Intracontinental Rifting and Inversion: Missour Basin and Atlas Mountains, Morocco[1]

Weldon Beauchamp,[2] Muawia Barazangi,[2] Ahmed Demnati,[3] and Mohamed El Alji[3]

ABSTRACT

The intracontinental High and Middle Atlas mountain belts in Morocco intersect to form the southern and western margins of the Missour basin, an intermontane basin formed as a result of the uplift and inversion of the Mesozoic Atlas paleorifts. These rifts were areas where the crust was greatly attenuated and more subject to deformation in response to nearby plate boundary tectonics. Data from observations based on seismic reflection profiles and wells over the Missour basin for hydrocarbon exploration and field mapping were used to understand the basin evolution, structural styles, and inversion timing of the nearby Atlas Mountains. Hercynian and Mesozoic normal faults were reactivated into high-angle reverse and thrust faults in the Mesozoic during the Jurassic, Early Cretaceous (early Alpine phase), and the Paleogene (late Alpine phase). The reactivation of synrift normal faults of the paleo-Atlas rifts inverted previous half grabens into anticlinal structures, with the axis of the half graben centered below the axis of the inverted anticline. The resulting inverted fold geometries are controlled by the geometries of the extensional planar or listric faults.

The Atlas paleorift system is one of the largest rift systems in Africa. Little hydrocarbon exploration has occurred within the Atlas Mountains and the margins of the paleo-Atlas rift system. Inversion of synrift structures can lead to both the destruction and preservation of synrift traps and the creation of new hydrocarbon traps. The study of the effects of inversion in the Missour basin may lead to the discovery of footwall subthrust hydrocarbon traps in the Mesozoic sedimentary sequence of the Atlas Mountains.

INTRODUCTION

Mountain belts located along convergent plate boundaries, such as the Andes or the Himalayas, have been and still are the focus of intense geological and geophysical studies. In contrast, intracontinental mountain belts, including the Atlas system in Morocco, lack even an agreed-upon first-order conceptual model of their deep structure and active deformation. Geological evidence suggests such intraplate belts have significantly contributed to the evolution of the continental lithosphere since the Precambrian.

Rifting during the Triassic and Jurassic was widespread around the world. The Atlas rift system of north Africa, the North Sea rift, the Andean rift system of Colombia and Venezuela, and the Palmyride rift of Syria are just a few of the intracontinental rift systems active during the Triassic and Jurassic. Some of these same rift systems were inverted into intracontinental mountain belts (i.e., the Atlas Mountains, Palmyride mountains, and the northern Andes). These rift systems were the focus of sedimentation during the synrift and postrift phases of rifting. Rift basins contain approximately 5% of the world's sedimentary volume, but they also contain 10–29% of the known hydrocarbon reserve base (~275 billion bbl) (Katz, 1995). This high concentration of reserves is partially due to the limited migration distance allowed by the geometries of rift systems.

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[2]Institute for the Study of the Continents and Department of Geological Sciences, Cornell University, Snee Hall, Ithaca, New York 14853-1504.

[3]Office National de Recherches et d'Exploitations Petrolieres, B.P. 8030, Rabat, Morocco.

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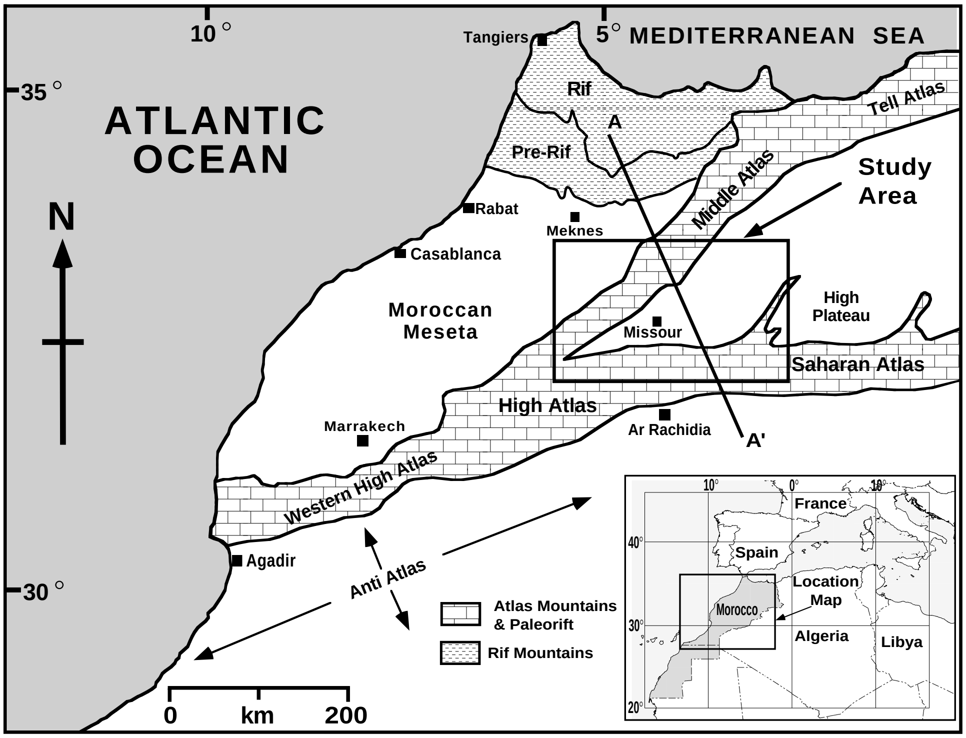

Figure 1—Location map of the Atlas mountains and Missour basin of Morocco. The Missour basin is bounded by the Middle Atlas and High Atlas mountains.

The uplift and inversion of hydrocarbon-bearing rifts can result in the remigration and redistribution of hydrocarbons into structures generated by the reactivation of preexisting faults formed during rifting. One must have a good understanding of the geometry of structures formed by the reactivation of synrift faults, because these structures have the potential to trap significant amounts of hydrocarbons. Additionally, one must generate models to understand the development of individual inverted structures, as well as the uplift and inversion of entire rift systems such as the Atlas Mountains, to better understand the potential of unexplored intracontinental rifts and mountain belts around the world. Our research in Morocco is a step toward understanding and resolving the history and present architecture of such belts.

GEOLOGIC SETTING

The Mesozoic and Cenozoic geological evolution of Morocco can be viewed as a response to two major geological events: (1) the opening of the North Atlantic and the western Tethys in the early Mesozoic, and (2) the Africa-Europe continental collision in the middle Cenozoic (Michard, 1976; Mattauer et al., 1977; Bensaid et al., 1985; Pique et al., 1987; Jacobshagen et al., 1988; Dewey et al., 1989; Westaway, 1990). These two major events shaped the present architecture of the four major geological structures of Morocco: the Rif fold-thrust mountain belt in the north, and the Middle Atlas, the High Atlas, and the Anti-Atlas mountain belts of central Morocco (Figure 1). The Rif belt is fundamentally different than the Atlas system. The Rif is an asymmetric, Alpine-type, fold-thrust belt with numerous, well-mapped thrusts and complex nappe structures (Loomis, 1975; Leblanc and Olivier, 1984; Morley, 1987; Doblas and Oyarzun, 1989; Ait Brahim and Chotin, 1990; Leblanc, 1990; Miranda et al., 1991), whereas the Atlas system is an intracontinental, largely symmetrical mountain belt.

Regional Tectonics and Rifting

The Atlas system evolved within the stable platform of North Africa. Two major events shaped the geological evolution of the system: early Mesozoic extension and rifting, and Mesozoic–Cenozoic compressional-transpressional phases that resulted in the inversion of the rift systems (Figure 2). The Atlas system is thus an intracontinental orogene “sandwiched” within the Proterozoic–Paleozoic northern African platform, and is fundamentally different from orogenes located along convergent/collisional plate boundaries. Thrusts, strike-slip faults, and block uplift tectonics characterize the Cenozoic deformation of the Atlas system (e.g., Schaer and

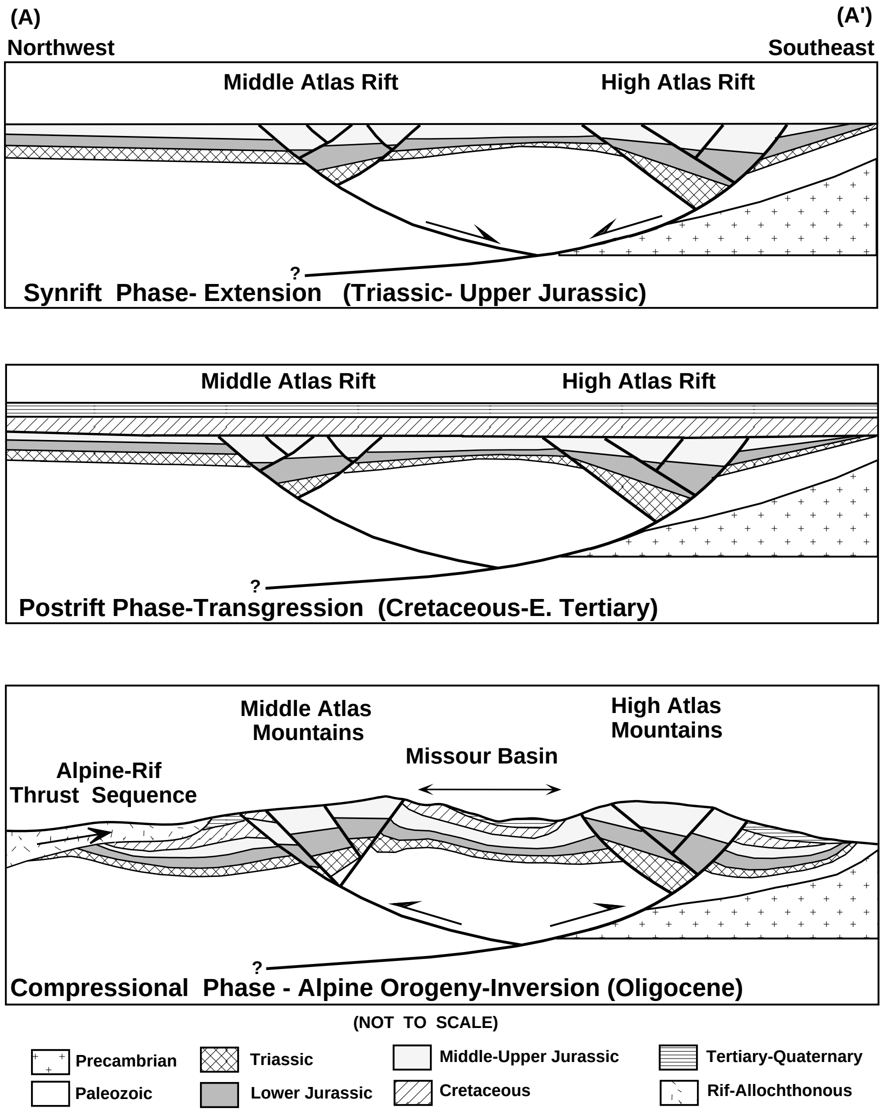

Figure 2—Conceptual model for the development of the Missour basin and the Atlas Mountains, Morocco. See Figure 1 for location of AA′.

Rodgers, 1987; du Dresnay, 1988; Fraissinet et al., 1988; Jacobshagen et al., 1988; Medina, 1988; Giese and Jacobshagen, 1992; Jacobshagen, 1992).

The Missour basin and the High and Middle Atlas mountain belts that form its boundaries (Figure 1) are examples of how large stresses can be transmitted to intraplate zones of weakness from the collision zones along the nearby plate margins. High strain rates created by the thinning of the continental lithosphere resulted in the deformation of the crust by extension and rifting in the North African plate at the end of the Permian and beginning of the Triassic (Brede et al., 1992). Sedimentation rates accelerated through the Jurassic as rifting continued with the breakup of Pangea, and the opening of the neo-Tethys Ocean and the North Atlantic (Ziegler, 1982). The High Atlas developed into one of the largest of the rifts, possibly reactivated along existing weaknesses and faults formed during the Hercynian orogeny. The High Atlas rift extends to the Atlantic margin where it forms a failed rift or aulacogen, and eastward (High Atlas/Saharan rift) across Morocco, Algeria, and Tunisia (Figure 1). The Middle Atlas rift and mountains trend northeast, where they extend beneath the thrusted Alpine Rif allochthonous sedimentary rocks. The intersection of the Middle and High Atlas rifts/mountains may represent a failed triple junction, or a focus of thermal upwelling.

Beginning in the Late Cretaceous–early Oligocene, dextral movement on the Newfoundland-Gibraltar fault zone increased the eastward drift of the Iberian plate (e.g., Brede et al., 1992). The geometric relationship between the Iberian plate and the African plate resulted in compressional stresses that were transferred to the North African rift systems. The

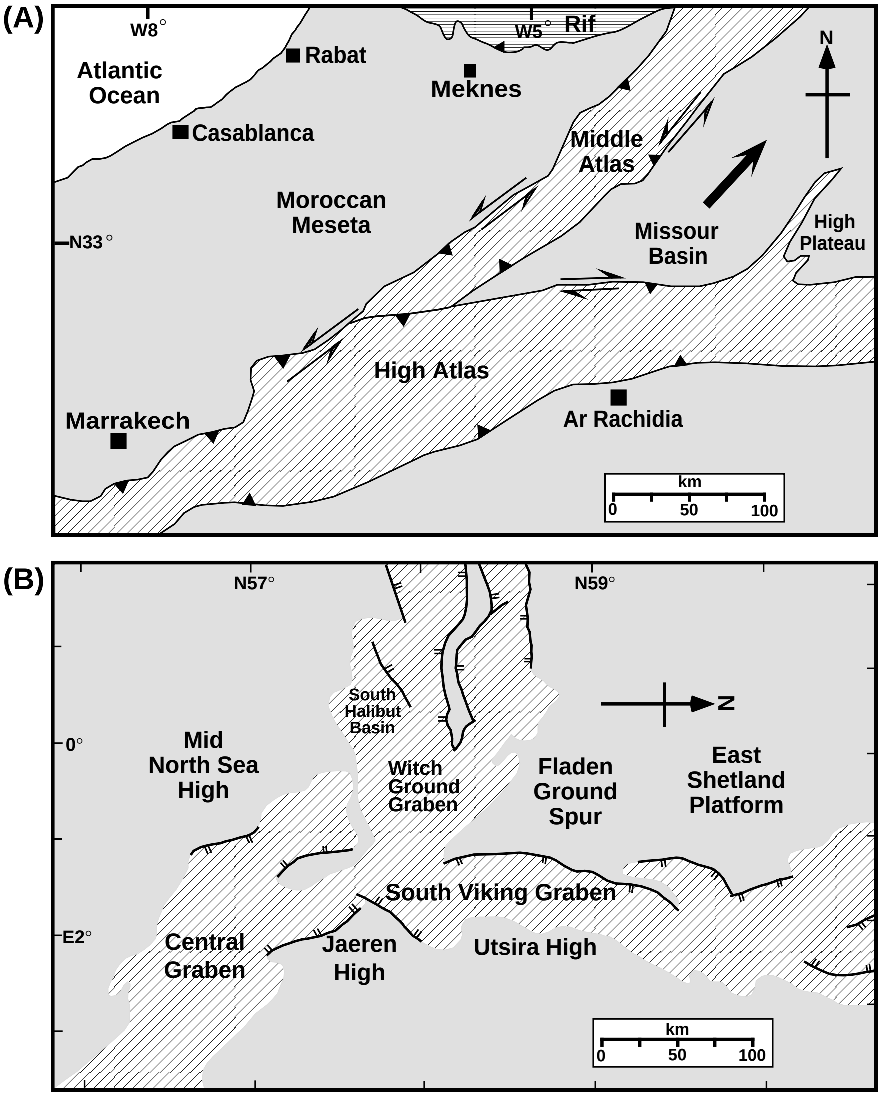

Figure 3—Comparison of the size and geometries of the Atlas and North Sea rift systems. Both rift systems were active during the Jurassic. The Missour basin (A) was a shelf margin much the same as the Fladen ground spur (B) of the North Sea. The Missour basin is bounded by faults that have a right-lateral component of slip to the south in the High Atlas and by faults with a left-lateral component of slip to the west in the Middle Atlas. The result is the uplift and escape of the Missour basin to the northeast. Modified after Stewart et al. (1992).

bulk of the intraplate stresses were absorbed by the High and Middle Atlas rift systems, resulting in shortening and subsequent inversion. The inversion of these rifts led to the reactivation of preexisting Mesozoic and Hercynian faults into reverse and thrust faults, with an oblique-slip sense of movement. The uplift of the Middle and High Atlas rifts formed the mountains that are now the boundaries of the Missour basin (Figure 2).

The orientation of compressional stresses relative to the orientation of rift bounding faults resulted in transpressional deformation in both a dextral and sinistral sense (e.g., Giese and Jacobshagen, 1992). The sense of movement on the bounding faults of the High and Middle Atlas mountains varied depending upon the direction of plate motion between the European and African plates. In the Early Jurassic spreading began in the central Atlantic, while the north Atlantic was in a rifting stage. This resulted in an eastward drift of the African plate in relation to the Iberian plate that was to the north of the Newfoundland-Gibraltar transform (Ziegler, 1982). During the Late Cretaceous–early Oligocene, the African plate was moving clockwise to the east, resulting in transtensional deformation in the North African rift systems. Plate rotation of the Iberian plate was counterclockwise as the Iberian plate moved eastward along the Newfoundland-Gibraltar fault/transform. This counterclockwise rotation is evident in the opening of the Bay of Biscay along the northern margin of the Iberian plate. The African plate was moving northward with respect to the Iberian plate during the late Miocene and Pliocene (Ziegler, 1982), with the same counterclockwise rotation, resulting in a rotation of primary stresses from

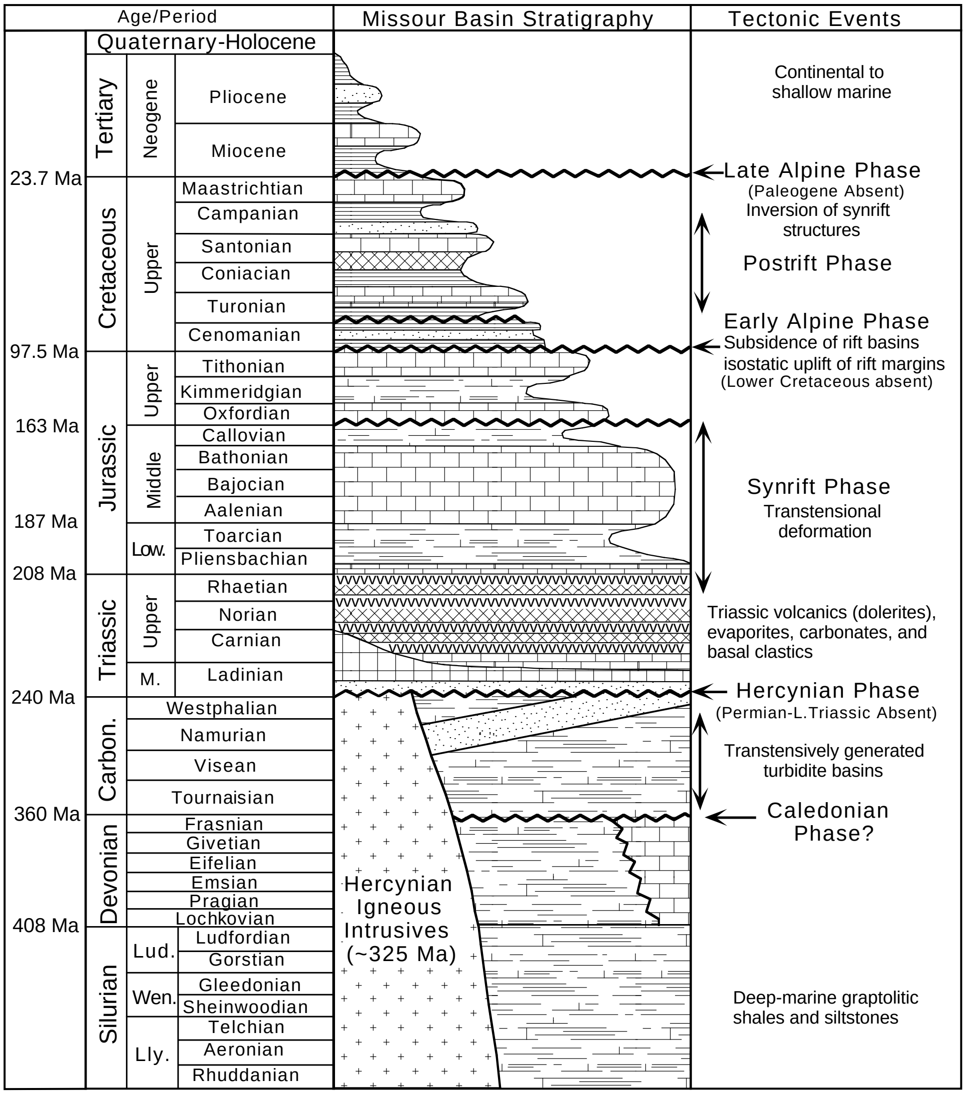

Figure 4—Stratigraphy of the Missour basin based on well penetrations (OSD-1, RR-1, KSAB-101, KSAB-102, and TT-1; see Figures 5 and 12, and Table 1), seismic stratigraphy, and outcrops within the basin. Several phases of deformation are related to major unconformities in the basin.

approximately 180 to 120°. Faults bounding the High Atlas rift yielded a right-lateral transpressive sense of deformation during the Late Cretaceous–early Oligocene (Figure 3). Folds in the central High Atlas generally trend east-northeast, at about a 20–30° angle to the High Atlas bounding faults (Studer and du Dresnay, 1980), further evidence of a right-lateral phase of deformation in the High Atlas Mountains. Later plate motion during the Oligocene to the Holocene has been that of convergence (Betic-Rif orogene) with some wrenching, because both plates have drifted eastward at a similar rate (e.g., Dewey et al., 1989).

For comparison, the High Atlas rift system is similar in size and geometry to the North Sea rift system (Figure 3). The actual geometry between individual rifts varies between the two rift systems. These differences may be related to the rates and direction of plate convergence between the Iberian plate and the African plate, and the subsequent deformation. Extension began in the North Sea and the Atlas rift systems during the Triassic and Jurassic (Figure 3). The Triassic sedimentary rocks penetrated by wells in the Missour basin contain a significant amount of tholeiitic volcanics interbedded with salts (Figure 4). These Triassic basalts extend over most of the Missour basin, are encountered in several wells, and are clearly identifiable on seismic reflection data.

Rifting in the Atlas continued into the Middle Jurassic when subsidence continued over the rift systems during the Late Jurassic–Early Cretaceous. Lower Cretaceous sedimentary rocks are not generally preserved in the Atlas Mountains, but may have been deposited in the Atlas rift systems during a postrift subsidence phase; if they were deposited,

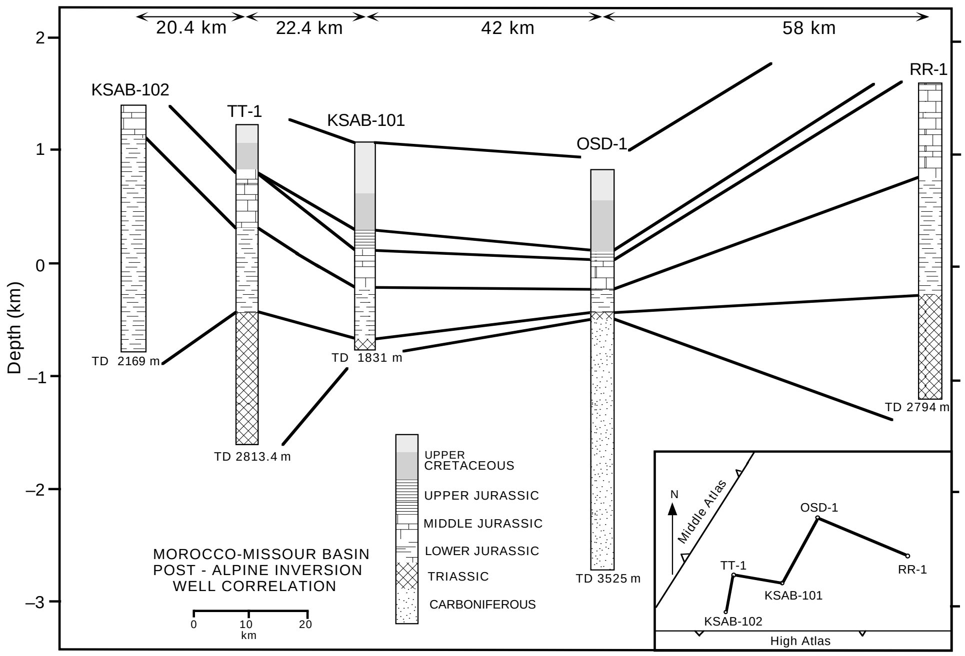

Figure 5—Well correlation between wells drilled in the Missour basin. Inversion can be seen by the dip of the base Cretaceous unconformity in the opposite direction of synrift thickening.

record of these sedimentary rocks was removed by uplift and erosion. Subsidence in the Atlas rift basins probably was coupled with isostatic uplift of the adjacent platform margins (Missour basin, High plateau, and Moroccan meseta). This isostatic uplift of the rift basin margins resulted in a thinning of the Upper Jurassic–Lower Cretaceous sedimentary rocks. The Upper–Middle Jurassic sedimentary rocks of the Missour basin are deeply eroded along the margins of the High and Middle Atlas mountains, a result of isostatic uplift and erosion by the base Cretaceous unconformity. Well data illustrate deep truncation by the base Cretaceous unconformity into the synrift sedimentary rocks from the rift margins into the paleo-Atlas rift basins. We found evidence of isostatic uplift of the rift basin margins during the Late Jurassic or Early Cretaceous (Figure 4). The oldest Cretaceous sedimentary rocks encountered in the Missour basin are Cenomanian (Figure 4), suggesting a subsidence phase in the Atlas rift systems that lasted 40–50 m.y., from the Late Jurassic to the Late Cretaceous. Subsidence slowed or ended during the Late Cretaceous because Cenomanian to Turonian sedimentary rocks were deposited uniformly across the rift systems and the rift basin margins. Subsequent uplift in the Paleogene, related to the Alpine orogeny, inverted the Atlas rift system and eroded the Lower Cretaceous sedimentary rock sequence from the present Atlas Mountains. Compression and transcurrent movements generated by the relative motion of the African and Iberian plates resulted in stresses being transmitted into the African plate, the net result being the shortening and inversion of the Moroccan rift systems (e.g., Laville and Pique, 1992).

Regional Stratigraphy of the Missour Basin and Atlas Mountains

Five wells have been drilled in the Missour basin, with three that penetrated the Hercynian unconformity and the Permian–Carboniferous clastic sedimentary rocks (sandstones, shales, and conglomerates). The Triassic section overlying the unconformity is recognized by a lower and upper salt series separated by layers of basalts. The Jurassic sequence consists primarily of marine limestones, dolomites, and shales. The postrift Cretaceous–early Tertiary sequence is made up of a shallow and marginal marine sequence of limestones, calcareous shales, dolomites, and interbedded anhydritic shales (Figure 4). A correlation of the wells in the Missour basin clearly indicates the regional effects of inversion (Figure 5). The Jurassic in the Missour basin thickens dramatically toward the old Middle and High Atlas rift systems. The thick Jurassic sequence in the center of the rift is composed mostly of shallow-marine carbonates (Studer and du Dresnay, 1980). On what is now the edge of the mountain belts, Jurassic carbonates exhibit basin-margin facies, such as reefs, platforms, and intertidal sedimentary rocks (du Dresnay, 1971). In the middle of the High Atlas Mountains, Jurassic carbonates measure up to 7 km thick (Studer and du Dresnay,

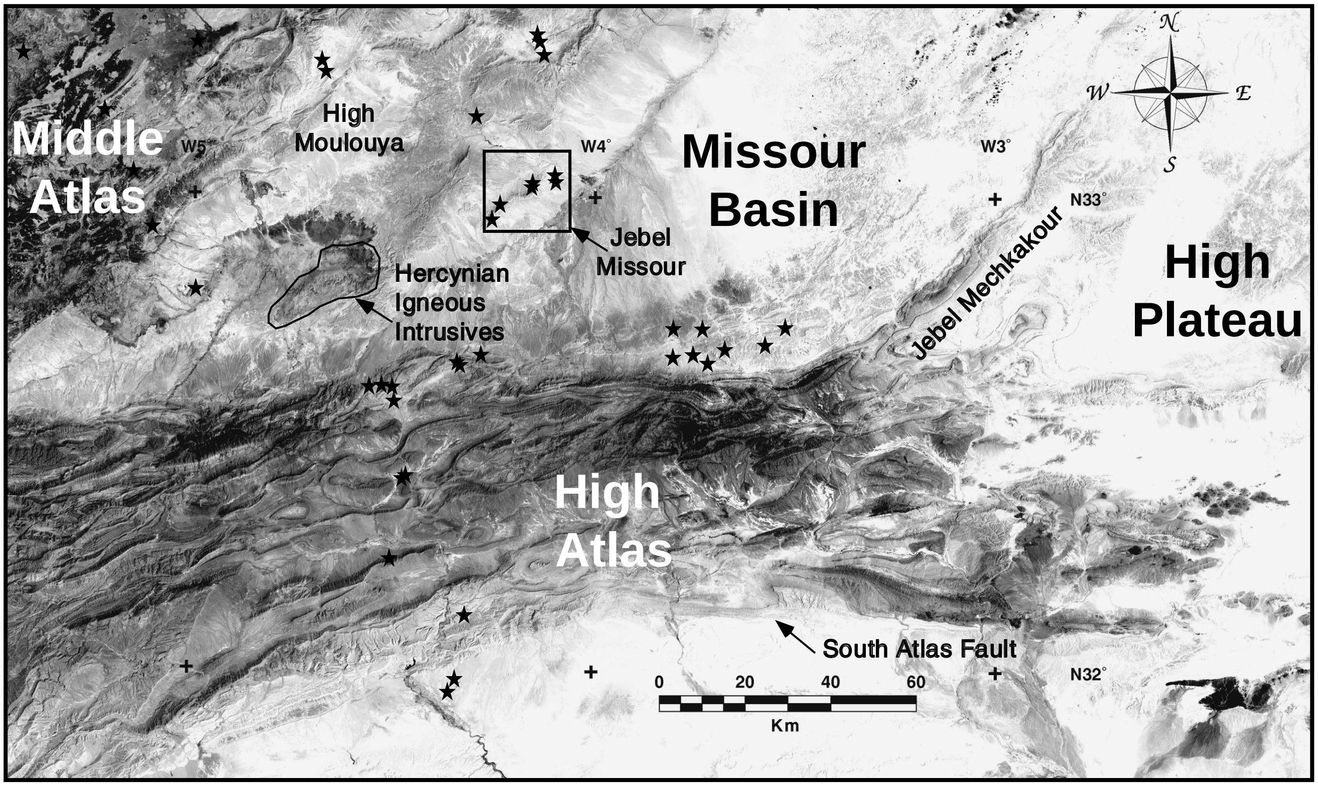

Figure 6—LANDSAT TM (band 5, infrared) mosaic of the Missour basin and parts of the High Atlas and the Middle Atlas mountains. Field locations where structural data were collected are shown as stars. The eastern margin of the Missour basin is bounded by the northeast-trending Jebel Mechkakour. The location of Jebel Missour is shown to the east of the High Moulouya. The structures seen in the High Atlas Mountains show polyphase deformation.

1980). Erosion in the Atlas has removed part of the Jurassic section related to inversion. Illite crystallinity in preserved sedimentary rocks (Early Jurassic) was used by Brechbuhler et al. (1988) to estimate almost 6–8 km of synrift and postrift thickness in the deepest part of the rift. The Triassic sedimentary rocks of the High Atlas are 4–4.5 km thick (Beauchamp, 1988). A composite thickness for the synrift sedimentary rocks in the High Atlas could be as thick as 10–12 km, based on a measured field sections in the High Atlas.

FIELD MAPPING AND ANALYSIS

We collected field data to constrain the interpretation and modeling of subsurface data. The Missour basin and the Atlas Mountains provide a means to study inversion structures in outcrop, and the structural characteristics helped us interpret subsurface structural relationships. Multiple phases of deformation along the margins of the Missour basin indicate a complicated tectonic history that developed from the beginning of the Triassic through the early Tertiary. The tectonic history of the Missour basin has developed in several phases of extension and compression rather than only one phase of extension in the Triassic and one later phase of compression in the Oligocene, as has been previously believed.

The primary goal of our field work was to locate exposures of fault zones along seismic reflection profiles and tie the two data sets together to provide models for structural styles of inversion. Most of the exposures in the Missour basin are located along the margins of the basin (Figure 6). The most important exposure within the basin relative to this study is Jebel Missour (Figure 6). This prominent topographic ridge trends northeast and is composed of two large anticlinal structures. Cretaceous and Jurassic sedimentary rocks are exposed in the two anticlines. The most important relationship of these two folds is that they verge in opposite directions (Figure 7). Aerial photographs used for mapping in the field illustrate the pronounced topographic expression of these anticlinal structures. The southernmost fold (F1-A, Figure 7) verges northwest, and the northernmost fold (F1-B, Figure 7) verges southeast. Both are asymmetric folds with steeply dipping to vertical limbs along one side of

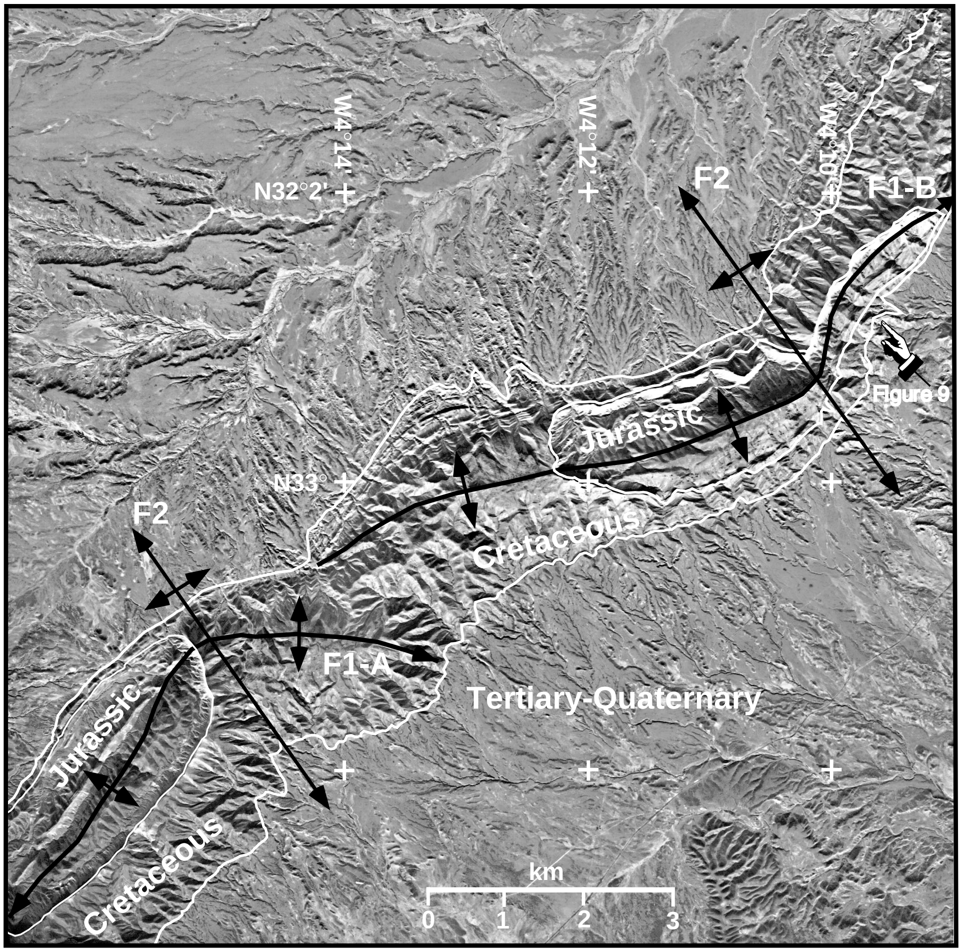

Figure 7—Aerial photograph of the Jebel Missour region (located on Figure 6). Two northeast-trending anticlinal structures show two phases of deformation (F1 and F2). Fold F1-A and F1-B are verging in opposite directions. Jurassic synrift sedimentary rocks are exposed in the core of both anticlines separated by the base Cretaceous unconformity. The Tertiary and Quaternary sedimentary rocks are flat lying and onlap the two structures. Location of Figure 9 is shown near F1-B.

the fold. Strike and dip data were collected along transects across the structures and plotted to illustrate the overall geometry of the structures (Figure 8). The northernmost fold (F1-B) is plunging to the northeast, and the southeast limb is steeply dipping to vertical along strike of the fold (Figure 9). The southern anticline (F1-A) has exposures of both synthetic and antithetic faults located in the core of the fold. Both the synthetic and antithetic faults are steeply dipping high-angle faults. Fault plane lineaments indicate a reverse sense of motion on the reactivated synthetic fault (up to the northwest). These faults displace Jurassic rocks and die out upsection in the anticlinal structure. There is a distinct change in dip between the postrift Upper Cretaceous sedimentary rocks and the synrift Jurassic rocks, and the examined faults do not cut the base Cretaceous unconformity.

These two structures (F1-A and F1-B) at Jebel Missour evolved initially from two opposing planar normal faults connected by a ramp (Figure 10). These two faults were active during rifting in the Triassic–Late Jurassic. During the postrift phase, the base Cretaceous unconformity eroded upper Jurassic synrift sedimentary rocks from regions of the Atlas rift system as subsidence began. Cenomanian–Turonian rocks were deposited in the Missour basin, and in the early Tertiary the two half grabens were inverted by an oblique compressional stress, possibly related to the Alpine orogeny. During the late Tertiary–Holocene, sedimentary rocks were deposited onlapping the existing structure formed by earlier phases of deformation. Late Tertiary–Holocene sedimentary rocks are flat lying and have not been affected by any significant deformation after the Oligocene phase of uplift and compression in Morocco.

Fault lineaments and slickensides indicate a reverse sense of movement on faults measured at Jebel Missour. These lineaments overprint earlier dip-slip and oblique-slip lineaments for which a sense of movement could not be determined. Previous lineaments indicate earlier phases of deformation, and may be associated with normal and transtensive phases of deformation related to the initial phases of rifting. The Middle Atlas Mountains

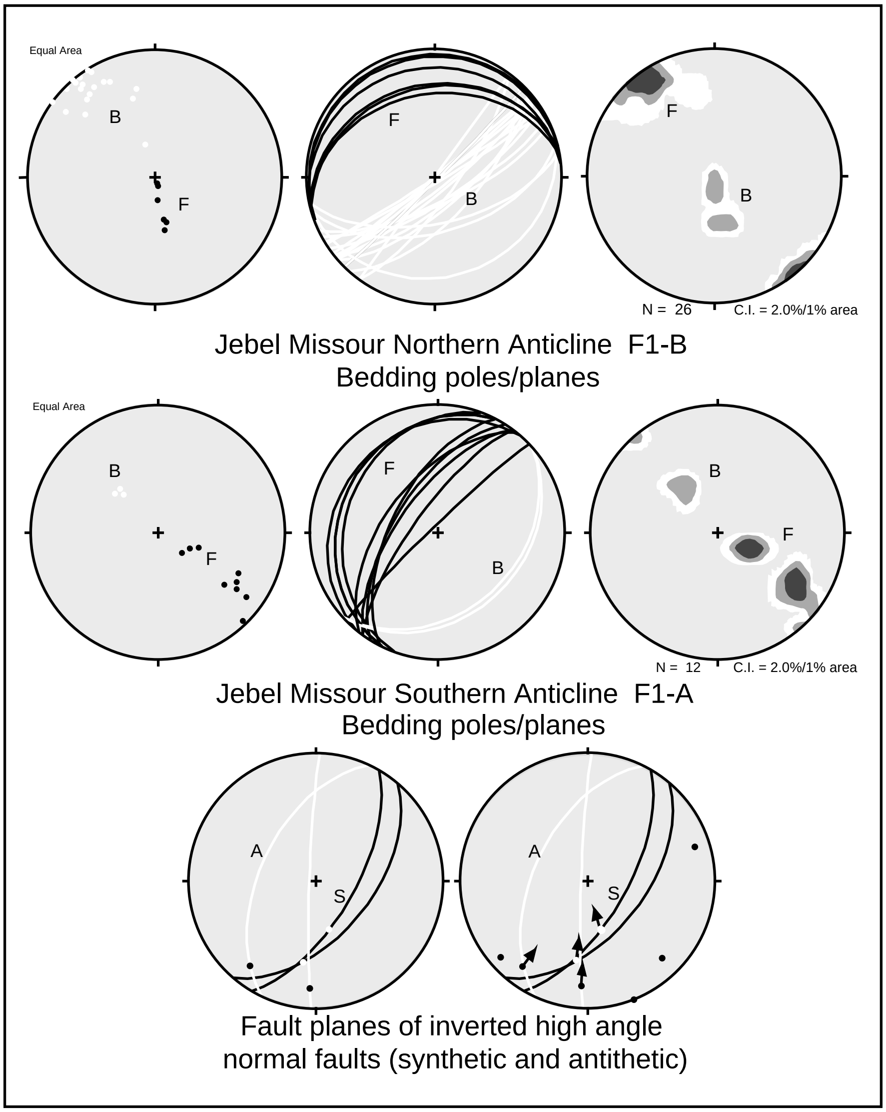

Figure 8—Field data collected from Jebel Missour. The northern anticline (F1-B) is verging to the northeast. The southern anticline (F1-A) is verging to the southwest. High-angle reverse faults were measured in the core of the southern anticline (F1-A). These faults are inverted planar normal faults (synthetic and antithetic). The vergence of the folds is related to the original dip of the synrift normal faults.

west of Jebel Missour are bounded by faults that have recent movement along inverted normal faults exhibiting a left-lateral sense of shear (Morel et al., 1993). These faults have been active recently, and offset Quaternary sedimentary rocks and older Neogene volcanics. Reactivated rift faults in the Middle Atlas have thrust Triassic sedimentary rocks over Pliocene and younger sedimentary rocks. The faults related to structures at Jebel Missour have not been active since the early Tertiary, indicating more recent convergence is being accommodated along larger fault systems in the Middle Atlas Mountains.

The exact geometry of the faults at depth at Jebel Missour is difficult to obtain. Based on the asymmetrical geometry of the associated folding, the faults may represent reactivated planar faults. The inversion of a planar fault usually results in a more asymmetrical geometry than an inverted listric fault, which upon inversion forms a more open symmetrical fault-bend fold (Mitra, 1993). The geometric styles generated by the inversion of listric and planar normal faults are controlled by the orientation of the maximum compressive stress. The inversion of a steeply dipping planar fault can accommodate a limited amount of shortening because of the geometry of the fault. Once shortening along a planar fault has occurred by uplift of the associated hanging wall, further stress generated by compression is accommodated by lateral strike-slip movement along the fault. Steeper faults with dips of approximately 40–60° can be reactivated only if there is a low coefficient of sliding friction (Coward et al., 1991). Because of the geometry of planar faults, steeper faults are more easily reactivated by oblique-slip or strike-slip motion. This type of deformation may have occurred along the faults associated with Jebel Missour (Figure 7). The apparent second phase of

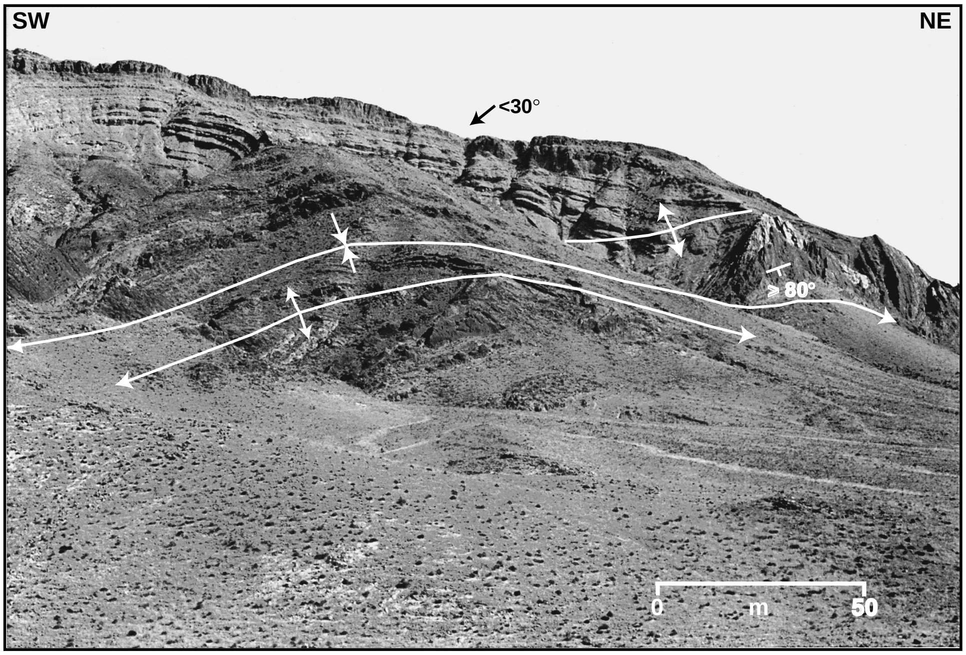

Figure 9—Photograph of Jebel Missour along the northeastern plunging F1-B fold. See location of photo on Figure 7. The fold is verging out of the picture. Steeply dipping to vertical beds can be seen along the flatirons in the right side of the photo. The fold is an asymmetrical fold formed by the inversion of a planar fault that dips to the northwest. The fault is most likely a fault-propagation fold. The steeply dipping limb is complicated by several smaller folds in the foreground.

folding affecting the structures is thought to be related to oblique-slip movement on the planar faults associated with the structures. The deformation of the original half grabens bounded by steeply dipping planar faults may have occurred as follows: inversion of the hanging-wall half graben along a planar normal fault, folding of the postrift Upper Cretaceous sedimentary rocks and synrift Jurassic rocks into an asymmetrical fault-propagation fold, refolding of the asymmetrical folds (F2, Figure 7) by oblique-slip movement along the planar fault, and onlap of the structures by the Neogene–Holocene sedimentary rocks. Jebel Missour is an example of how planar faults may respond to inversion within a particular rift system.

We used topographic maps and a GPS (Global Positioning System) receiver to find the surface location of faults identified on seismic lines. Faults identified on seismic profiles that appear to extend to the surface were commonly covered by Holocene sedimentary rocks. Many of the faults seen on seismic reflection profiles as individual faults were found to occur as zones of offset at the surface. We

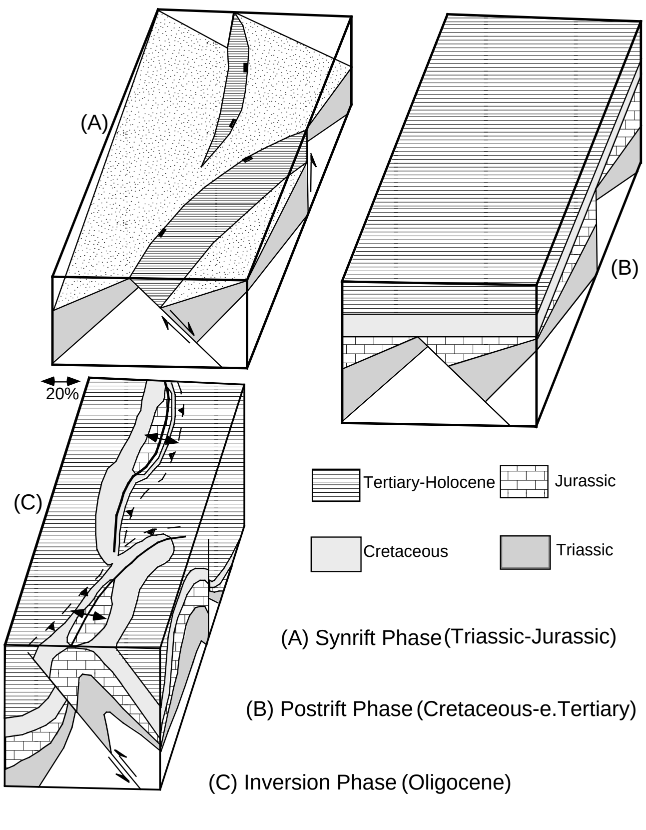

Figure 10—Schematic model depicting the structural evolution of Jebel Missour. (A) Synrift faults result in the deposition of sedimentary rocks in an asymmetrical half graben. The two normal faults are dipping opposite one another connected by a ramp or transfer zone. (B) The postrift phase begins the deposition of Cenomanian and Turonian age sedimentary rocks unconformably above the Jurassic. (C) Uplift and inversion reactivate opposing planar faults that both form oppositely verging fault-propagation folds. The inversion of (A) has resulted in approximately 20% shortening.

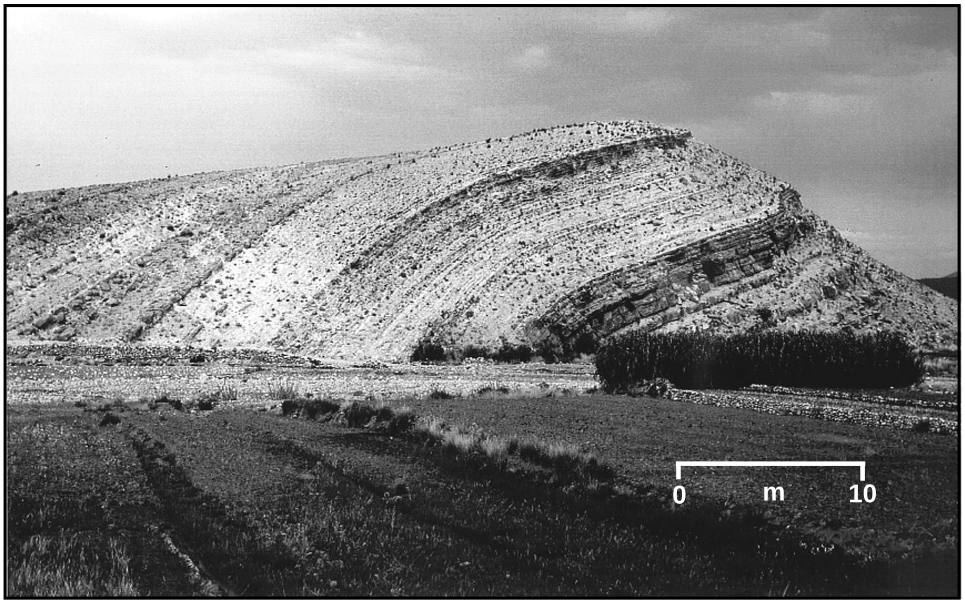

Figure 11—Fault-propagation fold that is verging to the north near the southern margin of the Missour basin. Onlap of growth strata can be seen from north to south across the structure.

were able to record dips of several rocks in the hanging wall and footwall of faults that define the overall geometry of the surface structure (Figure 11). Displacement in fault zones generally occurs along a system of related small faults in the zone of deformation. Slip, illustrated by kinematic indicators along bedding planes in the footwall and hanging wall of faults, gave a sense of shear across fault zones.

Many of the fault zones along the southern margin of the Missour basin indicate oblique-slip movement associated with the most recent phase of deformation. The sense of slip across all of the fault zones measured in the field along the southern margin of the Missour basin was either right-lateral oblique-slip or right-lateral strike-slip movement. The age of this right-lateral deformation is thought to be associated with an early Tertiary or older inversion phase because younger sedimentary rocks were not deformed. Lineaments and slickensides that record right-lateral oblique and strike-slip sense of movement cut across several (up to three) earlier lineations that record previous phases of movement on the same surface.

An important conclusion based on the study of the Missour basin is the concept that the entire basin may have been uplifted and inverted as a whole (Figure 2). Most of the deformation in the basin has occurred along the margins of the basin. Extensional features that are not near the flanks of the Atlas Mountains normally do not indicate evidence of reactivation. Reactivation and inversion of extensional faults may have occurred in the interior of the basin, but these faults still illustrate a "net" extension. This observation leads to the conclusion that shortening has been accommodated by previously existing synrift faults within the paleo-Atlas rift and current-day Atlas Mountains. The density of faults observed in the field indicates a direct correlation between the degree of inversion and preexisting synrift faults. This relationship may be true for the magnitude of the shortening and inversion (relative to the size), and the amount of throw and extent of synrift faults in the Missour basin and Atlas Mountains. These observations also may have a correlation with the present topography in the basin (Figure 12). Topography is generally related to the density of faults and structure in the Missour basin, as can be seen by Jebel Missour (Figure 7).

Left-lateral oblique and strike-slip offset in the Quaternary and Neogene recorded in the Middle Atlas (Morel et al., 1993), combined with right-lateral movement along the southern margins of the Missour basin, would indicate the overall relative movement of the Missour basin is to the northeast (Figure 3A). The concept of the Missour basin having been uplifted and inverted as a whole may be similar to the concept of "escape" tectonics proposed by Sengor et al. (1984). The basin may have been uplifted and inverted by the culmination of several phases of deformation. The region was previously part of the shelf margin or shoulder of the Atlas rift system, and has since been uplifted and translated to the northeast.

The basin is bounded to the east by Jebel Mechkakour (Figures 6, 12). The large-scale geometry of the basin as defined by the High Atlas to the south, the Middle Atlas/High Moulouya to the west, and Jebel Mechkakour to the east is rhombohedral. The

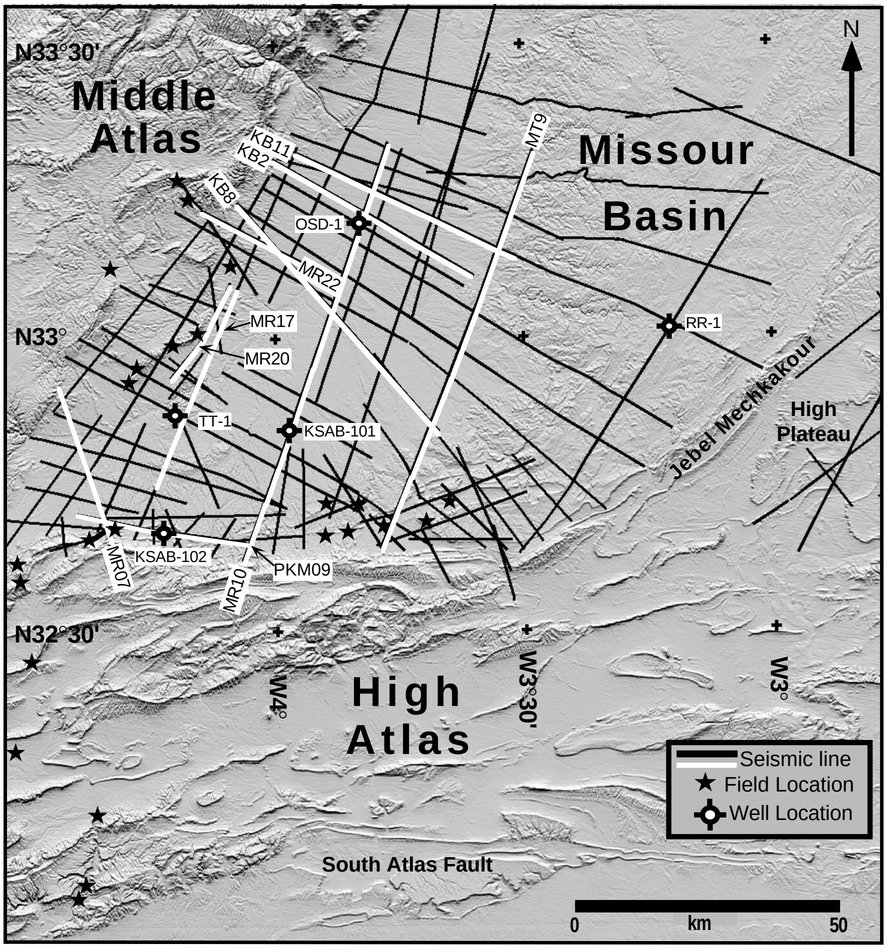

Figure 12—Map showing digital topography of the Missour basin and the adjacent High and Middle Atlas mountains; seismic reflection profiles, well data, and field locations are shown. A total of 3400 km of seismic lines were used to study the tectonic evolution of the Missour basin and Atlas Mountains. The seismic lines in white are those used in this paper; both black and white lines were used in the study.

High Plateau east of the basin (Figure 1) also is characterized by a more obvious rhombohedral shape. These shapes are inherent in transtensional pull-apart basins associated with rifting (Morley, 1995). The High plateau basin is distinctly different from the Missour basin because of a thick (>1000 m) sequence of salt penetrated by wells in the High plateau basin that is not present in the Missour basin. The anticlinal feature east of Jebel Mechkakour (Figure 6) was partially formed by the movement of Triassic salt. The distinct differences between the Missour basin and the High Plateau basin have been present since the early synrift phase in Morocco. The High Plateau basin was most likely an extensional pull-apart basin during the rift phase, and the Missour basin was topographically higher relative to the current High Plateau. The present Missour basin has been uplifted, inverted, and translated to the northeast by a style of escape tectonics along boundaries formed during rifting.

GEOLOGICAL AND GEOPHYSICAL ANALYSIS

A total of 3400 km of seismic reflection data have been acquired in the Missour basin and were used in this study. These surveys were acquired between 1974 and 1986, resulting in a collection of seismic reflection data with various qualities and processing parameters. The digital poststack data of several lines were obtained from ONAREP and were used for further processing, migration, and depth conversion for more accurate analysis and modeling. Velocity data in the form of time-depth curves and synthetic seismograms were used to tie wells in the basin to the seismic reflection data (Table 1).

The combination of surface and subsurface data in the Missour basin constrains the geometry of faults recognized at the surface into the subsurface. Seismic lines were migrated and depth converted prior to modeling, balancing, or interpreting the seismic data. Seismic lines used for modeling in this

Table 1. Wells Drilled in the Missour Basin

Coordinates & Elevation	Company	Year	Total Depth (m)	Fm. at Total Depth
Well TT-1 X = 611.916.7 Y = 252.593.2 EL = 1212.6 m	S.C.P.*	1954	2813	Triassic
Well RR-1 X = 704.372.2 Y = 271.197.5 EL = 1633 m	S.C.P.	1965	2794	Triassic
Well KSAB-101 X = 632.666 Y = 249.989 EL = 1395.5 m	Phillips	1983	1831	Triassic
Well KSAB-102 X = 608.889 Y = 230.609 EL = 1395.5 m	Phillips	1983	2188	Jurassic
Well OSD-1 X = 648.824 Y = 288.959 EL = 839 m	ONAREP**	1986	3525	Carbonif.

*Societe Cherifiene des Petroles.
**Office National de Recherches et d'Exploitations Petrolieres.

study were reprocessed by applying an FX deconvolution and coherency filters, migrating the data using a Stolt FK migration, and then depth converting the line using interval velocities. This process is normally bypassed due to time constraints or the lack of digital seismic data. The migration and conversion of key seismic lines in the Missour basin proved to yield important interpretations and structural models in the basin.

Two important regional stratigraphic horizons were clearly identifiable on most seismic data in the basin: (1) the base Cretaceous unconformity, and (2) the Hercynian unconformity (Figure 4). These horizons form the stratigraphic boundaries for the postrift and synrift sedimentary sequences mapped throughout the basin. The base Cretaceous unconformity is usually identifiable on dip lines as an angular unconformity. The Hercynian unconformity is characterized by an angular unconformity between the Paleozoic and the synrift sedimentary sequence. The Hercynian unconformity can also be recognized as the base of the highly reflective Triassic sedimentary rocks composed of salts, anhydrites, volcanics, dolomites, and clastics (Figure 13). Reflections from within Paleozoic strata were evident on many of the seismic sections in the basin. On several seismic sections, strong reflections were present to 7 s two-way traveltime. Paleozoic structures are present on several lines in the basin. Wells drilled in the Missour basin did not penetrate deeply enough into the Paleozoic section to allow us to correlate the units within the Paleozoic. The only structures that could be defined in the Paleozoic were at the structural level of the Hercynian unconformity.

Styles of Faulting

Low-angle thrusts in the Atlas Mountains have been documented on geological maps and in previous field studies. These thrusts have been interpreted previously on published cross sections as low-angle faults that detach at the top of the synrift Triassic salts. The results of our study indicate that these low-angle thrusts may be related to the reactivation of synrift listric faults that detach well below the synrift Triassic sedimentary rocks. Many faults in the Atlas are steep to vertical, thus making it difficult to recognize the direction of dip of the fault. The footwall and hanging wall of the fault also are difficult to recognize. Although it is common for extensional faults related to Mesozoic rifting to be inverted upon compression in the Missour basin and the Atlas Mountains, it is difficult in many cases to document the dip of the fault plane and the sense of movement on the faults using only seismic reflection data.

We found it common for large-scale (>5 km, map view) faults to dip both toward the paleorift basins and out of the basins. This relationship is common in many rift systems (Rosendahl et al., 1986). When the relationship of extensional and dual fault polarity is applied to an inverted rift system, the results are that thrusts and reverse faults verge both into and away from the paleorift basins.

Sedimentary relationships on seismic data that illustrate extension and active sedimentation during rifting are important to recognize. Otherwise, determining whether a fault is a reverse fault, thrust fault, or a reactivated synrift fault is difficult. Seismic line 85KB11 (Figure 14), for example, shows a well-defined high-angle planar fault that dips to the northwest toward the Middle Atlas Mountains. This fault is not exposed at the surface, but the highly reflective package of the Triassic sedimentary rocks above the Hercynian unconformity indicates the sense of throw and the amount of offset. The Cretaceous is not present west of the fault on line 85KB11. The sense of throw on the fault is reverse, but it is difficult to determine if the fault is a reactivated normal fault or a fault that was newly formed as a reverse fault.

Another consideration when interpreting reactivated faults is the uplift of the hanging-wall half graben above what has been previously referred to as the null point (Williams et al., 1989). A fault may have been a normal fault during rifting, with

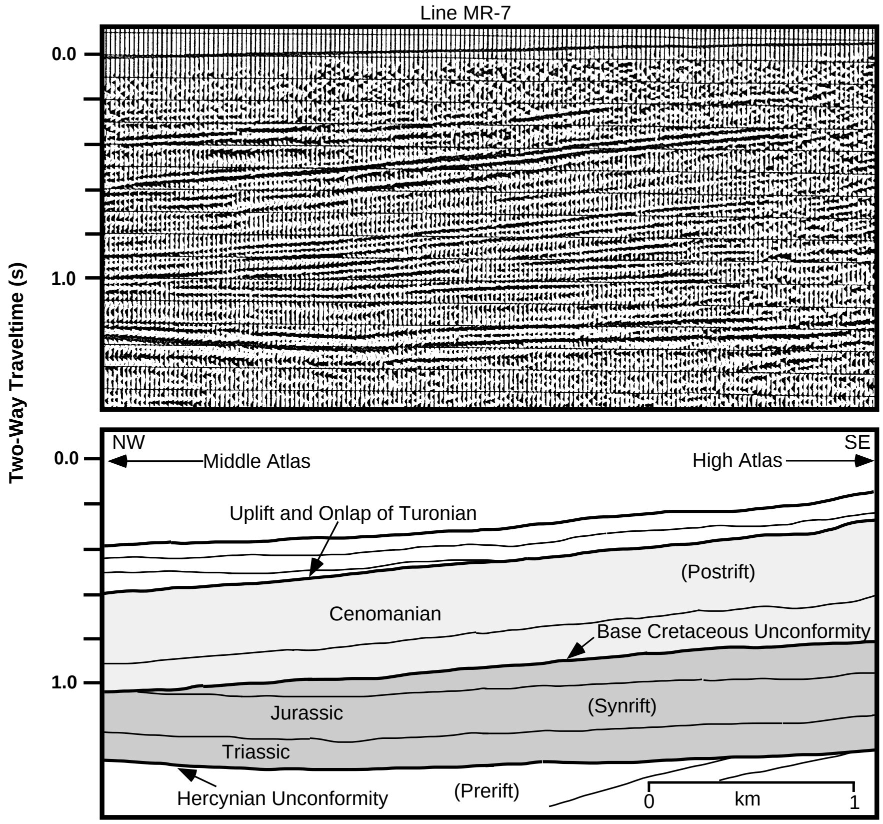

Figure 13—Major unconformities that illustrate tectonic phases (Hercynian, base Cretaceous, and Turonian?) are seen on seismic line MR-7. The Hercynian unconformity has been "flattened" by the inversion of the stratigraphic section. The synrift and postrift sections have been rotated upwards reversing the original sense of regional dip (location on Figures 12, 17).

thickening of synrift sediments into the active extensional fault. Upon inversion, the hanging wall is uplifted until the prerift unconformity (Hercynian) is uplifted above the prerift unconformity in the footwall. The null point, as referred to by Williams et al. (1989), would occur when there is no stratigraphic displacement of the prerift unconformity across a fault. This relationship can result in interpretations that assume deformation by extensional tectonics, when a significant amount of compression normal to the fault may have occurred. Identifying inversion on faults is important because inversion may affect hydrocarbon migration and trapping in either a positive or negative manner. For example, on seismic line 85KB11 the null point would occur when the base Triassic–Hercynian unconformity (Figure 14, AA′) is juxtaposed across the fault that is dipping to the west.

An example of a reactivated fault that has been uplifted above the null point can be seen on seismic line 86MR17 (Figure 15). This line has been migrated and depth converted to help position and restore the fault geometry. There has been an apparent uplift of the base Cretaceous unconformity to the north of the fault by at least 2 km. North of the fault, reflections in the Jurassic can be seen truncating beneath the base Cretaceous unconformity. The highly reflective Triassic basalts can be seen clearly above the Hercynian unconformity. The reactivation of this fault may have occurred along a previous synrift fault or by reactivation of a prerift fault. Steeply dipping planar faults allow for a limited amount of shortening normal to the fault plane. Faults such as the fault on line 86MR17 reactivate by initial slip along the fault plane, inverting the hanging wall, and forming a fault-propagation–style fold above the synrift fault (below the base Cretaceous unconformity). Further shortening across the fault zone was accommodated by the generation of a fault-propagation fold (verging to the south). This fold was later cut by the breakthrough of the fault upward along the forelimb of the fold. The syncline to the south of the fault on line 86MR17 (Figure 15) is the conjugate fold related to the initial fault-propagation fold. If the principal compressive stress was oriented at an angle oblique to the fault plane, oblique or strike-slip deformation would be expected to accommodate further strain across the fault (Coward et al., 1991). This style of deformation is similar to the style of deformation that was mapped at Jebel Missour (Figure 7).

Another more subtle criterion that indicates inversion is seen on seismic line PKM-09 (Figure 16). This seismic line ties well KSAB-102 drilled by

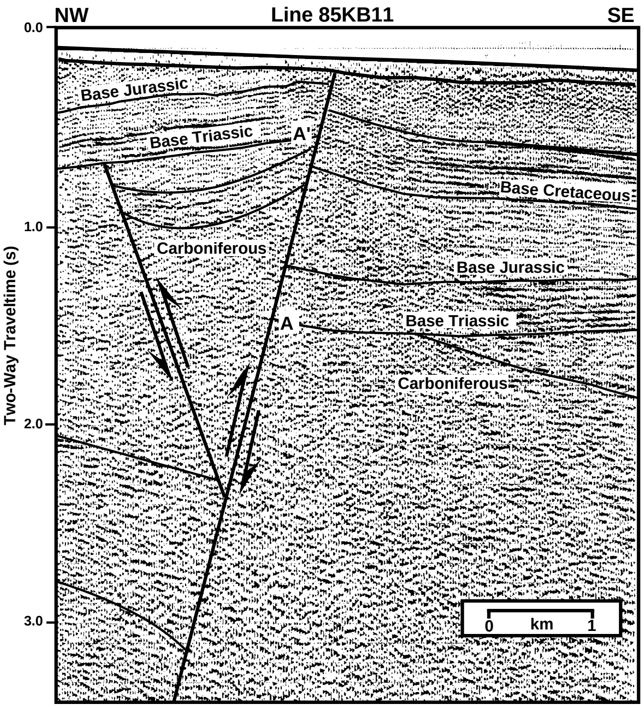

Figure 14—Seismic profile 85KB11 located near the southeast margin of the Middle Atlas Mountains (location on Figure 12). The null point is the point at which AA′ is adjacent across the fault. Note the uplift of the Triassic unconformity. Erosion by the base Cretaceous unconformity has removed any indication of whether the fault was a reactivated synrift fault or a newly formed reverse fault.

Phillips in 1983 that reached total depth in the Jurassic. Line PKM-09 shows a thickening of the Jurassic from east to west across the section, from 644 to 826 ms two-way traveltime. This thickening occurred during rifting, and the sedimentary rocks thicken toward a reactivated normal fault to the west. The inversion has resulted in an anticlinal structure (in the subsurface and surface) where there was previously a half graben.

A common feature of rifting is syndepositional growth strata or a progressive unconformity associated with an extensional half graben. Major unconformities, such as the base Cretaceous, commonly appear to have been flattened due to uplift and inversion. These unconformities originally dipped basinward as a result of postrift subsidence (Figure 17). Regional seismic lines that extend across the basin were tied to wells drilled in the basin using synthetic seismograms and time-depth curves, and major stratigraphic boundaries were mapped throughout the basin. These interpreted stratigraphic boundaries were then digitized and redisplayed to produce the interpreted cross sections in Figure 17. One important feature is the lack of faulting in the Missour basin as a whole, with the overall deformation having occurred along the margins of the basin both during the extensional synrift phase and in later inversion phases of deformation (Figure 17). A common inversion characteristic recognized on the seismic data in the basin is dip reversal relative to the direction of sedimentary thickening (Figure 13).

Evidence of a previously unrecognized phase of uplift (Turonian) or a change in sea level can be seen on seismic line MR-7 (Figure 13) based on growth strata. The lack of Lower Cretaceous (Berriasian–Albian) sedimentary rocks above the base Cretaceous unconformity indicates a missing 40 m.y. of sedimentary rocks in the Missour basin (Figure 13). The lack of deposition during this time may be related to isostatic uplift of the Atlas rift shoulders or margins. The basin was positioned on such a shoulder or margin during the onset of the postrift subsidence phase. This isostatic uplift of the rift margins (Missour basin, High Plateau, and Moroccan meseta, Figure 1) during the return of the rift to thermodynamic equilibrium would have resulted in the deposition of Lower Cretaceous sedimentary rocks into the subsiding Atlas rift basin. The Lower Cretaceous sedimentary sequence would not necessarily have been represented on the shoulders of the Atlas postrift subsidence basin (Missour basin). Some Lower Cretaceous sedimentary rocks (Albian) are preserved in the High Atlas Mountains to the south of the Missour basin. The inversion of the postrift Atlas basin would have resulted in the uplift and erosion of the Lower Cretaceous sedimentary rocks from most of the Atlas Mountains.

Fault Restorations

Both planar and listric faults were formed in the extensional phase of rifting of the Atlas rift systems. Listric faults interpreted in the Missour basin shallow to a detachment in the Paleozoic. One such example is seen on seismic line MR22 and trends northwest along the margin of the Middle Atlas Mountains (Figures 12, 18). Thickening of the synrift sequence is clearly evident from the southeast to the northwest into a listric normal fault that dips to the southeast. This line was migrated, depth converted, and plotted at a one-to-one scale for modeling and balancing of the section. Line MR22 was correlated to a cross line that was then tied to well OSD-1 using a time-depth curve that is north of line MR22 (Figure 12). The base Cretaceous and Hercynian unconformities diverge from southeast to northwest, and the Hercynian unconformity has been uplifted so that it is near horizontal. This

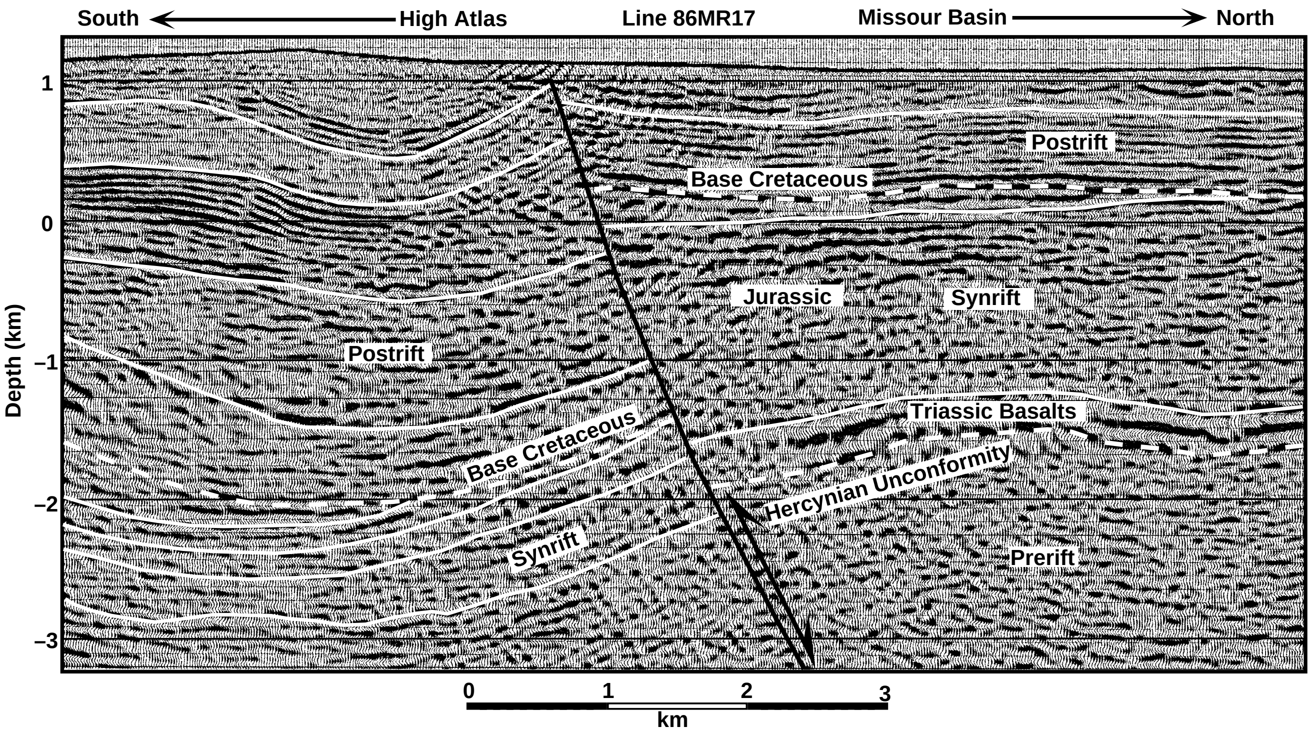

Figure 15—Seismic profile 86MR17 shows the uplift of the Hercynian unconformity above the null point. There has been an apparent uplift of 2 km on the Hercynian unconformity. The amount of shortening normal to the fault is limited due to the geometry of the fault, and subsequent strain is accommodated by strike-slip or oblique-slip movement (location on Figure 12).

seismic line is important, as it illustrates what is believed to be a common inversion structural style in the Missour basin and the Atlas Mountains. Listric normal faults as illustrated on line MR22 are easier to reactivate than steeper planar faults due to a lower friction on the fault plane, particularly when the maximum compressive stress is horizontal. The listric fault on line MR22 was initially inverted by slip along the lower part of the fault, because the hanging-wall half graben was rotated up the fault plane. As the dip of the fault plane steepened, it became easier to generate a new fault that cut through the footwall as a lower angle thrust fault than to continue the inversion of the hanging wall up the steeper section of the original synrift normal fault (Figure 19A). This new shortcut fault formed a ramp-flat geometry similar to that generated in a fault-bend fold style of deformation associated with purely compressional tectonics. Continued shortening across the fault zone developed a fault-bend fold over the ramp in the footwall. The generated fold is an open fold that is slightly asymmetrical. Further shortening across the fault zone results in the initiation of a breakthrough fault along the forelimb of the fault-bend fold, and continued shortening is accommodated by uplift along the steeper reverse fault (Figure 19B). This breakthrough by reverse faulting occurs instead of further shortening along the ramp by the fault-bend fold. Reconstruction of line MR22 to the base Cretaceous unconformity (Figure 19C) illustrates the geometry of the half graben prior to inversion. Stratigraphic relationships in the half graben east of the listric fault indicate there may have been a phase of uplift prior to the Cretaceous, because erosion and folding are apparent in the synrift sedimentary rocks. The synrift geometry may also represent the fold geometry associated with the synrift listric fault.

Using relationships from the restoration of line MR22 to a postrift preinversion phase, we can estimate the amount of shortening across the fault zone. This technique has been proven to be effective for estimating β as defined by McKenzie (1978) for normal faults across tilted fault blocks (Le Pichon and Sibuet, 1982):

$$\beta = \sin\phi / \sin(\phi - \psi)$$

where ϕ = angle between listric fault and prerift unconformity and ψ = angle between prerift unconformity and a synrift stratigraphic horizon;

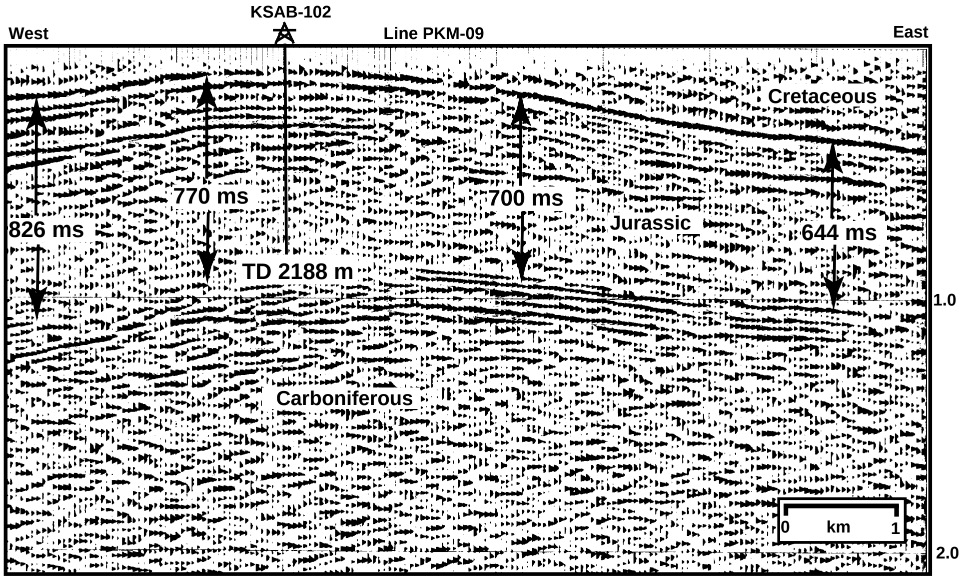

Figure 16—Seismic profile PKM-09. Inversion can be demonstrated by the uplift of a previous half graben. Thickening from the right to left across the section can be seen from a reflector in the synrift sequence to a reflector at the top of the Triassic basalts (location on Figure 12).

thus, $\phi = 22°$, $\psi = 12°$, $\beta = 2.15$ (stretching factor, $1/\beta = 0.46$).

The amount of stretching obtained for this half graben (2.15) in the Missour basin is the ratio of the crust before and after extension as defined by McKenzie (1978). Values of β for the North Sea (Figure 3) based on seismic reflection data are approximately 1.4 (Barr, 1987). Stretching values (β) for the Rhine graben are 1.15, the Armorican margin is 1.53, and the Afar rift system is 3.0 (Le Pichon and Sibuet, 1982).

Similarly, the subsequent amount of shortening across the fault zone can be calculated using the distance between the pin line and loose line of the restoration of line MR22 (Figure 19). The distance between the pin line and loose line prior to restoration is 17 km, and the distance before shortening is 20 km. The resulting amount of shortening across line MR22 is approximately 15%.

High-angle normal faults such as interpreted on line MR17 (Figure 15) will accommodate much less shortening with stress oriented normal to the fault plane. Steep faults in the Missour basin are accommodating strain created by horizontal compression by strike-slip or oblique-slip deformation. A significant amount of strain may be accommodated by the strike-slip and oblique-slip movement on high-angle normal faults, but the amount of strain and shortening across these faults is difficult to quantify due to movement in and out of the plane of the seismic section. The combination of both high-angle and listric normal faults in the Missour basin and Atlas Mountains results in a complex tectonic history after inversion. Horizontal stress applied to the synrift fault systems of the Atlas probably resulted in deformation by oblique-slip reverse movement, as well as fault-bend folding, and a thin-skinned style of deformation resulting from inversion.

INVERSION TECTONICS

Structural inversion related to intracontinental rifting occurs when extensional rift faults reverse their sense of motion during subsequent episodes of compressional tectonics. Features generated by extension, such as half grabens, are uplifted to form positive anticlinal structures.

It is important to validate that a structure is actually an inversion feature or a newly generated compressional structure, because reactivated rift faults have prospective stratigraphic relationships. A common feature of rifting is syndepositional growth strata or a progressive unconformity associated with an extensional half graben. Reactivation of the growth fault by later compression normal to the fault will result in a thicker synrift section in the hanging-wall anticline than in the footwall syncline. Inversion is sometimes difficult to recognize when uplift of the hanging wall has occurred to the point where erosion has removed any indication of the original thickening associated with the half graben.

The reactivation of normal synrift faults inverts previous half grabens into anticlinal structures, with the axis of the half graben centered below the axis of the inversion anticline. Anticlinal structures in the Missour basin and Atlas Mountains frequently represent an inverted half graben. Because of this relationship, hanging-wall anticlines formed by the inversion of synrift half grabens will have a thicker

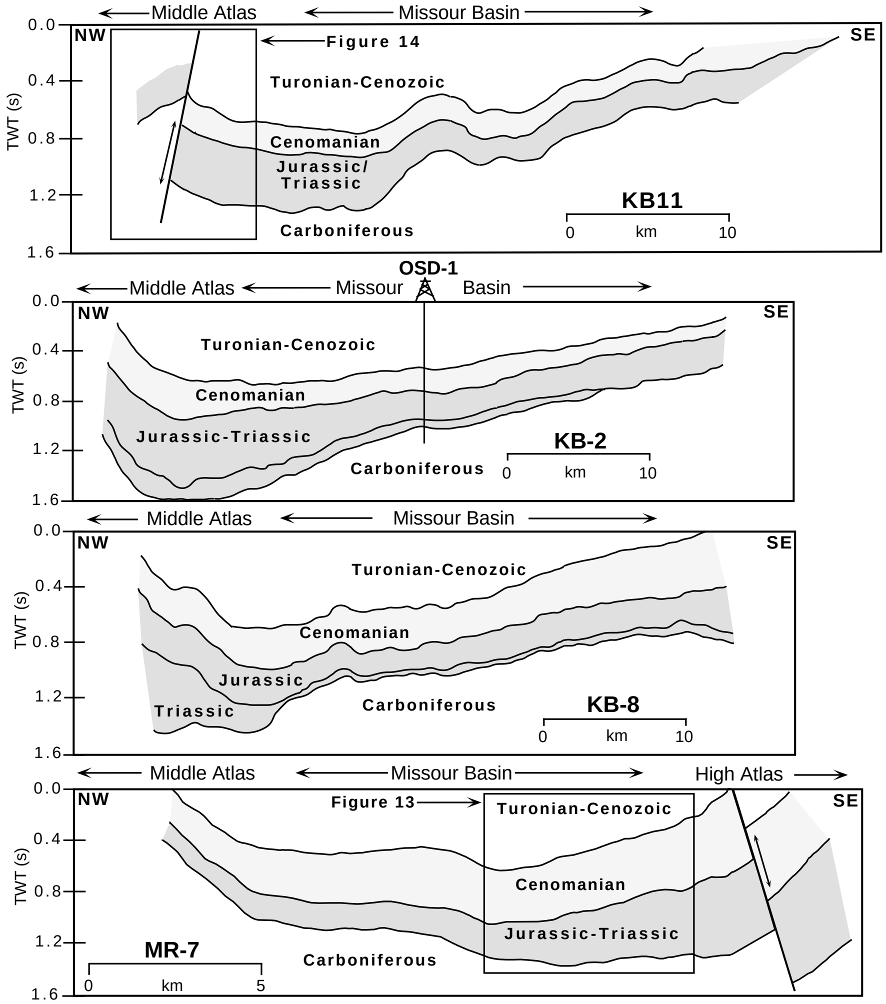

Figure 17—Interpretations of regional seismic profiles across the Missour basin. Note the thickening of the synrift sequences (Triassic–Jurassic) out of the Missour basin into the paleo-Atlas rifts (Middle and High Atlas mountains). Regional inversion effects can be seen by the uplift of the stratigraphic section near the basin margins. The base Cretaceous unconformity in some cases may have removed the sense of synrift thickening into the rift (KB-2). The locations of Figures 13 and 14 are shown. TWT = two-way traveltime.

synrift section in the hanging wall than in the footwall even though the hanging wall may be above the footwall. The resulting inverted fold geometry is controlled by the geometry of the extensional fault (planar or listric) and the depth of detachment (e.g., Mitra, 1993). Reactivated listric faults normally form inversion anticlines that exhibit fault-bend fold geometry, and allow for greater shortening than planar faults. This style of inversion and shortening may have contributed to the creation of the high elevations (>4000 m) in the High Atlas Mountains. Inversion along listric faults can generate a compressional fault-bend fold that is more open or symmetrical than a fault-propagation fold generated by the reactivation of a planar fault (Mitra, 1993). Folds generated by reactivated normal faults are commonly associated with fault breakthrough along the forelimb of the anticlines, as well as footwall thrusts.

Half grabens formed during rifting are divided into a synrift and postrift sequence separated by an unconformity (base Cretaceous in the Missour basin) (Figure 13). Sedimentary rocks associated with the postrift sequence normally have lower dips, usually associated with regional subsidence into the paleorift basins. The synrift sequence, however, is associated with steeper dips related to the original hanging-wall fold shape and stratigraphic growth. The dips of sedimentary rocks in the inverted anticlinal structure are steeper in the core of the anticline than along the flanks of the inverted structure. Planar faults that do not develop hanging-wall anticlines frequently preserve the relationships of steeper dipping synrift sedimentary rocks after they are inverted into fault-propagation folds. The structure at Jebel Missour exhibits this relationship, where flat-lying postinversion Neogene sedimentary rocks onlap more steeply dipping Upper Cretaceous rocks that, in turn, overlie Jurassic rocks exhibiting yet even steeper dips.

Listric faults that generate hanging-wall rollover folds during extension must be "unfolded" during

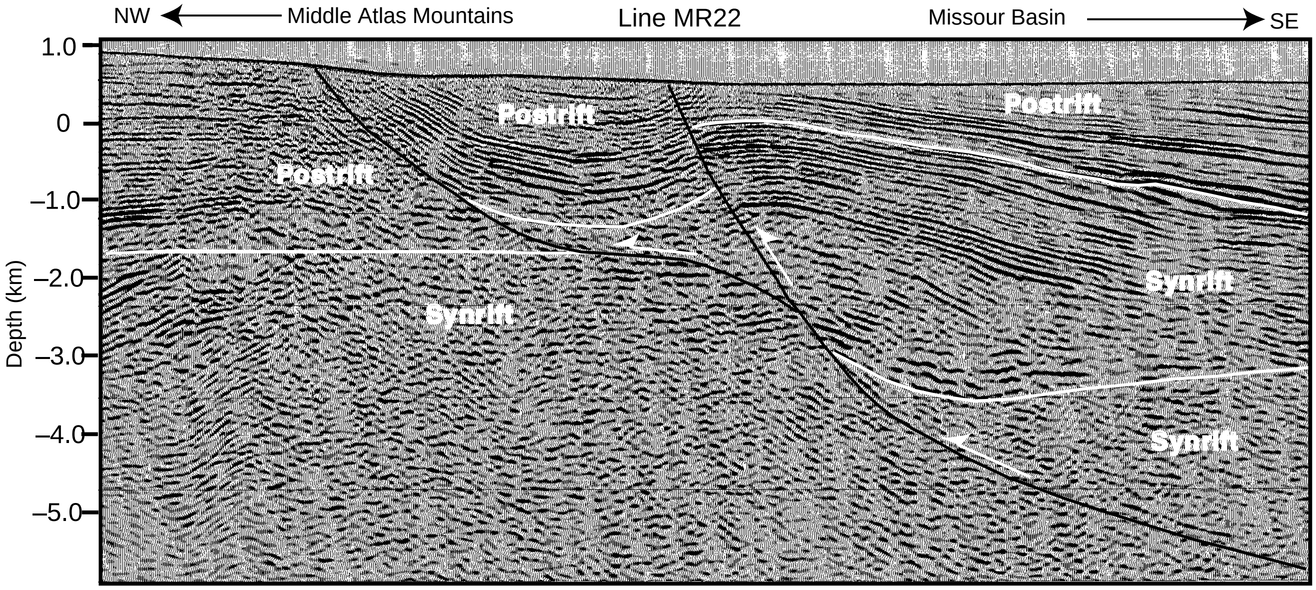

Figure 18—Seismic line MR22 was migrated and depth converted to enable the modeling of the reactivated listric normal fault seen on the seismic profile. Thickening of the synrift sedimentary rocks is evident from the southeast to the northwest into a listric normal fault that dips to the southeast.

inversion before the hanging wall can be refolded into an inversion anticline (Mitra, 1993). The restoration of the inverted listric fault on seismic line MR22 (Figures 18, 19) shows that there are synrift reflectors indicating dips that may be related to an earlier extensional hanging-wall rollover fold. An inverted listric normal fault is difficult to restore to the exact geometry present prior to inversion, possibly due to slip out of the plane of the section.

Inverted structures are important exploration objectives because extensional half grabens may contain source rocks and reservoir rocks. Hydrocarbons generated during rifting are generally trapped in the synrift sequence updip along the crests of footwall anticlines associated with extensional half grabens, such as in the North Sea. The inversion of faults associated with footwall anticlines results in the uplift of the hanging-wall graben above and sometimes over the top of the original footwall anticline (Figure 19). The result of this inversion is the creation of a hanging-wall compressional fault-bend fold in combination with a subthrust footwall anticline/ramp. This relationship produced by inversion tectonics creates the opportunity for stacked structural traps, both in the original footwall anticline and in the inverted hanging-wall fold. This type of potential trap could be important with significant shortening and inversion. Large amounts of horizontal shortening may place Triassic sedimentary rocks containing salts and evaporites above Jurassic source and reservoir rocks in the footwall, providing an effective seal. This seal formed by the thrusting of the Triassic sequence could help to maintain traps formed during rifting in the Jurassic and help to form a new trap that can collect hydrocarbons that are remigrated by subsequent inversion.

HYDROCARBON POTENTIAL

The Missour intermontane basin was formed by the uplift and inversion of the margins of the Atlas rift system. The stratigraphic relationships of the Missour basin are such that the distribution of synrift sedimentary rocks (Triassic–Jurassic) of source rock facies, as in most rift basins, would not be expected to be along the margins of the rift. Most source rocks related to the synrift phase of the Atlas rift system would have been deposited in what is now the High and Middle Atlas mountains (Atlas paleorift). For this reason, the most prospective areas for hydrocarbon traps in the basin are along the margins of the High Atlas and Middle Atlas mountains. These regions are important exploration fairways because hydrocarbons generated during the synrift and postrift phases of the Atlas rift system would have migrated updip toward the basin margins. Hydrocarbons trapped in the original rift structures may have remigrated toward the margins of the Atlas Mountains upon the inversion of the rift system. Two potential

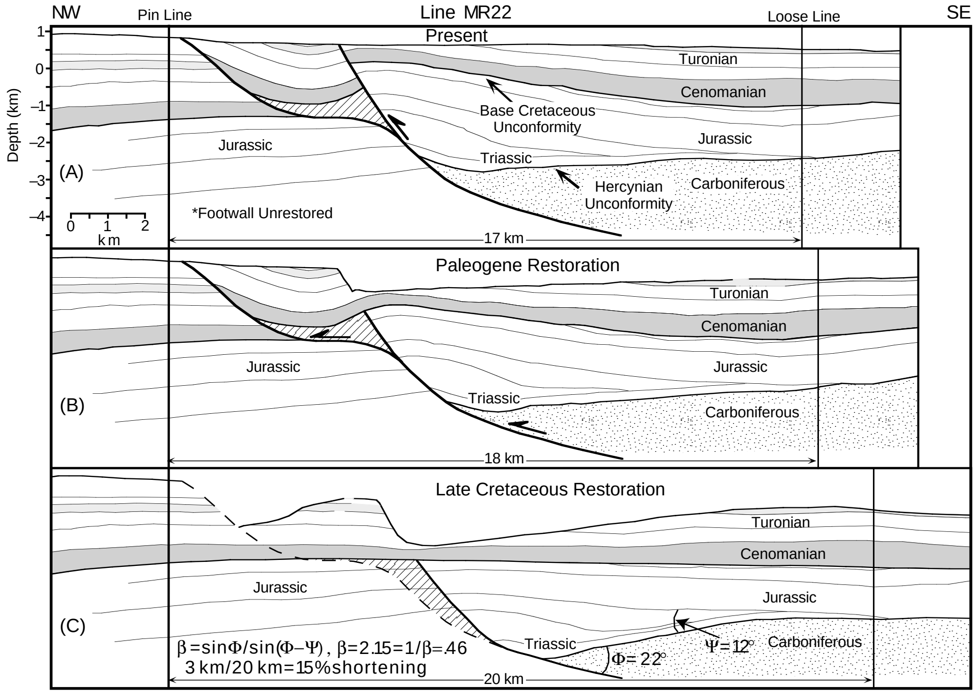

Figure 19—Restoration of migrated and depth converted seismic reflection line MR22. Reactivation of the synrift listric fault occurs until the fault steepens, and the synrift fault is bypassed. Shortening is then accommodated by a thrust that cuts the footwall at a lower angle (C). A fault-bend fold forms over the new footwall ramp (B), and is later faulted along the forelimb by the reactivation of the original synrift normal fault (A). Shortening then occurs in the hanging wall along the high-angle reverse fault. Shortening of the original half graben is approximately 15%. The thinning factor β is approximately 0.46 that is the inverse of McKenzie's (1978) stretching factor β.

hydrocarbon systems are present in the Missour basin and Atlas Mountains: (1) the Paleozoic–Triassic system sourced from the Paleozoic and sealed by Triassic salts and basalts with potential Triassic sandstone reservoirs, and (2) the post-Triassic system with potential sources and reservoirs in the Jurassic and Cretaceous. The structural models developed for the inversion of synrift normal faults in the Missour basin and High Atlas Mountains are favorable for trapping hydrocarbons in the following three scenarios.

(1) The inversion of a listric normal fault may position Jurassic source rocks in the footwall of a fault-bend fold-style structure, creating the possibility of moving immature synrift source rocks into the oil window in the footwall of a thrust. Triassic evaporites in some cases may be thrust over source and reservoir rocks in the footwall, creating an effective top seal.

(2) Inversion creates the possibility of preserving hydrocarbons trapped during rifting. As observed along the margins of the Atlas Mountains, not all synrift faults are reactivated. Some extensional structures that trapped hydrocarbons during rifting may be preserved beneath thrust faults originating from reactivated listric faults (footwall shortcut faults).

(3) Paleozoic source rocks (Carboniferous–Silurian–Devonian) are more prospective in the Missour basin and the margins/shoulder areas of the paleo-Atlas rift systems. Paleozoic source rocks in the Atlas rift probably would have been buried too deeply to have any remaining source rock potential. A lower geothermal gradient and burial depth in the Missour basin and other rift margins may yield potential traps sourced by Paleozoic source rocks. Hydrocarbons sourced from the Paleozoic may be trapped in Triassic sandstones and sealed by overlying and interbedded salts, anhydrites, and basalts of the Triassic.

Source rock samples collected in the field in the Middle Atlas Mountains west of the Missour basin indicate favorable source rock parameters (Table 2). Upper Pliensbachian source rocks yield total organic carbon values between 1.66 and 3.87%. The T_{max} (Rock-Eval) values of 421–437°C for these upper Pliensbachian marls (type II) are approximately equivalent to vitrinite reflectance values of 0.5–0.6 (Miles, 1989). These data indicate that the upper Pliensbachian (Dommerian) source rocks are too immature for oil generation. These source rocks may be similar to source rocks of the same age found in the Paris basin and other parts of central and southwestern Europe (Hallam, 1987). Additional potential may be present in Pliensbachian–Bajocian reefs developed along the margins of the basin, such as those found at Jebel Mechkakour and sourced by rocks of the same age (Figures 6, 12) (El Alji and Ouazzaba, 1995). Maastrichtian source rocks yield high total organic values (~18%) and have excellent potential for generating hydrocarbons when they occur in the footwall of a subthrust-style structure. These Maastrichtian source rocks may be related to other known source rocks deposited in the Late

Table 2. Geochemical Data from the Middle Atlas Mountains and Well OSD-1*

Latitude	Longitude	Depth (m)	TOC	S_1	S_2	S_3	T_{max} (°C)	HI	OI	Age
Middle Atlas Mountains										
33°25.46′N	4°20.65′W		3.87	0.81	2.5	0.96	437	323	25	Upper Pliensbachian
33°25.66′N	4°20.65′W		1.66	6.61	8.4	0.23	421	506	14	Upper Pliensbachian
33°08.53′N	5°09.48′W		18.12	6.21	117.4	2.22	419	648	12	Maastrichtian
Well OSD-1										
33°11.24′N	3°48.12.5′W	1768	1.92	0.09	0.27	0.23	474	14	11	Westphalian
33°11.24′N	3°48.12.5′W	2066	1.64	0.01	0.43	0.14	452	26	8	Westphalian
33°11.24′N	3°48.12.5′W	2401	11.44	0.52	18.7	0.62	439	163	5	Namurian
33°11.24′N	3°48.12.5′W	2556	1.28	0.04	0.52	0.15	453	40	11	Namurian

*TOC = wt. % organic carbon; T_{max} = pyrolitic yield in °C; S_1, S_2 = mg hydrocarbons/g rock; HI = $S_2 \times 100$/TOC; S_3 = mg carbon dioxide/g rock; OI = $S_3 \times 100$/TOC.

Cretaceous during a transgressive phase; these deposits were widespread organic-carbon–rich sediments in Morocco (Schlanger et al., 1987). Shales and similar deposits grade into laterally equivalent phosphorites of Late Cretaceous to early Tertiary age laid down on the southern margin of Tethys, stretching from North Africa into the Middle East (Hallam, 1987). The OSD-1 well drilled in the western Missour basin near the Middle Atlas Mountains (Figure 12) shows favorable source rock characteristics (type III) in Westphalian and Namurian marls and shales (Table 2). The geochemical parameters for the upper Pliensbachian, Maastrichtian, and Paleozoic source rocks, combined with the aforementioned trapping mechanisms, create exploration potential for hydrocarbon accumulations along the margins and within the Atlas Mountains.

CONCLUSIONS

The integration of surface geological mapping, seismic reflection data, well data, and remote sensing has given a better understanding of the tectonic processes, timing, and structural styles resulting from the various deformational phases forming the Atlas Mountains and associated basins.

The Missour basin was a stable shelf margin separating the High and Middle Atlas rift systems. Regional shortening across the region during the Late Cretaceous and Tertiary resulted in the uplift of the entire Missour basin region contemporaneously with the uplift/inversion of the paleo-Atlas rifts. Shortening across the region has occurred mainly along the margins and the interior of the paleo-Atlas rift systems. Most of the shortening across these rift systems was along preexisting faults formed during Mesozoic rifting or the previous Hercynian orogeny. The geometries of structures generated by inversion are controlled by the type of extensional faults formed during rifting and the orientation of the maximum compressive stresses relative to these faults (Figure 20). There are a variety of fault types (planar and listric), fault polarities, and fault distributions present within the Missour basin and the adjacent Atlas Mountains.

Several phases of deformation resulted in the shortening and inversion of the paleo-Atlas rift system and the Missour intermontane basin: uplift related to the Hercynian orogeny, an uplift phase in the Middle Jurassic, uplift in the Early Cretaceous related to subsidence, a major uplift/inversion phase in the Early Tertiary (Paleogene), recent deformation in the Neogene–Quaternary (left-lateral oblique slip) along the Middle Atlas-Missour basin margins, and right-lateral oblique-slip movement along the High Atlas–Missour basin margin (Figure 3A). The Missour basin may have been uplifted/inverted by the culmination of several phases of deformation. The region was previously part of the shelf margin or shoulder of the Atlas rift system and has been uplifted and translated to the northeast.

The combination of both high-angle and listric normal faults in the Missour basin and Atlas Mountains results in a complex tectonic history following inversion. Horizontal stress applied to the synrift fault systems of the Atlas has resulted in deformation by oblique-slip reverse movement, as well as fault-bend fold, thin-skinned style of deformation resulting from inversion. Applying structural inversion models to observed structures in the Atlas Mountains may present new exploration opportunities that have not previously been attempted as an exploration strategy in Morocco.

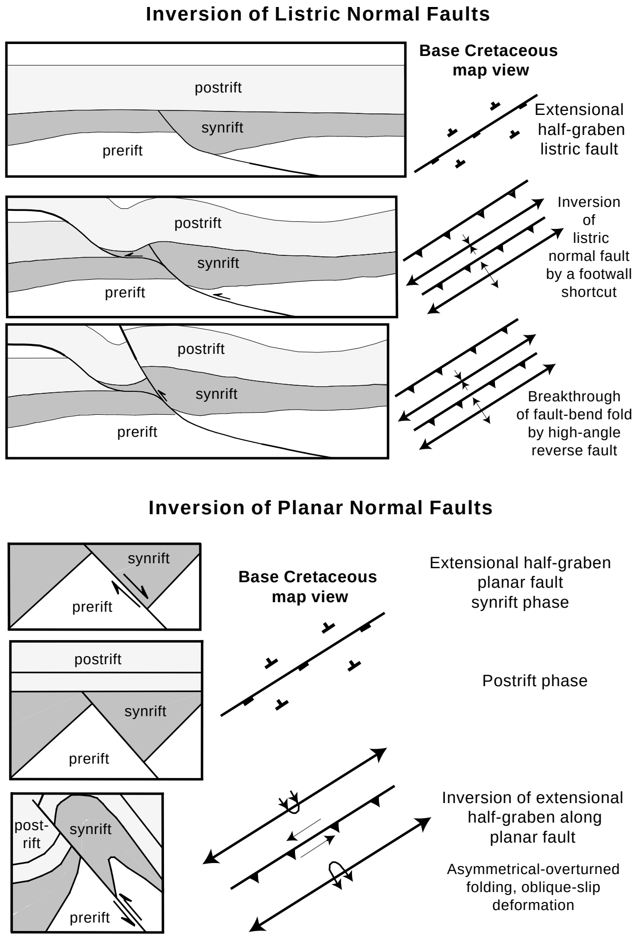

Figure 20—Faults associated with the Atlas rift system occur as both listric and planar normal faults. Fault-bend folds are frequently formed by the reactivation of listric faults, when compression is applied normal to the fault plane. Fault-propagation folds can form when compression is normal to a fault plane of reactivated planar faults. Listric faults reactivate by dip-slip movement when subjected to normal compression, whereas planar faults commonly reactivate by oblique-slip movement.

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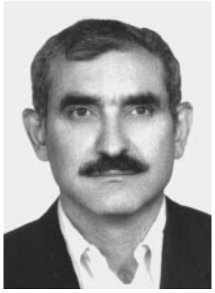
ABOUT THE AUTHORS

Weldon Beauchamp

Weldon Beauchamp received a B.A. degree in geology from New England College, New Hampshire, and an M.S. degree in geology from Oklahoma State University. He worked for Sun Exploration and Production Company in Oklahoma City, Oklahoma, and Dallas, Texas, as a geologist in the mid-continent region, prior to joining Sun International Exploration and Production Company in Dallas, Texas, and London, England. He worked for Sun as a new venture exploration geologist in the North Sea, Africa, and the Middle East regions. Currently, he is working on his doctorate in geophysics at Cornell University, Institute for the Study of the Continents. Recent interests are in the Atlas mountains of Morocco and the tectonics of North Africa.

Muawia Barazangi



Muawia Barazangi is a senior scientist and faculty member in the Department of Geological Sciences and the Institute for the Study of the Continents (INSTOC), Cornell University. He is the associate director of INSTOC, and leader and coordinator of the Middle East and North Africa Project at Cornell University. Academic background includes a B.S. degree in physics and geology from Damascus University (Syria), an M.S. degree in geophysics from the University of Minnesota, and a Ph.D. in seismology from Columbia University, Lamont-Doherty Earth Observatory (New York). Professional experience includes global tectonics, tectonics of the Middle East and North Africa, structure of the continental lithosphere, and structure of intracontinental mountain belts.

Ahmed Demnati

Ahmed Demnati is currently heading an exploration division of the Moroccan national oil company ONAREP (Office National de Recherche et d'Exploitation Petrolieres), where he is acting as chief geophysicist. Prior to joining ONAREP he was responsible for the geophysical and sedimentary basin division of the Moroccan Geological Survey. He holds an M.S. degree in geophysics from the Bergakademie Clausthal-Z, and a Ph.D. from the University of Hamburg in Germany.

Mohamed El Alji

Mohamed El Alji received a petroleum exploration engineering degree from ENIM (Ecole Nationale de l'Industrie Minerale) in 1987. Since this date he has been working for ONAREP (Office National de Recherche et d'Exploitation Petrolieres) as a petroleum geologist. He participates in the studies of different Moroccan basins and his interests are the Missour basin and the Prerif region.