hédil" involves units as young as Messinian, indicating that renewed deformation was post-Messinian (post 5 m.y. B.P.). The timing for the progressive deformation in the study area is therefore bracketed as post-Burdigalian and pre-Messinian. This compressional event was followed by the development of longitudinal normal faults; these are thus younger than the post-Burdigalian deformation but older than the post-Messinian renewed thrusting. Because Miocene-Pliocene molasse

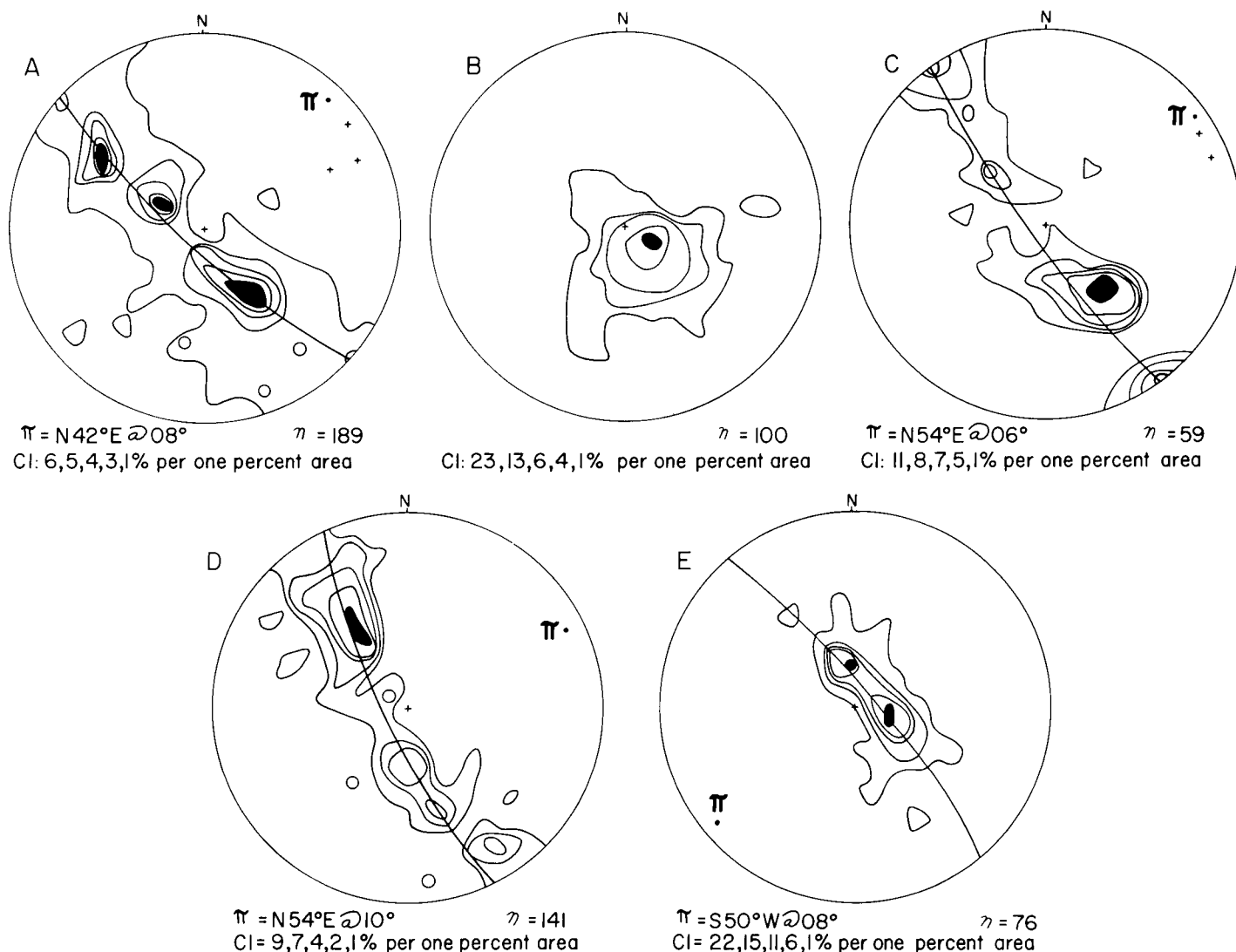


Figure 6. Lower hemisphere stereonet diagrams of poles to bedding (S_0) and derived (π) fold axes. A. Djebel Tiour el Lil-anntra anticline; B. Hennchir en Nemra syncline; C. Djebel el Hara anticline; D. nose and southern flank of Djebel Hassane; E. Ae es Sottara-Kef el Kattous anticline; see Figure 3 for locations. Crosses refer to measured fold axes; CI = contour interval; n = number of poles; π = derived fold axis.

was deposited unconformably after the progressive deformation, the normal faulting and molasse deposition are apparently coeval events. The original unconformable relationship between Messinian and older units is obscured at the surface by the fault contact between Abiod limestone and the molasse; it is known at depth, however, at the Semène mine (Kujawski, 1969). The younger, post-Messinian thrusting represents a compressional event that continues to the present (MacKenzie, 1970).

Regional Correlations

North of the study area, in the Mogods (Fig. 1), Biely and Rouvier (1970) found evidence that Miocene-Pliocene molasse was deposited following middle Miocene emplacement of the Numidian flysch complex. The molasse was later mildly folded during post-Messinian time. Carr and Miller (1979), in the westernmost

Mogods, and Rouvier (1977) and Glaçon and Rouvier (1972) in the Kroumerie, found evidence for a similar deformational history with: (1) middle Miocene (Langhian-Serravallian) emplacement of the Numidian flysch complex; (2) bimodal (basalt-rhyolite) volcanism, K/Ar dated at 10.4 to 6.6 m.y., associated with graben development and molasse deposition; and (3) renewed, minor post-Messinian thrusting. Thus, in the Hédil as well as farther north, a middle Miocene deformational event, with a southeast-directed maximum principal compressive stress, is followed by an extensional interlude and again by renewed, though minor, deformation.

PLATE-TECTONICS FRAMEWORK

Microplate rotations and marginal basin spreading systems (Alvarez and others, 1974; Boccaletti and Guazzone, 1974) form the bases for current dynamic models of post-Eocene western

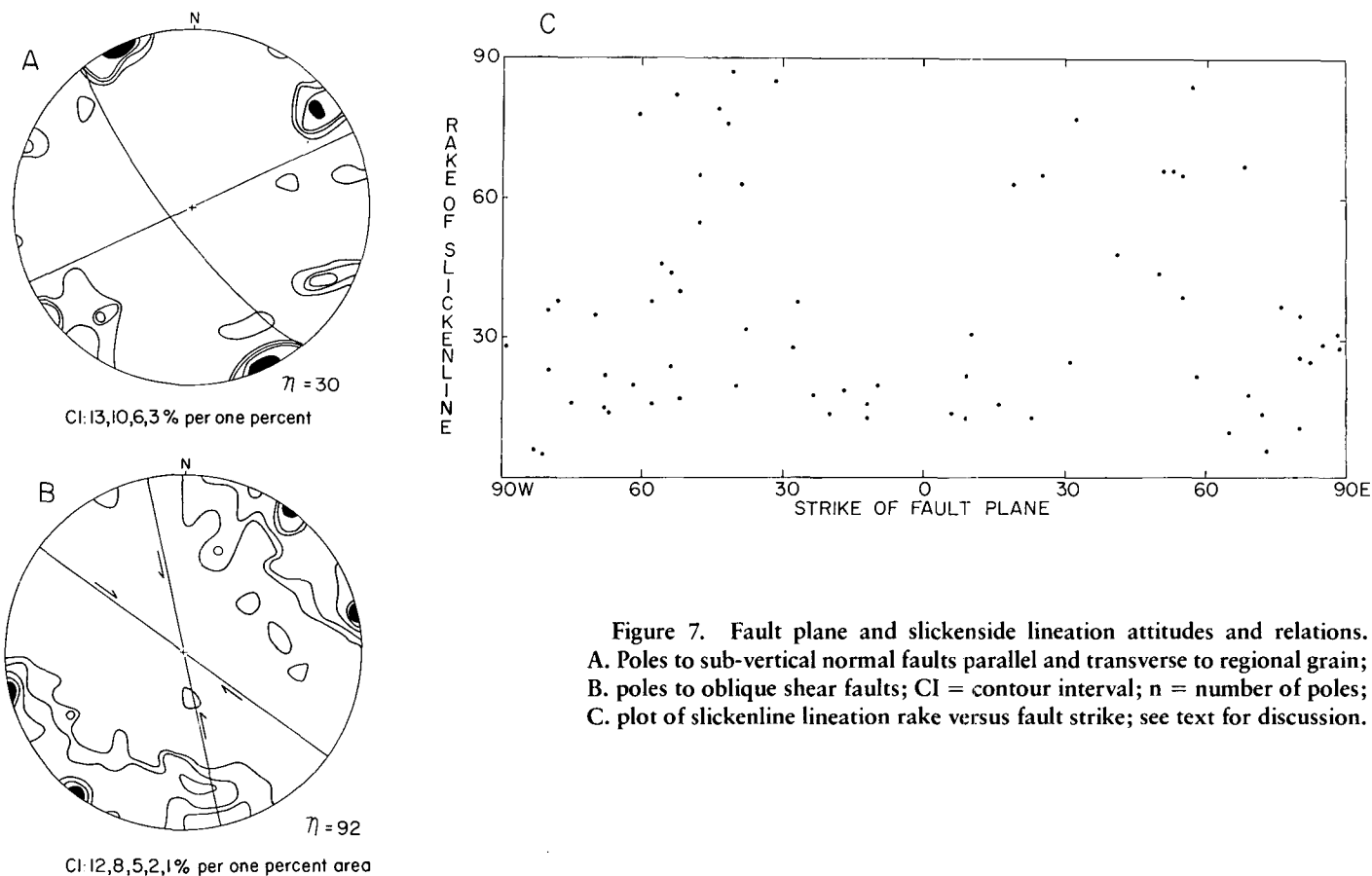


Figure 7. Fault plane and slickenside lineation attitudes and relations. A. Poles to sub-vertical normal faults parallel and transverse to regional grain; B. poles to oblique shear faults; CI = contour interval; n = number of poles; C. plot of slickenside lineation rake versus fault strike; see text for discussion.

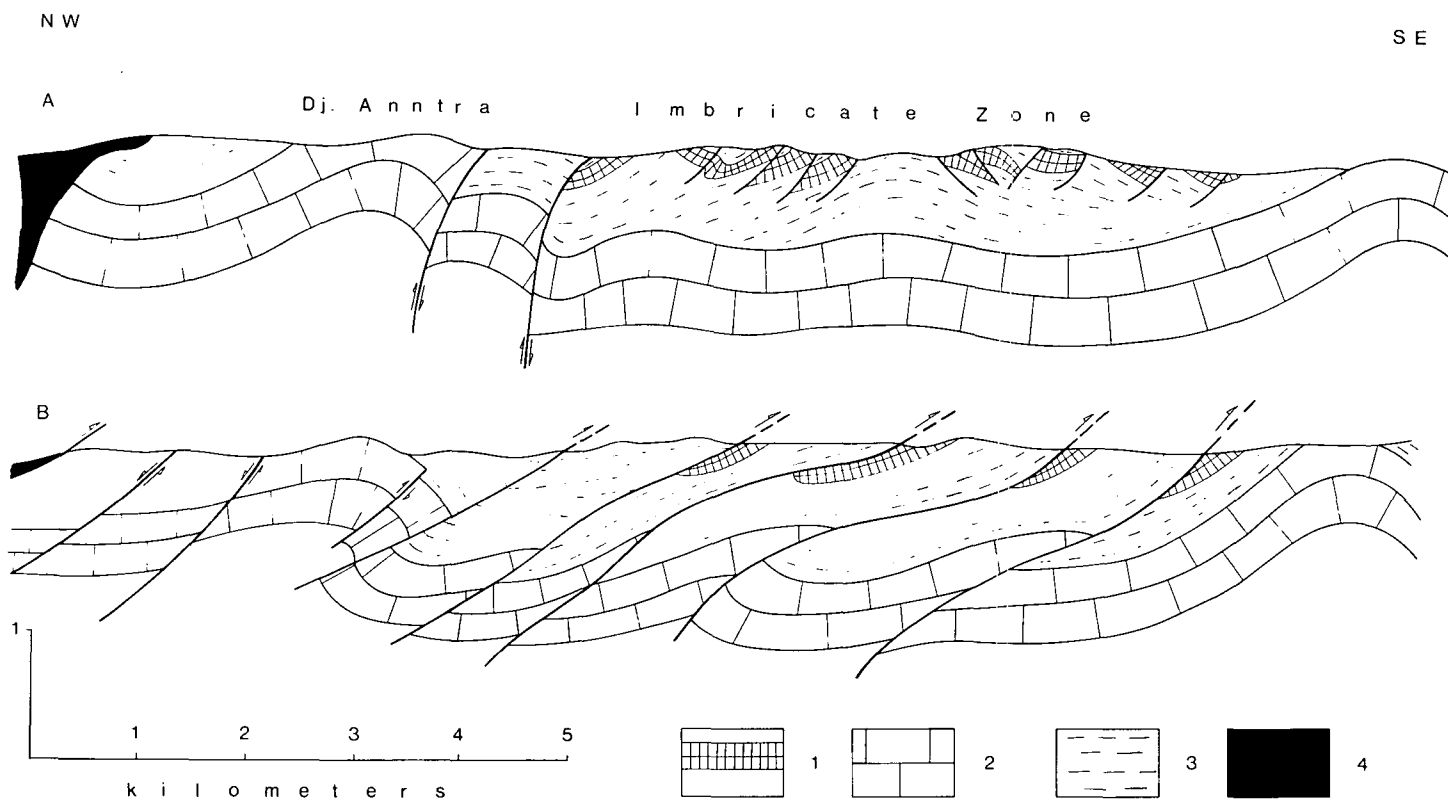


Figure 8. Structure sections of previous workers showing contrasting interpretations of the style of deformation in the southern Hédil. A. After DeJong (1975); B. after Caire and others (1971). Note inferred intrusive relations versus thrust relations of Triassic contact. 1 = lower Eocene Metlaoui limestone; 2 = Upper Cretaceous Abiod limestone; 3 = Cretaceous-Paleocene El Haria shale; 4 = Triassic evaporites.

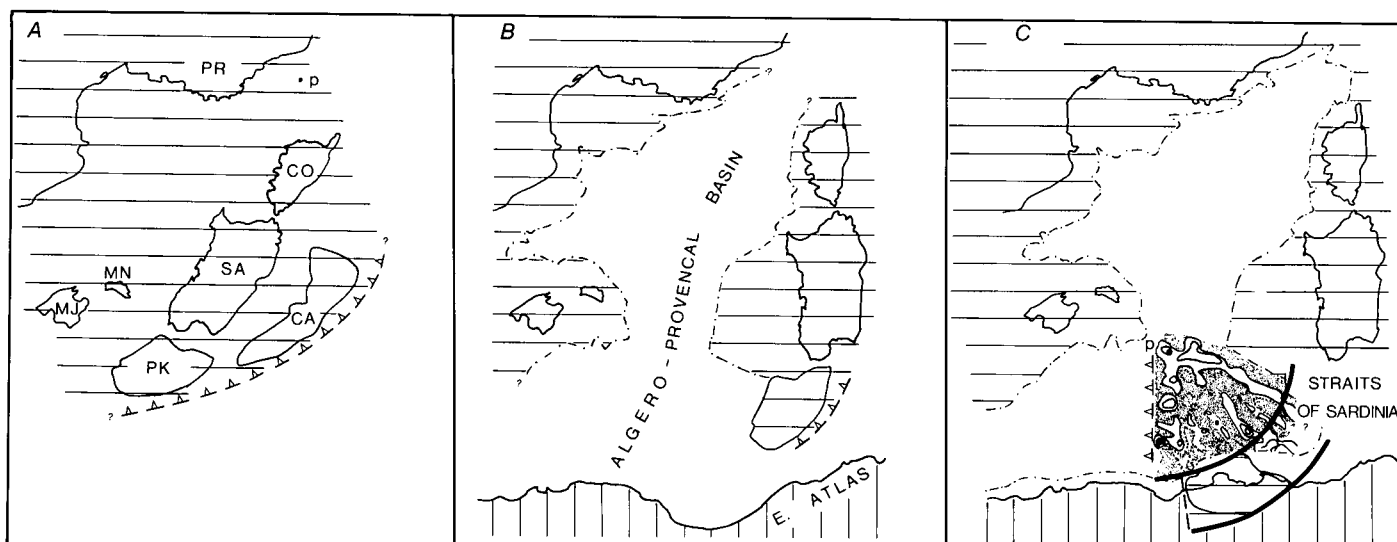


Figure 9. Plate-tectonic evolution of eastern Atlas. A. Late Oligocene-Aquitainian reconstruction of western Mediterranean region. Symbols: PR = Provence; CO = Corsica; SA = Sardinia; CA = Calabria; PK = the Petit Kabylie; MN = Menorca; MJ = Majorca; horizontal ruling = continental crust; teeth = trench axis. Volcanic arc terrane known in Sardinia and the Petit Kabylie is related to this south-facing trench; B. back-arc spreading during the Burdigalian (17 to 15 m.y., Bellon and others, 1977) results in the counterclockwise rotation of the Corsica-Sardinia-Petit Kabylie (-Calabria, not shown) plate away from Provence, forming the Algero-Provençal basin. Consumption of oceanic crust south of the plate's leading edge culminated in its collision with the continental margin of Tunisia and formation of the major, southeast-vergent fold-thrust structure of the eastern Atlas; C. sphenochasm spreading during the Tortonian (11 to 7 m.y. B.P.) results in an extensional environment in northern Tunisia (bimodal volcanism, normal faulting, and molasse deposition) and clockwise rotation of the Petit Kabylie away from Sardinia. This rotation occurred with left-lateral movement along the North Tunisian fracture zone (lower arc). The wedge-shaped area of the sphenochasm, in which alternating positive and negative magnetic anomalies converge on the point p (pole of sphenochasm), is covered by Messinian evaporites, indicating that spreading ceased by this time. The implication that the Petit Kabylie was emplaced in eastern Algeria during the Tortonian agrees with evidence from structural studies (see text for discussion).

Mediterranean tectonics. The early Miocene rotation of the Corsica-Sardinia microplate and associated opening of the Algero-Provençal basin are particularly well documented (Ryan and others, 1973; Alvarez and others, 1974; Cravatte and others, 1974; Bellon and others, 1977). Along the eastern, leading edge of the Corsica-Sardinia plate, consumption of oceanic crust was coeval with the formation of the Algero-Provençal basin. This occurred along a west-northwest-dipping subduction zone (Bellon and others, 1977; Carmignani and others, 1978) and resulted in middle Miocene deformation extending from the northern Apennines (Kligfield and others, 1977) through the eastern Atlas (Rouvier, 1977). It is the latter which is of interest here.

Alvarez and others (1974) proposed that Sardinia collided with the Tunisian continental margin after rotating through *two* successive 30° increments. The first rotation occurred during Aquitainian and the second during Burdigalian-Langhian time (Alvarez and others, 1974). It was the second rotational increment that is suggested to have caused the Miocene deformation in northern Tunisia (Alvarez and others, 1974). Bellon and others (1977), however, demonstrated that Sardinia rotated only through a single 30° increment in the Miocene, during the Burdigalian (17 to 15 m.y.). Moreover, there is a distinct gap between the continental margins of Sardinia and Tunisia, delineated by the 2,000-m isobath and by free air and Bouguer gravity anomalies (Morelli and others, 1975). We concur with Galdeano and Rossignol (1977), that the area west of the Straits of Sardinia is underlain by oceanic crust. It is thus

difficult to envision Sardinia colliding with Tunisia in the manner proposed by Alvarez and others (1974).

On the other hand, magnetic anomalies mapped by Bayer and others (1973) clearly describe a fan pattern of alternating positive and negative stripes in the area west of the Straits of Sardinia (Fig. 9C). The fan has its apex (pole) near $39^\circ 02' N$, $5^\circ 18' E$. Bayer and others (1973) interpreted the pattern as a fossil spreading system related to clockwise rotation of the Petit Kabylie away from Sardinia. Because the area of this sphenochasm is covered by Messinian evaporites (Auzende and others, 1974), spreading must have ceased by latest Messinian.

If the Petit Kabylie is rotated counterclockwise from its present-day position, along the North Tunisian fracture zone (Auzende and others, 1974), both the area of the sphenochasm and the present-day gap between Sardinia and Tunisia are nicely filled (Fig. 9B). This strongly suggests that it was the Petit Kabylie which was involved in middle Miocene collision with the Tunisian continental margin rather than Sardinia. Hence it was probably the Petit Kabylie, as part of the Corsica-Sardinia plate, which was involved in the formation of the eastern Atlas Mountains. This geometry explains middle Miocene south-vergent thrusting in the Petit Kabylie (Raoult and Velde, 1971; Raoult, 1975; Bouillin and others, 1977).

Following collision between the Corsica-Sardinia-Petit Kabylie microplate and the Tunisian continental margin, sphenochasm spreading moved the Petit Kabylie away from Sardinia. This prob-

ably occurred in the Tortonian (Fig. 9C). The extensional regime in northern Tunisia and compressional regime in eastern Algeria are both related to this Tortonian sphenochasm spreading.

CONCLUSIONS

Available data from the Petit Kabylie, the Tunisian Atlas, and the Straits of Sardinia support the two-stage regional framework outlined here. The middle Miocene phase of deformation in the Hédil, Mogods, and Kroumerie regions of Tunisia as well as in the Petit Kabylie immediately postdates opening of the Algero-Provençal basin during 17 to 15 m.y. B.P. (Bellon and others, 1977). During this opening, the Corsica-Sardinia-Petit Kabylie microplate rotated counterclockwise through 30°, the southern part of the plate (the present-day Petit Kabylie), colliding with the Tunisian continental margin. Following this middle Miocene collision, Tortonian sphenochasm spreading occurred in the area west of the Straits of Sardinia, displacing the Petit Kabylie to its present-day position in eastern Algeria. This phase of plate motion resulted in bimodal volcanism, graben development, and molasse deposition in northern Tunisia and in renewed deformation in the Petit Kabylie.

The model presented here implies that the second 30° counterclockwise rotational movement postulated by Alvarez and others (1974), during which opening of the Straits of Bonifaccio and deformation in northern Tunisia would have resulted, is unnecessary. A middle Cretaceous rotation of Sardinia, coupled with that of Iberia (Bayer and others, 1973; Cohen, 1979), is far more reasonable to explain both Sardinia's paleomagnetic and northern Tunisia's structural data.

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