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Beauchamp, W., 2004, Superposed folding resulting from inversion of a synrift accommodation zone, Atlas Mountains, Morocco, *in* K. R. McClay, ed., Thrust tectonics and hydrocarbon systems: AAPG Memoir 82, p. 635–646.

Superposed Folding Resulting from Inversion of a Synrift Accommodation Zone, Atlas Mountains, Morocco

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ABSTRACT

The conspicuous offset of the northern margin of the High Atlas Mountains is composed of several large superposed folds, one of which is known as the Ait Attab Syncline. The original northeast-trending syncline (F1) was folded by a second set of fold axes (F2) that trend to the northwest. The superposed folding was generated by one phase of compression, with thrusting of synrift rocks northwestward over a prior accommodation zone formed during rifting. This accommodation zone is expressed in the exposure of synrift rocks, the exposure of Paleozoic strata in the footwall, and a coincident offset of topography. Inversion was accomplished by the transport of synrift strata along reactivated normal faults and newly formed thrusts. The unique pattern of refolding is believed to be characteristic of inversion.

INTRODUCTION

2-D Models of Inversion

Many existing models of inversion are 2-D, accordion-style models that assume that both extension and subsequent compression are orthogonal to faulting. Rift systems characterized by long, straight faults bounding the rift system result from orthogonal extension (McClay and White, 1995). The inversion of rift systems where compression and extension are orthogonal produces structures that trend parallel to the preexisting rift structures.

However, many rift systems show patterns of en echelon normal faulting and segmented faults (McClay and White, 1995) that are the product of oblique extension during rifting. We can expect that compression relative to structures produced by oblique extension would produce structural geometries that are a result of 3-D strain. The study area in the High Atlas Mountains displays accommodation zones, en echelon normal faults, and pull-apart basins, indicating that extension was oblique during rifting. During inversion in the Tertiary, compression resulted in an unusual pattern of superposed folding that was influenced by preexisting extensional structural geometries.

Tectonic Setting of the Atlas Mountains

Tectonic inversion in the Atlas Mountains and elsewhere has shown that many intracontinental mountain belts are related to the uplift of preexisting intracontinental rift systems (Bally, 1984; Beauchamp et al., 1996). The High Atlas Mountains represent a major Mesozoic rift system (~2000 km in length) that was uplifted and inverted during the Cenozoic (Figure 1) (Beauchamp et al., 1996). The convergence of the African and Iberian plates in the Tertiary resulted in the inversion of Mesozoic synrift strata along preexisting synrift faults and also, by the transport of synrift strata, along newly formed low-angle thrusts.

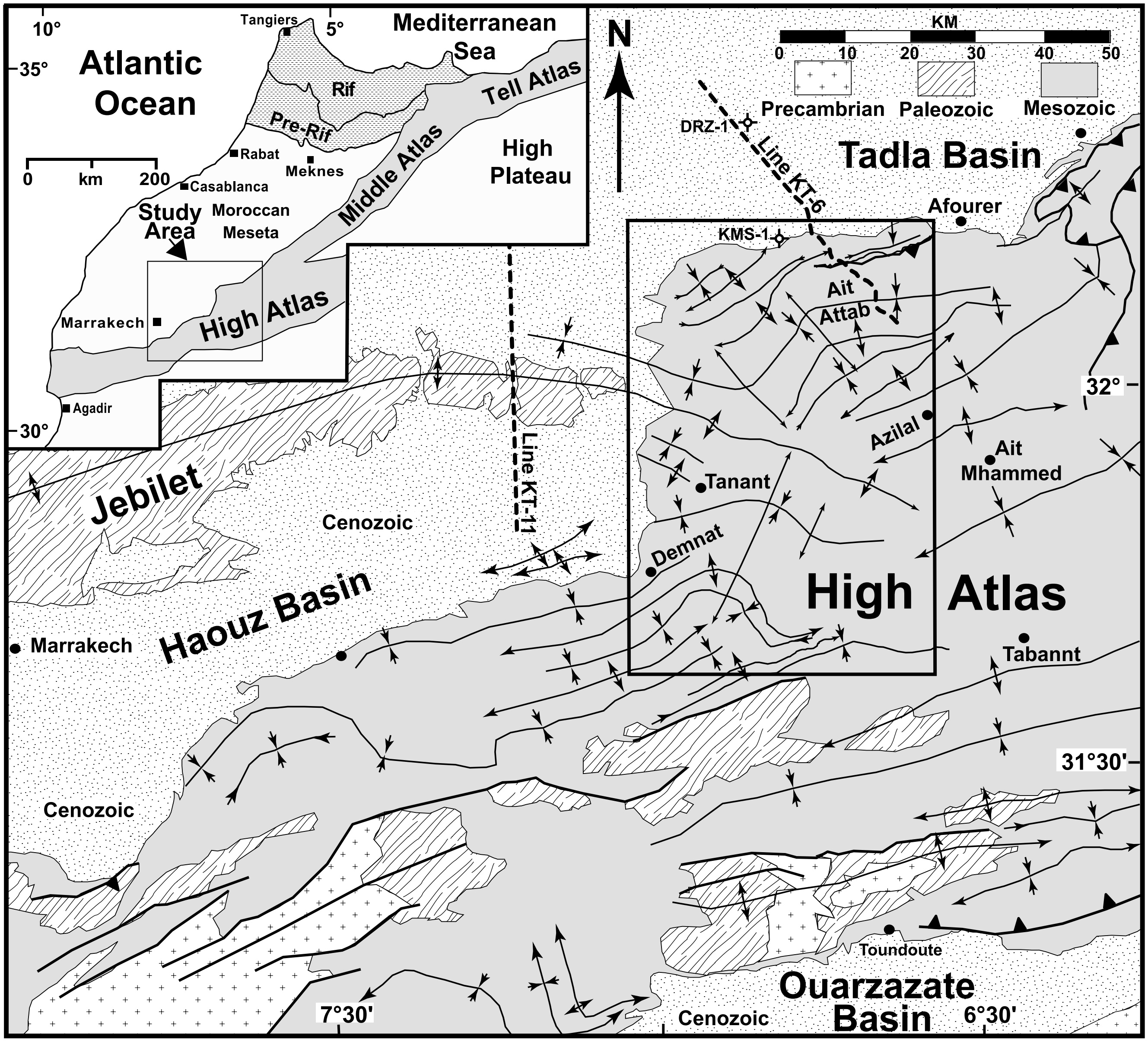


FIGURE 1. Location and simplified tectonic/structural map of the study area in the High Atlas Mountains, Morocco. Fold axes in the High Atlas are approximately parallel to the orogen and normal to the direction of thrusting, except where preexisting accommodation zones have influenced the regional stress field, resulting in polyphase deformation. Also, shown is the location of a more detailed geological map that displays superposed folding (Figure 3). Compiled from geological maps (Saadi et al., 1977; Rolley, 1978; Saadi et al., 1985; Jenny, 1988).

The Jebilet Accommodation Zone

The northern margin of the High Atlas Mountains contains a conspicuous offset (~90°) of the topography and exposure of the synrift Mesozoic rocks (Figure 1). Synrift strata thicken dramatically to the south and east, into the High Atlas Mountains. The present-day Tadla, Haouz, and Ouarzazate Basins were the shelf/platform margin areas of the paleo-Atlas rift (Figure 1). Synrift Jurassic-age strata are noticeably thinner or absent to the northwest in the Tadla and Haouz Basins (Jabour and Nakayama, 1988). Mesozoic strata are absent along the eastern margins of the Jebilet, where Paleozoic-age rocks crop out (Figure 1). Immediately to the south and east of the Haouz Basin and the exposed Paleozoic rocks of the Jebilet are 2–3 km of preserved synrift strata (Beauchamp et al., 1999). North of the Ait Attab Syncline (Figure 1), well data show that synrift Jurassic strata are absent and Triassic strata are condensed to a thickness

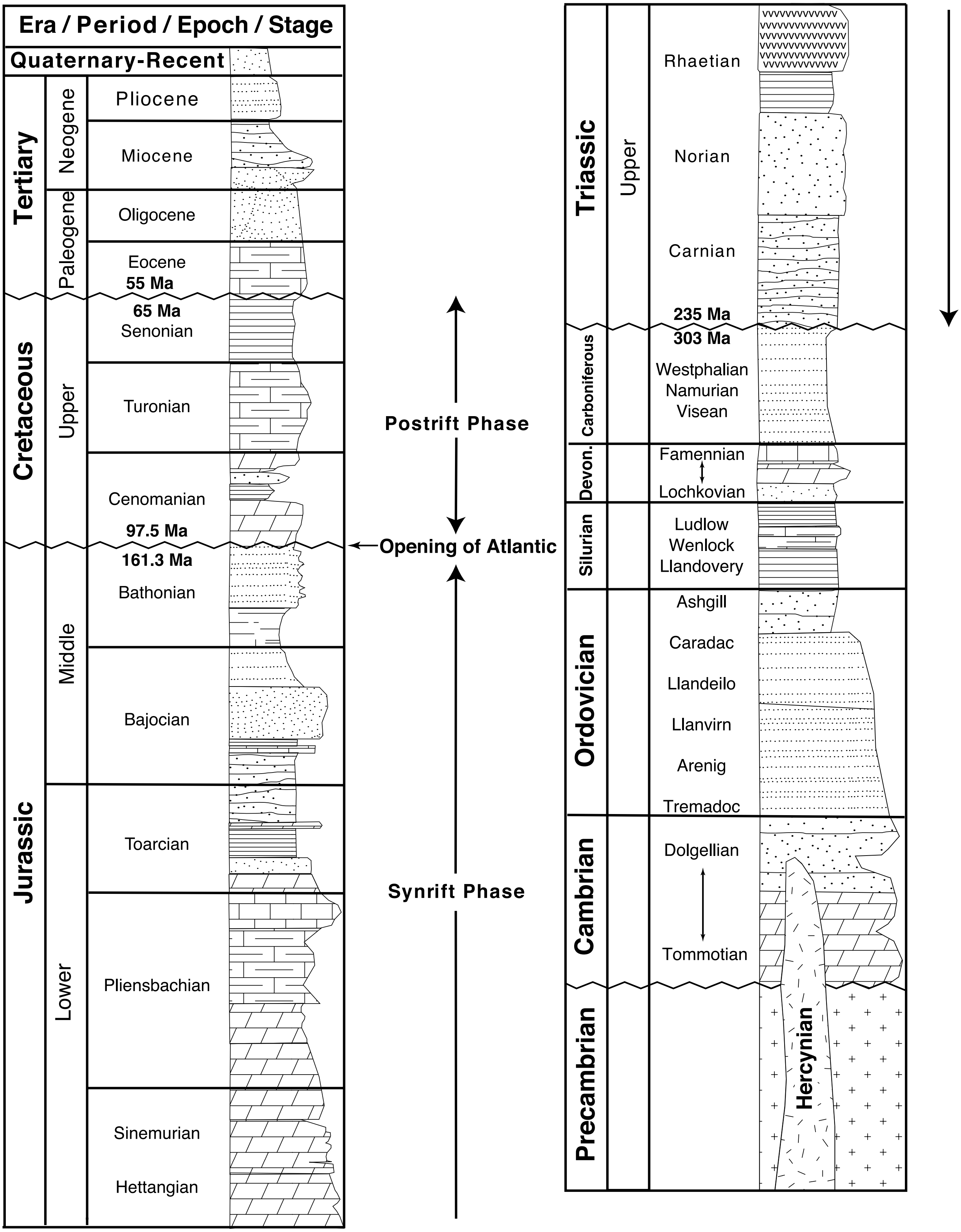


FIGURE 2. Generalized stratigraphic section of the High Atlas Mountains. Compiled from geological maps (Saadi et al., 1977; Rolley, 1978; Saadi et al., 1985; Jenny, 1988), measured sections (Rolley, 1978; Jabour and Nakayama, 1988; Jenny, 1988), and well data.

of less than 500 m (Jabour and Nakayama, 1988) (Figure 2). The Jebilet and topographic offset are related to a synrift accommodation zone. The accommodation zone affected the deposition of synrift strata during rifting, and later, it influenced the thrusting of synrift strata northward from the rift basin to the shelf margins. The geometry of this accommodation zone also controlled the thrusting and subsequent superposed folding (Figure 3).

The Jebilet extends eastward across the accommodation zone, where the anticlinorium plunges to the southeast (Figure 1). This anticline separates the Guettioua Syncline and the Ait Attab Syncline (Figure 3).

GEOPHYSICAL EVIDENCE OF AN ACCOMMODATION ZONE

The Paleozoic strata of the Jebilet are believed to be in the hanging wall of a thrust system that verges northward from the Atlas Mountains. This thrust may have formed as a footwall shortcut fault that transported Paleozoic rocks from the margin of the rift basin (Figure 4). Seismic line KT-11 extends across the Haouz Basin to the north across the Jebilet and onto the Moroccan Meseta. The condensed Mesozoic section found in the Haouz Basin was deposited on the margin of the rift basin. A thrust fault is interpreted that transports Paleozoic-age rocks in the hanging wall northward, to where they crop out in the Jebilet.

The Ait Attab Syncline is well imaged on seismic line KT-6 (Figures 1 and 5). The KMS-1 well north of the Ait Attab Syncline did not encounter rocks of Jurassic age, which indicates that the well was drilled on the rift-basin margin. Surface structural dips are in good agreement with those extracted from the seismic data, and a thrust is interpreted beneath the syncline. Thickening of the Middle and Lower Jurassic rocks across the syncline, from southeast to northwest, indicates that the synrift rocks were deposited in the hanging wall of an active normal fault that dipped southward into the paleo-Atlas rift basin. The synrift normal fault acted as a ramp during subsequent compression in the Tertiary, and the synrift rocks were transported northward along a footwall shortcut fault (Figure 6). This fault, interpreted on line KT-6 (Figure 5), is exposed east of the seismic line, where Jurassic-age rocks are thrust over rocks of Late Cretaceous age (Figure 3) (Beauchamp et al., 1999).

CENOZOIC REFOLDING PATTERNS

Ait Attab Area

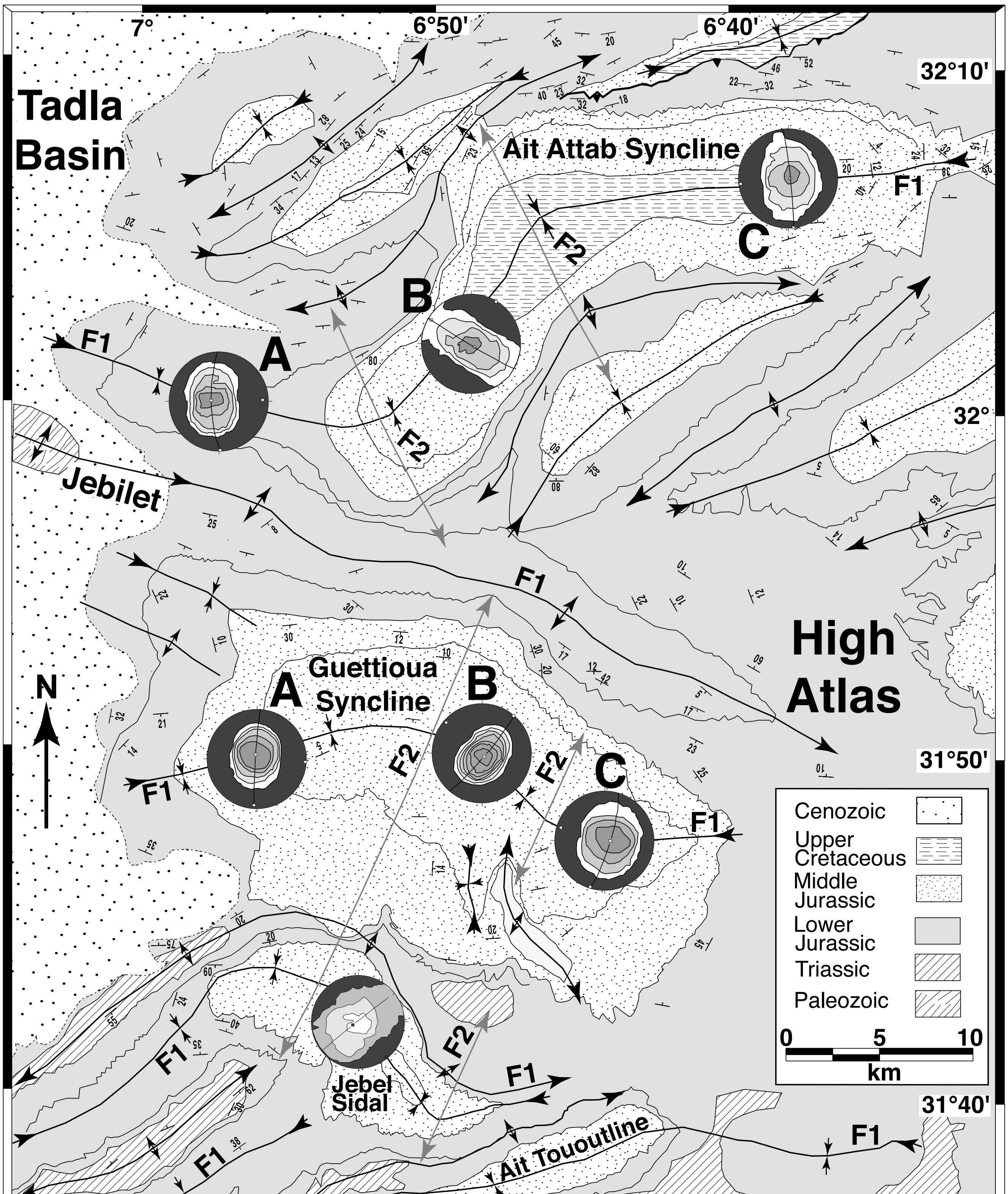
Prominent large-scale refolded folds bound the accommodation zone (Figures 1 and 3). Although superimposed folding is a common structural occurrence in orogenic belts, the timing and sequence of folding in the Atlas Mountains display a unique pattern of folding. Folds trend approximately parallel to the margins of the Atlas mountain belt (Figure 1) on either side of the accommodation zone, indicating that the direction of transport (thrusting) was normal to the orogen.

Folding within the accommodation zone (Figure 3) displays two phases of folding activity (F1 and F2). The Ait Attab Syncline demonstrates an early phase of folding (F1) that was oriented northeasterly and that was refolded by a later oblique inversion phase (F2) oriented north-northwesterly. The western end of the Ait Attab Syncline is parallel to the Jebilet Anticline (Figure 1).

Jebel Guettioua-Sidal Area

Farther to the south, the Guettioua Syncline displays an early phase of folding (F1) that was oriented northwesterly followed by a later phase of folding (F2) that was oriented to the north-northeast. The Jebel Sidal Syncline was folded first (F1) along a northeasterly trend and folded later by a second phase (F2) that was north-northeasterly. The sequence and timing of folding in the area of study (Figure 3) indicate that the first phase of folding (F1) seen in the Ait Attab and Jebel Sidal structures was oriented to the northeast. These fold axes (F1) are normal to the first phase of folding (F1) of the Guettioua structure (to the northwest). The orientation of the second phases of folding illustrates a similar discrepancy. The second phase of folding (F2) of the Ait Attab Syncline (Figure 3) is normal to the second phase (F2) of folding of the Guettioua and Jebel Sidal structures.

FIGURE 3. Detailed geological map of the accommodation zone along the northern margin of the High Atlas (see Figure 1 for location). The first phase of folding (F1) of the Ait Attab and Jebel Sidal structures is normal to the first phases of folding in the Guettioua structure. Likewise, the second phase of folding (F2) of the Ait Attab and Guettioua synclinal structures are also normal to one another. The sequence and orientation of folding necessitates that folding was influenced by a preexisting accommodation zone during tectonic inversion The map was compiled from fieldwork, Landsat-TM images, and geological maps (Huvelin, 1972; Saadi et al., 1985; Jenny, 1988). Stereoplots of poles to bedding show the dip domains of folding.


7°
6°50'
6°40'
32°10'
32°
31°50'
31°40'
Tadla Basin
Ait Attab Syncline
Jebilet
High Atlas
Guettioua Syncline
Jebel Sidal
Ait Touowaytline
A
B
C
F1
F2
N
Cenozoic
Upper Cretaceous
Middle Jurassic
Lower Jurassic
Triassic
Paleozoic
0 5 10
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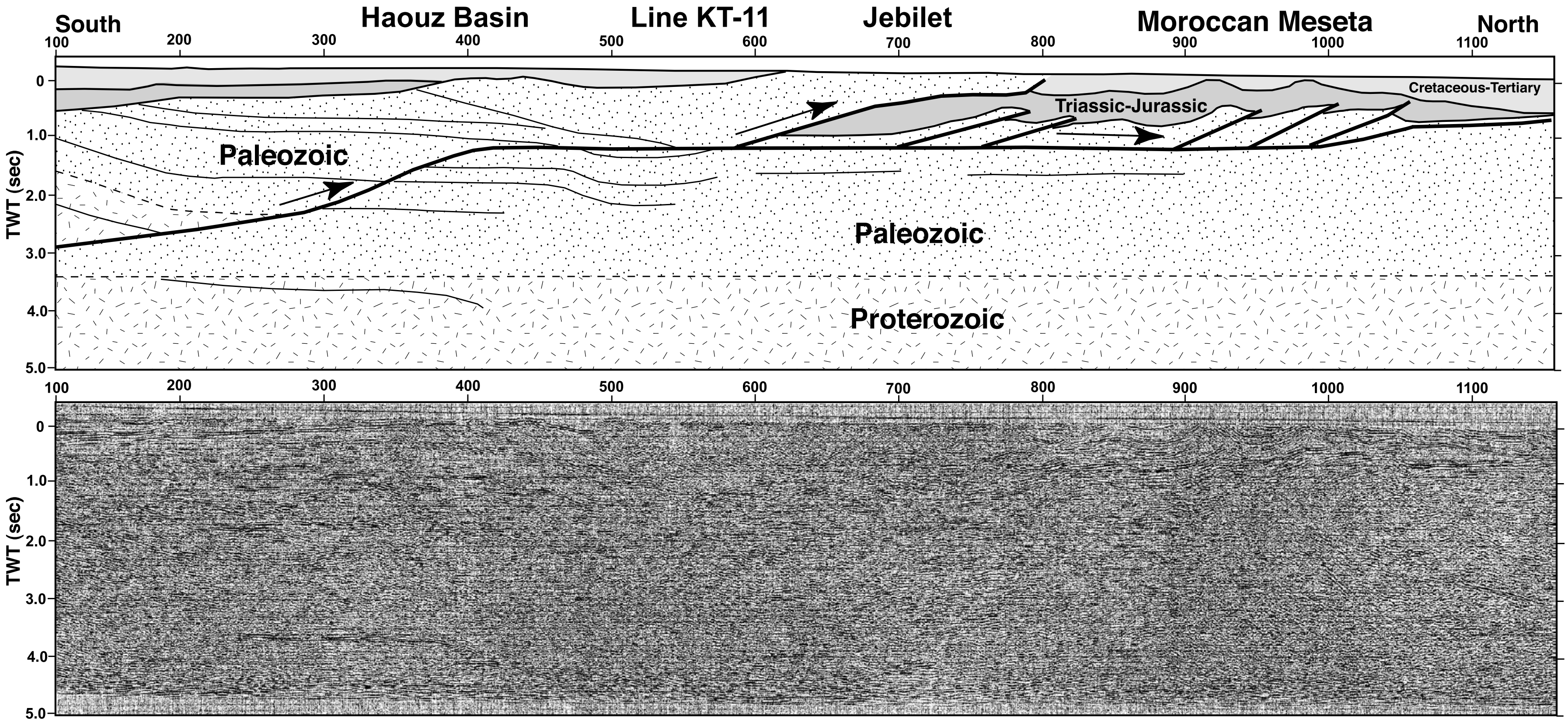

FIGURE 4. Seismic line KT-11 (see Figure 1 for location) extends northwards across the Haouz basin and the Paleozoic exposure in the Jebilet. Thin Mesozoic strata interpreted on part of this seismic line and in wells, indicate this region was on the margin of the rift basin. Shortening across the rift margin resulted in the transport of synrift rocks northwards up a preexisting normal fault, and then along a newly formed footwall short cut fault. Paleozoic rocks were transported to the north where they are exposed in the Jebilet.

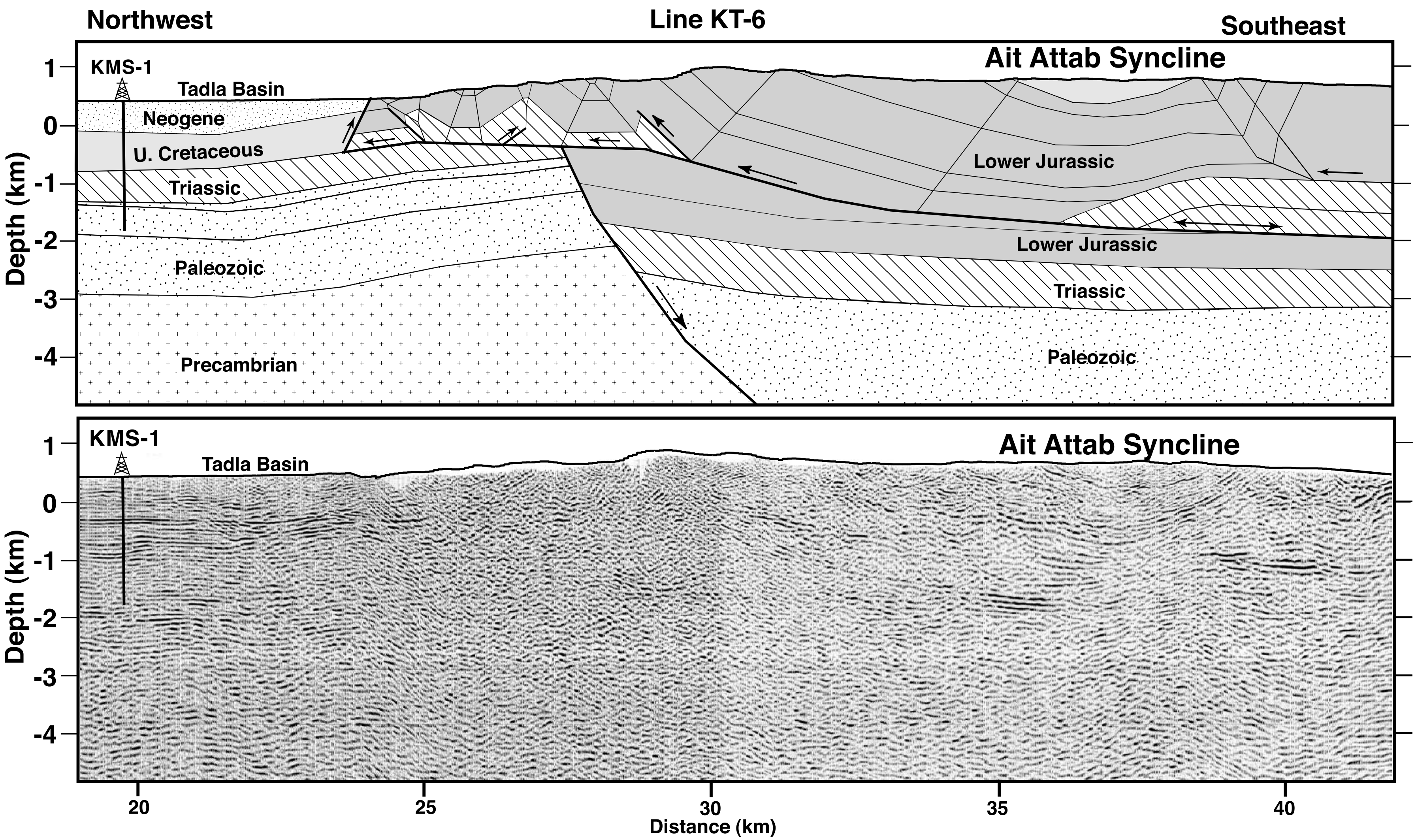

FIGURE 5. The southern part of seismic line KT-6 illustrates the absence of Jurassic age rocks in well KMS-1. Immediately to the south 2-3 km of Jurassic crops out in the Ait Attab Syncline (see Figures 1 and 3 for location). The Ait Attab Syncline shows a thickening of Jurassic age rocks northwards that are thought to have been deposited in a synrift half graben, and later thrust northward along a newly formed footwall shortcut fault similar to the fault interpreted on Figure 4.

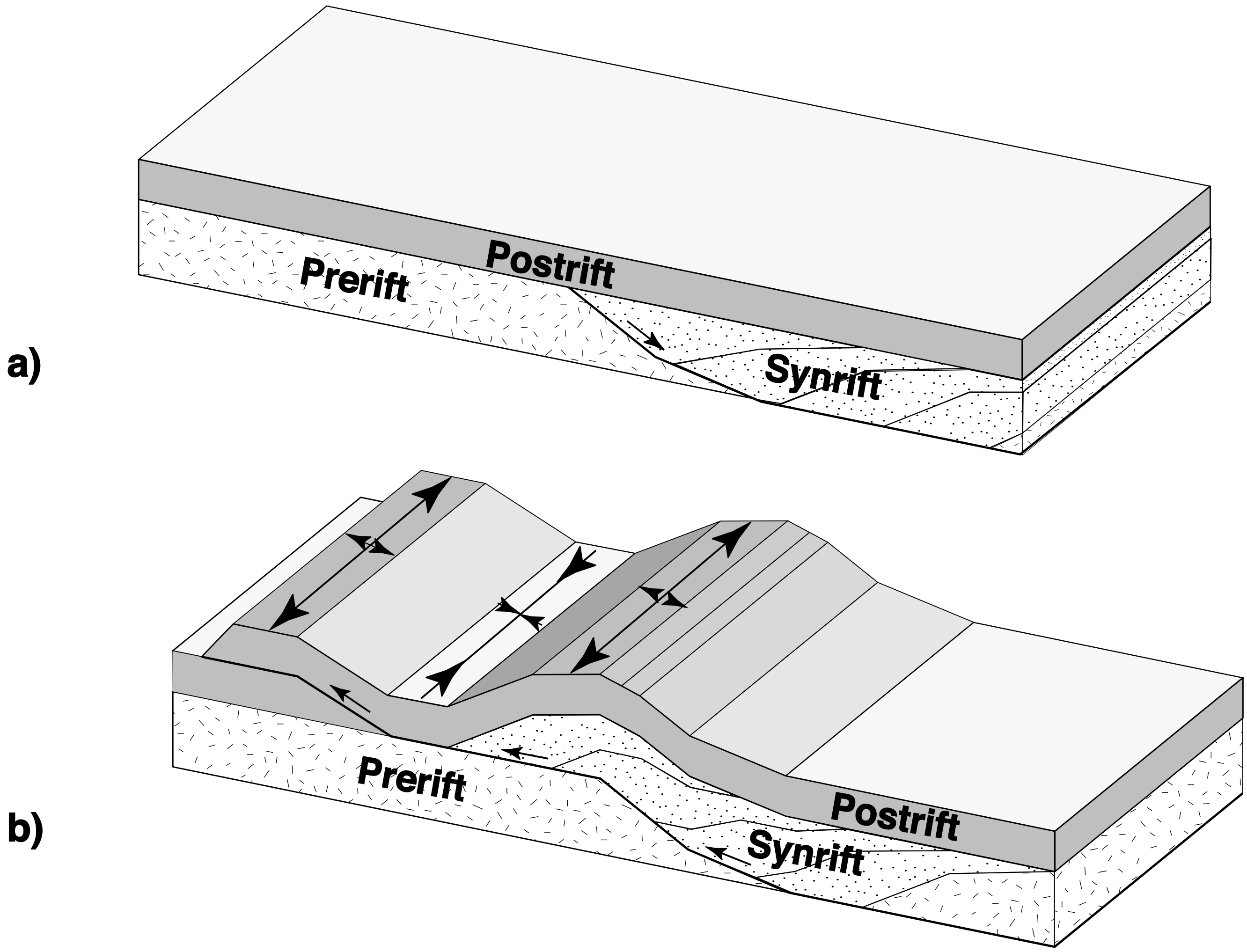

Figure 6. The shortening and inversion of the half graben may have occurred by the transport of strata from the hanging wall of the synrift half graben northward along low-angle thrust faults (a and b).

SUMMARY

Paradox of Different Orders of Superposition across the Accommodation Zone

The sequence of folding seen in the study area (Figure 3) implies that two separate, nonhomogeneous phases of deformation could not have generated the unique pattern of folding, without the presence of preexisting structural elements. Offsets in the basin margins result in 3-D strain across the accommodation zone. During compression and subsequent inversion across these accommodation zones, a 3-D strain is produced that is coupled to the preexisting accommodation zone. The structures formed by compression across these accommodation zones are caused by 3-D strain and result in unique refold patterns.

The Paleozoic exposure of the Jebilet Anticlinorium trends eastward and then plunges to the southeast (Figure 3). The expression of this anticline can be seen by the gentle dips in the Jurassic on both limbs of the fold. The trend of the Jebilet Anticline is not affected by the second phase of folding (F2) that refolds the Ait Attab and Guettioua Synclines. This unusual fold relationship was likely generated as a result of the fold forming parallel to the ramp of an accommodation zone, rather than forming over a preexisting normal fault.

Interpretation of the Structural Evolution of the Refolding Geometry: Accommodation Zone

Accommodation zones are common features of rift systems. The geometries of these extensional structures result from a change in strike of the rift-basin margin, produced by a ramp/relay fault system or transfer fault (McClay and White, 1995). The steplike accommodation of two parallel normal faults by a higher angle fault forming a ramp is a common feature in extensional rift basins (Rosendahl et al., 1986). En echelon normal faults have been found to form in rift systems when extension is oblique to the margin of the rift system (McClay and White, 1995). Transfer faults are also a common characteristic of extensional terrains and allow for the "transfer" of extensional slip between faults. These faults are analogous to lateral ramps in thrust tectonic terrains. Extensional transfer faults transport rotational strike and dip components during rifting, as do lateral ramps (Gibbs, 1984). These transfer faults occur as oblique or lateral accommodation zones and may involve a change in fault polarity. A transfer fault in cross section may have a high-angle flower geometry during rifting (Gibbs, 1987), in which case the fault may be normal to the basin margin, or it may be more oblique and involve a lower angle extensional ramp. Faults offset by these transfer faults can be parallel to the rift basin and have a planar, listric, or extensional fault-ramp geometry. The geometry of transfer faults often influences the development of younger folds upon inversion (Alonso, 1989). The transfer faults or ramps may be oblique or normal to the basin margin, and the orientation of the extensional/compressional ramp will result in differential movement in the hanging wall (in the sense of the transport direction) on the oblique ramp during inversion (Casas-Sainz, 1993).

Comparison with Other Studies of Refolding during Inversion

Superimposed folding is often associated with a change in the orientation of a regional stress field through time. Superimposed folds may occur by successive deformational events separated by long time intervals, multiple deformational phases in one orogenic cycle, continuous deformation in one orogenic cycle, and simultaneous folding from several directions in one orogenic phase (Ramsay and Huber, 1987).

The Cobar Basin of Australia is an inverted Paleozoic basin that exhibits superposed folding (Smith and Marshall, 1992). Superposed folding in the Cobar Basin is proposed to have occurred as a result of margin-normal shortening followed by progressive oblique deformational shear. The Davenport Province of Central Australia (Stewart, 1987) is another region where superposed folding of Proterozoic-age rocks resulted from two episodes of deformation that used preexisting synsedimentary normal and transfer faults that were reactivated in reverse and strike-slip senses, respectively. In this region, major sedimentary faults such as those associated with accommodation zones in a rift system, controlled the structural domains of each fold trend.

Steeply dipping faults offer greater resistance to reverse dip-slip movement during compression and may form buttresses where displacement is concentrated (Velasque et al., 1989). Folding can result from preexisting structures (e.g., folds, faults, or diapirs), which provide buttresses that concentrate strain. The geometry or configuration of preexisting structures will control or alter the stress field affecting folding. I propose that in the High Atlas Mountains, a single continuous phase of deformation across a preexisting structural feature, such as a extensional accommodation zone, resulted in the unique pattern of superposed folding. The sequence of superposed folding in the High Atlas Mountains of Morocco shows that these styles of folding are an important characteristic of inversion.

Exploration Potential

The unique style of folding found in the Atlas Mountains has useful applications for exploration in tectonic settings that involve the reactivation of structures created in previous tectonic phases. Unusual folding styles, such as those documented in the Ait Attab region of Morocco, may signal that significant shortening and tectonic burial could have placed potential source rocks in an active petroleum-generating setting. Hydrocarbon exploration may have been overlooked in Morocco because of the lack of well-developed foreland basins adjacent to the Atlas and Rif mountain belts. Source rocks that are immature on the paleomargins of the Atlas rift system and the present-day Moroccan Meseta may be in the oil window beneath thrust systems that have buried these rocks along the margins of the mountain belt.

DISCUSSION AND CONCLUSIONS

Laville (1981) attributed the superposed folding along the northern margin of the High Atlas Mountains to successive rotation of compressional phases, from the west-southwest–east-northeast to the north-northeast–south-southwest. Superposed folding in the eastern High Atlas Mountains was recognized by De Sitter (1960), and was attributed to separate tectonic phases and stress orientations.

However, we relate the unusual sequence and relationship of folding to preexisting structural control. Separate tectonic phases and stress orientations would have yielded a different pattern of folding than is found in this region of the High Atlas Mountains. Superposed folding resulting from two different stress orientations often yields two phases of folds (F1 and F2), each phase having parallel fold axes (Figure 7a and b). In the Atlas Mountains, as in the Davenport Province, oversteepened fold limbs (common in the Atlas) were probably caused by the second phase of folding. Both the examples from

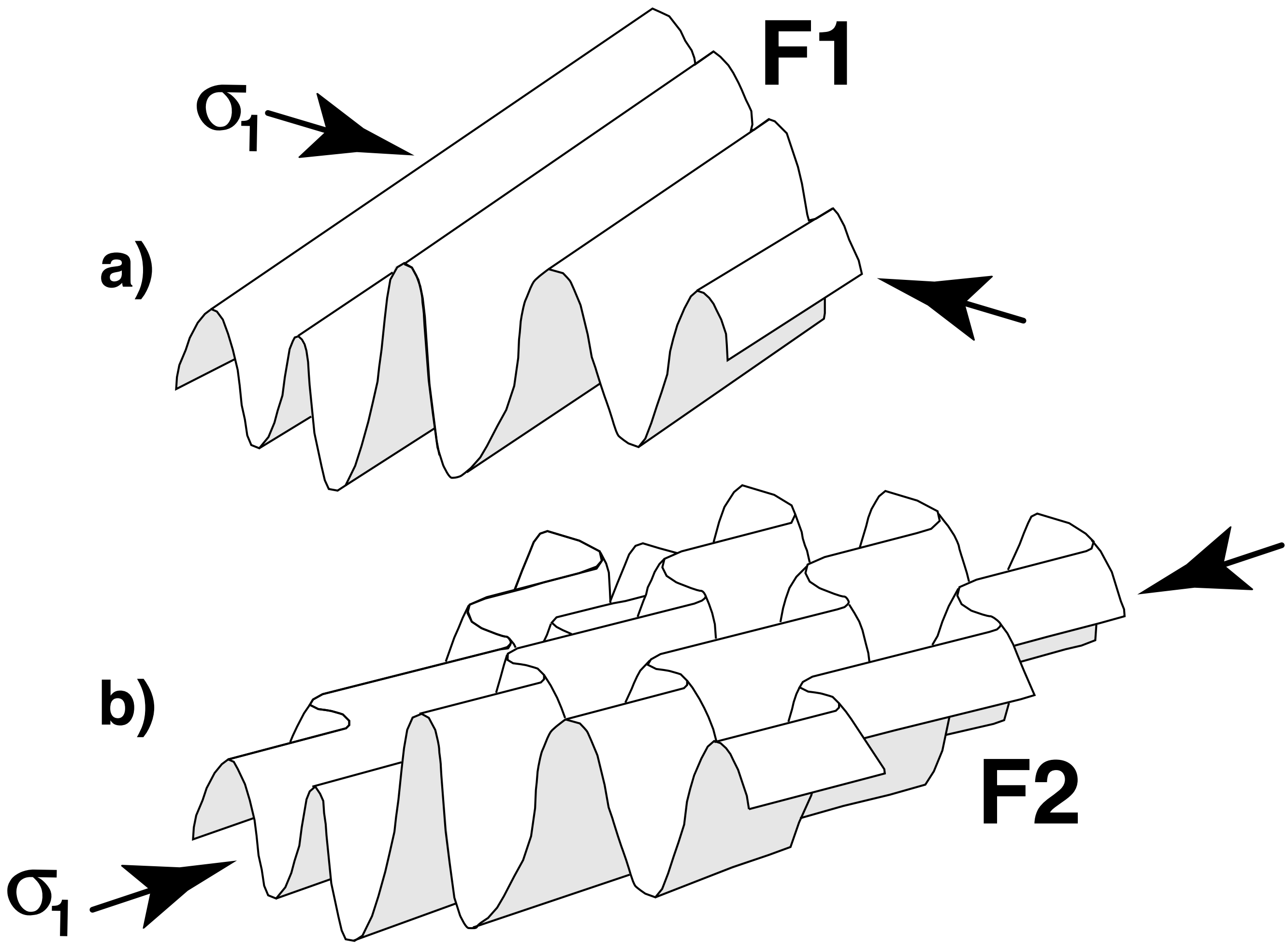

FIGURE 7. Schematic models show the formation of superimposed folding as a result of two different stress orientations (a and b). σ_1 = principal stress component; maximum principal stress.

Australia exhibit Type 1 and 2 interference patterns (Ramsay and Huber, 1987). The folding in the study area of the Atlas Mountains exhibits a Type 2 interference pattern (Ramsay and Huber, 1987), where the axial surfaces of the first folds are folded along with the limbs of the first folds. The superposed folding in the Atlas Mountains may have resulted from a synrift accommodation zone made up of a ramp/fault relay, or a transfer fault normal to the basin margin. This ramp transfers slip laterally between two major down-to-the-basin (southward-dipping) normal faults (Figure 8a). Folding in the area of this study yielded folds that are normal to one another in both phases (F1 and F2) (Figure 8b and c). Continued shortening across the accommodation zone may have created interference with the first F1 folds. The refolding of the F1 folds resulted in the F2 phase fold axes.

The presence of preexisting structural geometries, such as accommodation zones, fault ramps, fault relays, en echelon folding, and other features formed by rift processes, will have an effect on subsequent compressional stress fields generated by plate convergence and other tectonic processes. These structural geometries formed during rifting will affect the 3-D strain field, and that may result in superposed folding that is disharmonic. Superposed disharmonic folding may, in fact, be a unique characteristic of the inverted rift systems that result in intracontinental mountain belts.

ACKNOWLEDGMENTS

This study would not have been possible without the assistance of ONAREP (Office National de Recherches et d'Exploitations Petrolieres) and the Geological Survey of Morocco. Many thanks to my colleagues at Cornell that helped in this study and in the review of this manuscript. I would also like to thank Tarik Djebbar and C. Elders for their constructive review. Also, I would like to thank ARCO for assistance and expenses in the preparation of this manuscript.

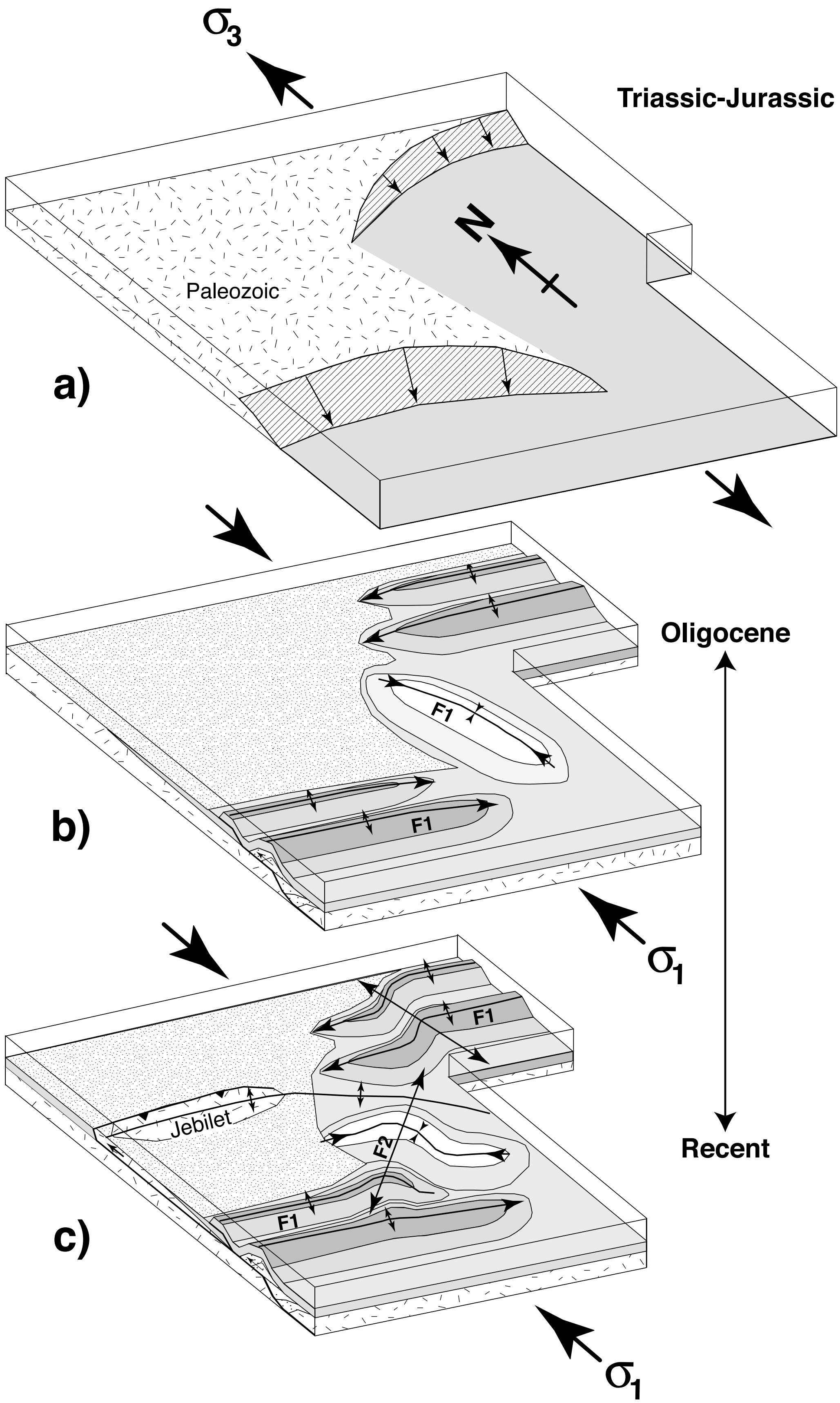

FIGURE 8. The inversion of a synrift accommodation zone (a) by margin-normal shortening created first folds (F1) that are oriented parallel to preexisting ramps and down-to-the-basin normal faults (b). Continued compression across the accommodation zone results in the interference of the first F1 folds and the formation of F2 folding (c). σ_1 = principal stress component; maximum principal stress.

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