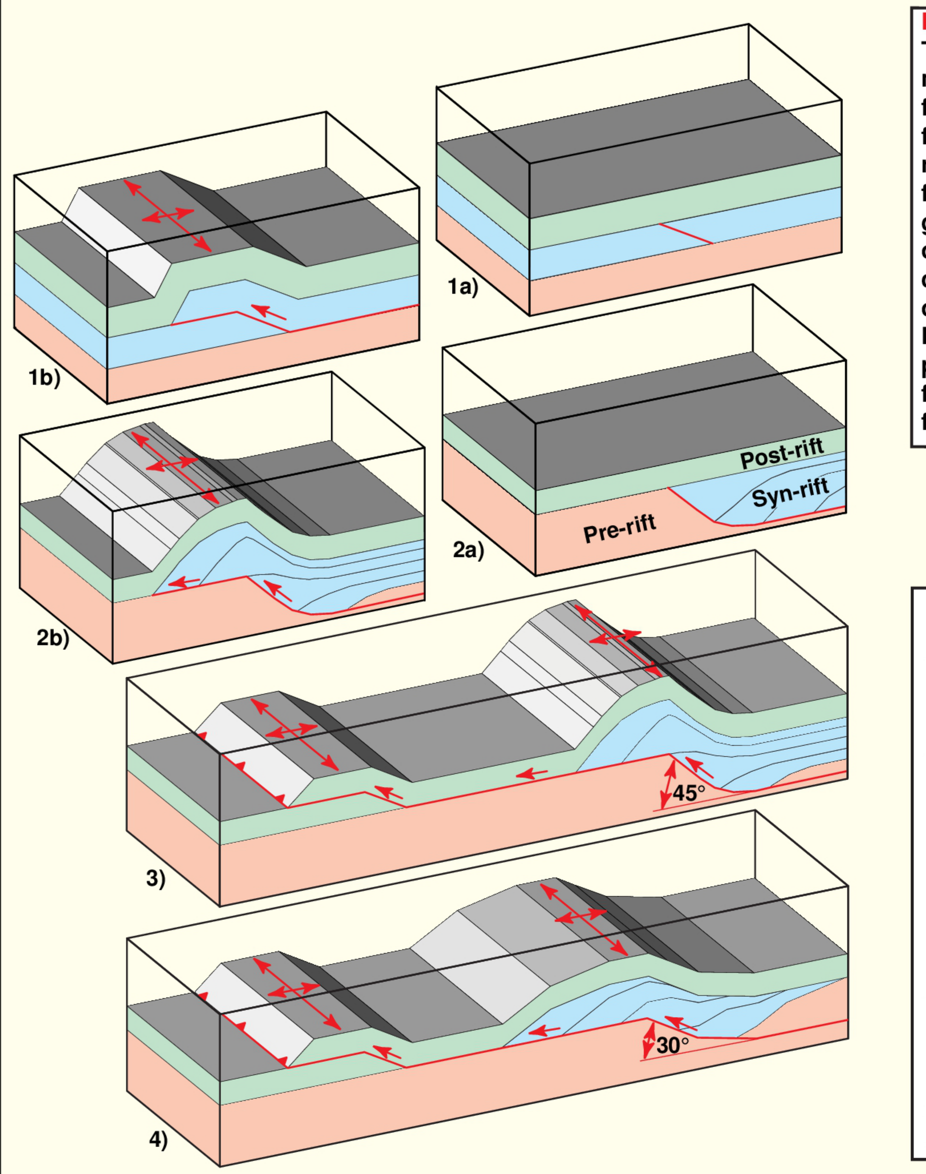
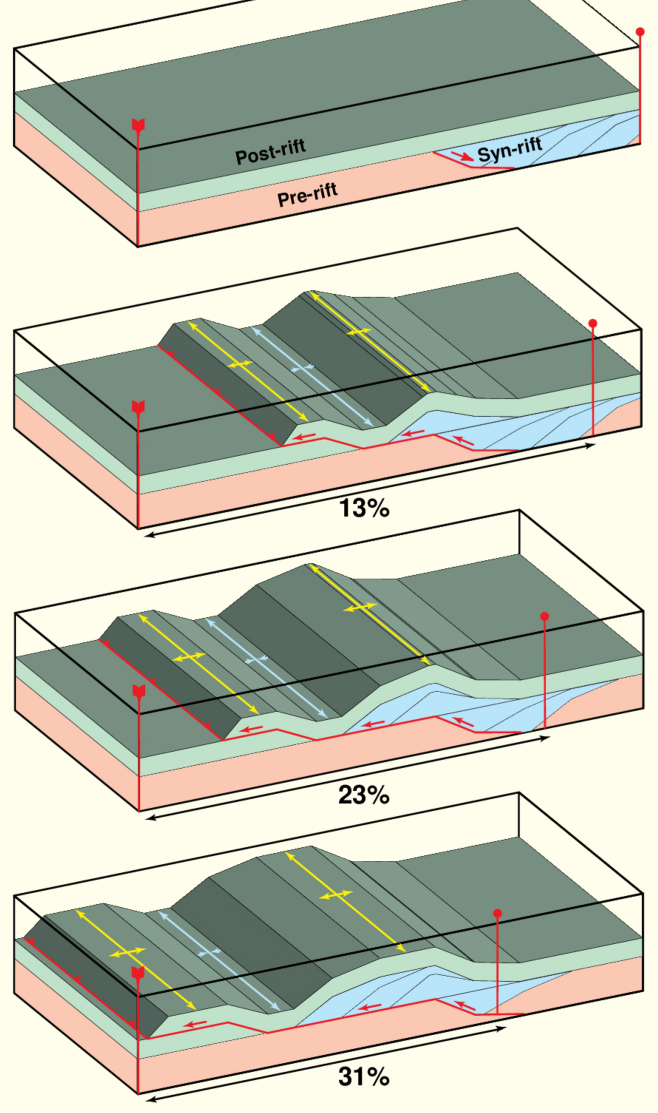
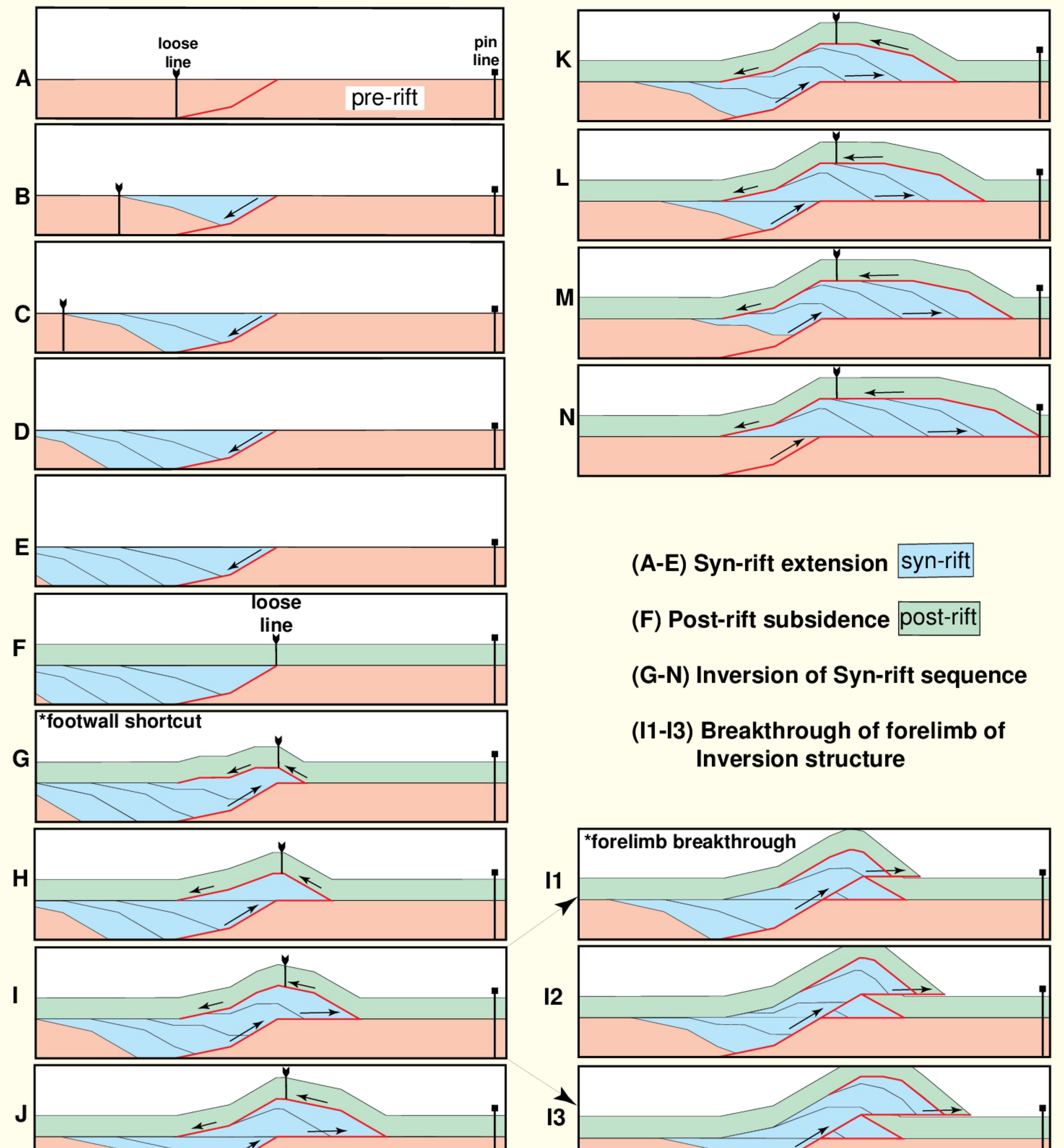
Models of Tectonic Inversion

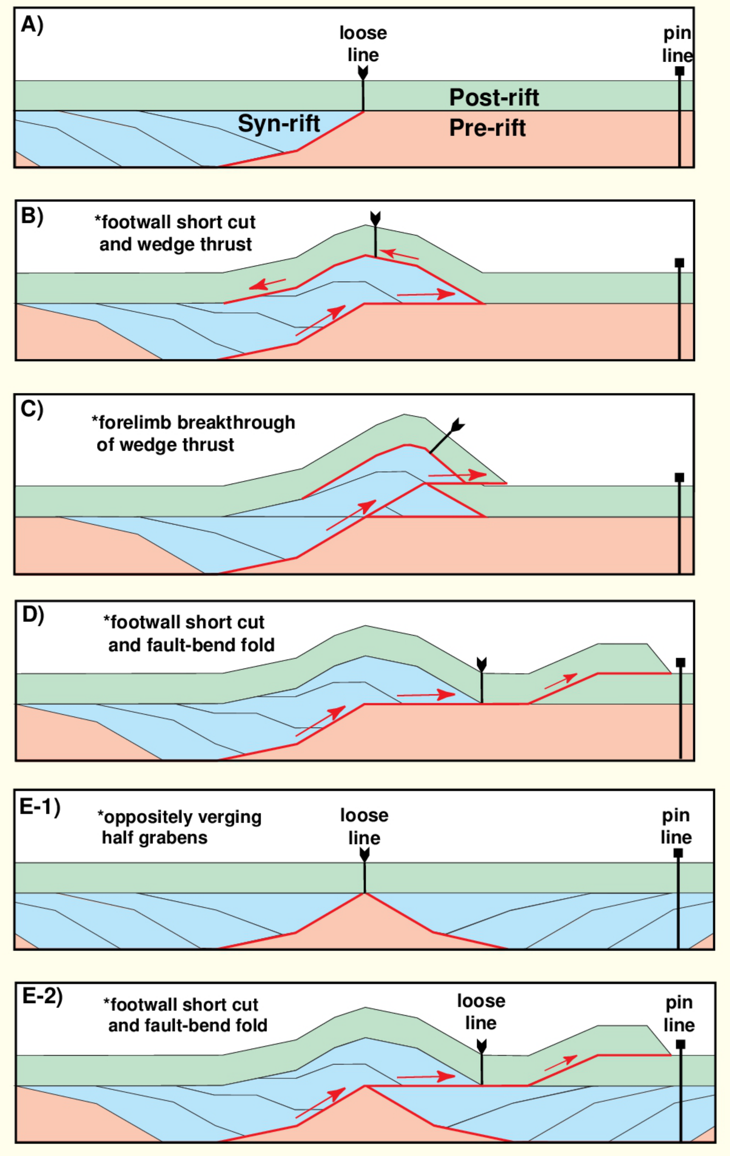


Left)
The tectonic evolution of the Atlas mountains involved newly formed fault-bend and fault-propagation folds (1a-1b) combined with reactivated syn-rift faults and footwall short cut faults (2a-2b). The geometry and amount of displacement of the original normal fault (2a-2b, 3 & 4) control the geometry and structural style of the resulting ramp anticline. Reactivated rift faults will transport previously deformed rocks along footwall short cut faults and newly formed thrust faults.

Right)
Reactivation of pre-existing faults and the inversion of extensional half grabens can lead to significant amounts of shortening. The southern margin of the Atlas mountains are believed to have deformed in a similar manner as the models to the right. Uplift of the graben bounding fault resulted in the formation of a more efficient low-angle thrust. Continued shortening across the rift margin resulted in the accomodation of strain by new fault-bend folds southward out of the rift basin (see transect A-A'). The uplift and inversion ofsyn-rift sedimentary rocks up the older syn-rift fault creates a fault-bend fold over the ramp as the fault steepens. These strata are then transported along the newly formed low-angle thrust fault.



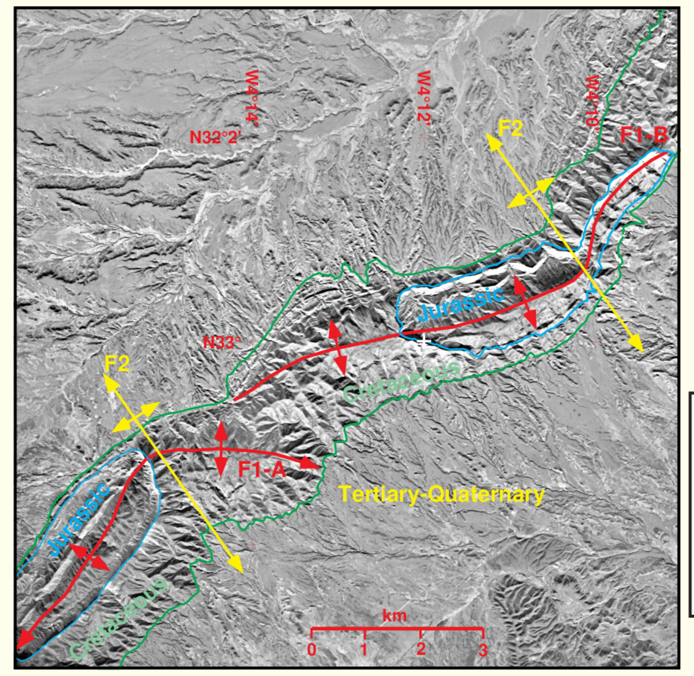




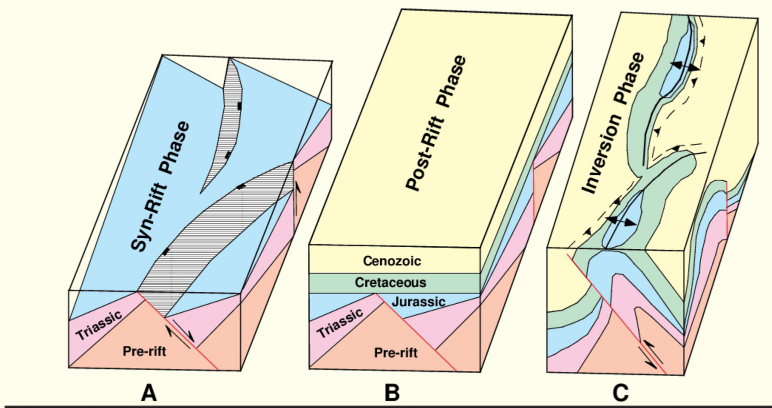
Above) Computer models were used in this study to simulate the structural relationships found in the field and on seismic reflection data in the Atlas mountains. A computer program by Wilkerson and Associates (Fault II) was used to create a listric normal fault with an assocated hanging wall rollover (A-E). A post-rift phase was added (F), and pin and loose lines to measure displacement. The above model then assumes that shortening is accomodated by a new thrust between the post-rift and pre-rift strata in the footwall of the previous normal fault. Shortening is achieved by the formation of a wedge thrust (G-N). Further deformation and shortening occurs by a forelimb breakthrough (I1-I3). This style of deformation may have taken place along the northern margin of the Atlas mountains along transect A-A'.

Above) Some possible variations related to inversion tectonics and fault reactivation are:
A) the initial formation of a syn-rift listric normal fault and associated hanging wall rollover.
B) uplift and inversion result in the formation of a wedge style thrust
C) followed by a forelimb breakthrough
D) reactivation of the syn-rift fault may lead to new thrusts and fault-bend fold style deformation
E1-E2) opposing half grabens may lead to reactivation of one or both of the grabens. These structures offer attractive structural relationships for hydrocarbon traps.

Geological Field Studies and Models

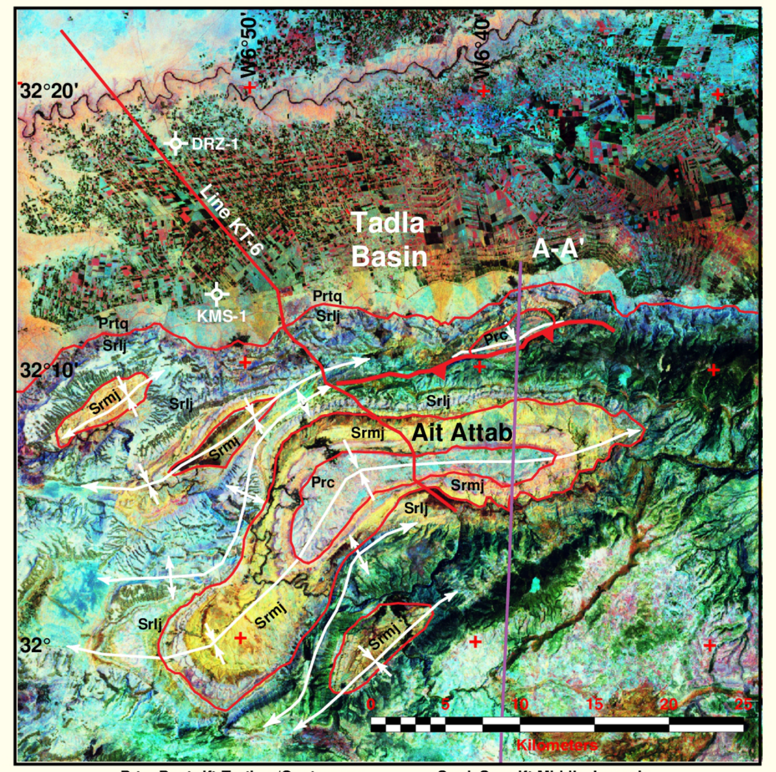


Jebel Missour, Missour basin, Morocco. These two structures (F1-A & F1-B) have an opposite sense of vergence, and were formed by the reactivation of pre-existing half grabens. A second phase of folding occurred related to compression oblique to the faults formed during the syn-rift phase (F-2).



These block diagrams show a palinspastic reconstruction of Jebel Missour (left), illustrating the effects of pre-existing syn-rift structures upon structures resulting from inversion.
A) Two syn-rift half grabens separated by an accomodation zone.
B) Deposition of Late Cretaceous and Cenozoic post-rift sedimentary rocks.
C) Reactivation of normal faults resulting in a fault-propogation style fold with forelimb breakthrough. These folds have the opposite vergence resulting in the transport of thicker syn-rift strata from the hanging wall over thinner syn-rift strata from the footwall.

Kinematic data were collected along faults exposed in the study area. Slickensides and fault lineations record the sense of shear and whether a fault has been reactivated. Often faults will yield multiple slip indicators which record a complex structural history. (55°/195° dip of lineations, 60°/288° dip of plane, reverse sense of shear)



Prtq=Post-rift;Tertiary/Quaternary
Prc=Post-rift;Upper Cretaceous
Srmj=Syn-rift;Middle Jurassic
Srlj=Syn-rift;Lower Jurassic

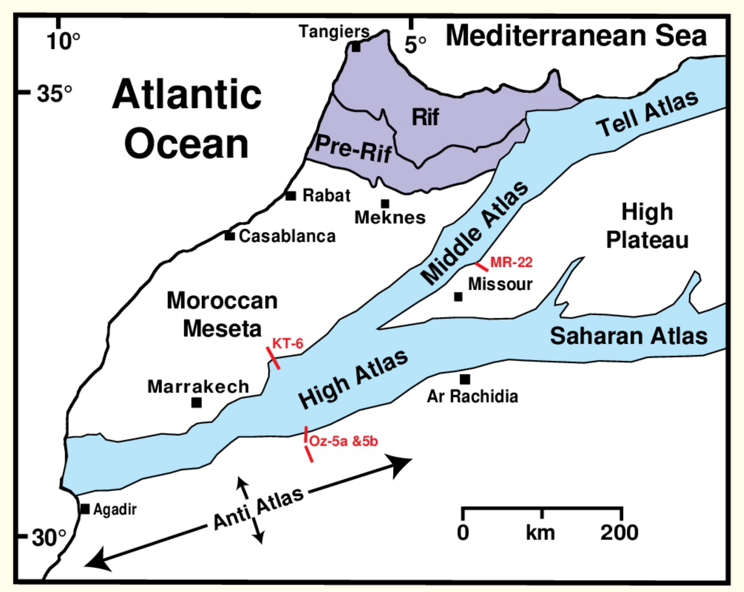
Simplified geological map of the Ait Attab syncline along the northern margin of the High Atlas mountains. Shown are the locations of seismic line KT-6, wells DRZ-1 and KMS-1 and transect A-A'. Fold axes, fault traces and stratigraphic contacts were mapped from field data and overlain on a LANDSAT-TM image (band ratio 7/1-red, 5/4-green, 3/2-blue).

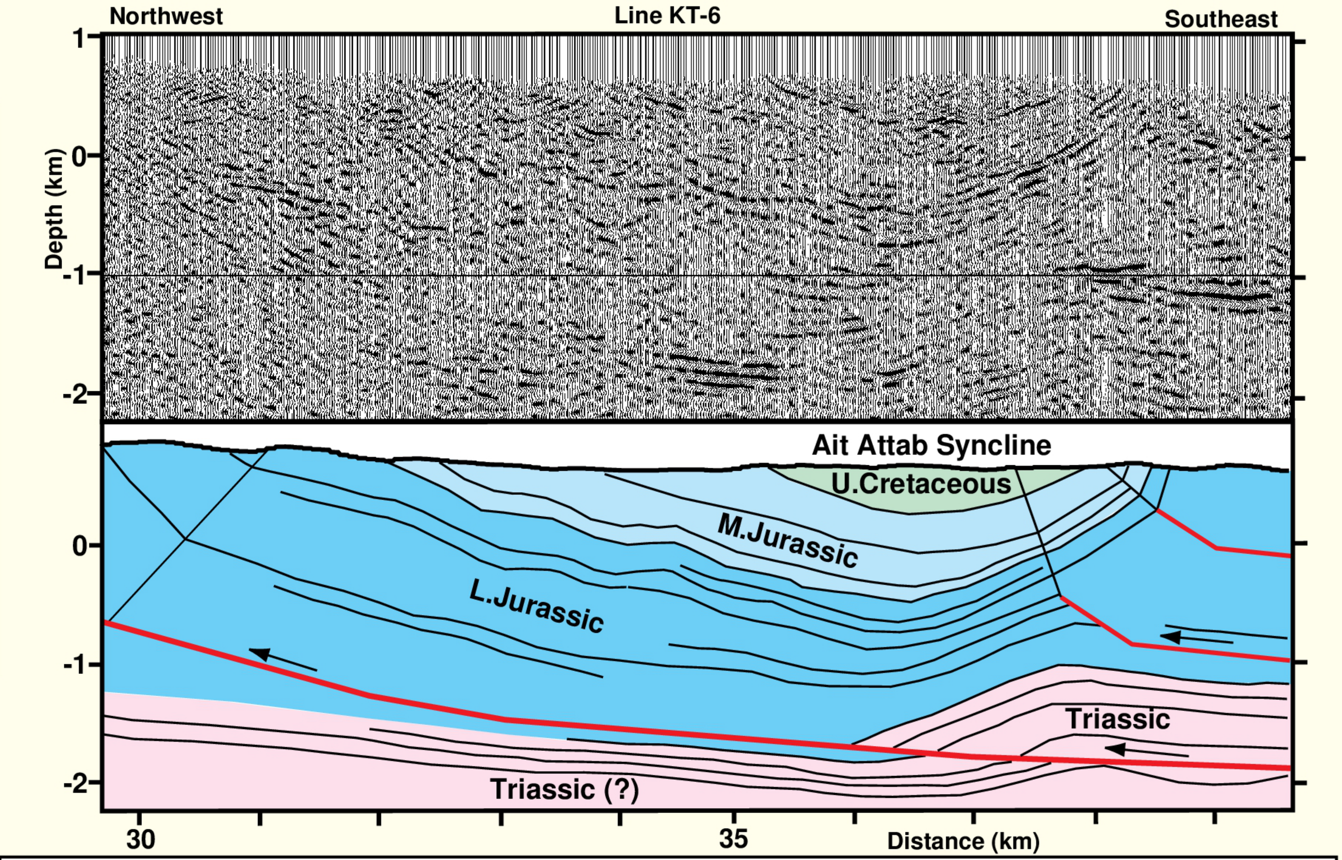
Lower-Middle Jurassic syn-rift sedimentary rocks exposed along the northern limb of the Ait Attab syncline (shown in TM image at left). The Ait Attab syncline is composed of syn-rift and post-rift strata which is believed to have been transported northward along a newly formed thrust fault upon inversion of the original half graben where these sediments were deposited (see Transect A-A' &Line KT-6). The Ait Attab syncline is one of the few areas in the High Atlas where Upper Cretaceous sedimentary rocks are preserved.

Small scale folding in the hanging wall of a major thrust fault along the northern margin of the High Atlas, south of Beni Mellal. Small folds such as these were not accounted for in the calculation of the overall shortening of the High Atlas (36 km/32%). If folds of this scale had been included, estimates of shortening would have been significantly higher, which may imply the estimate of 36 km shortening from transect A-A' is a minimum.

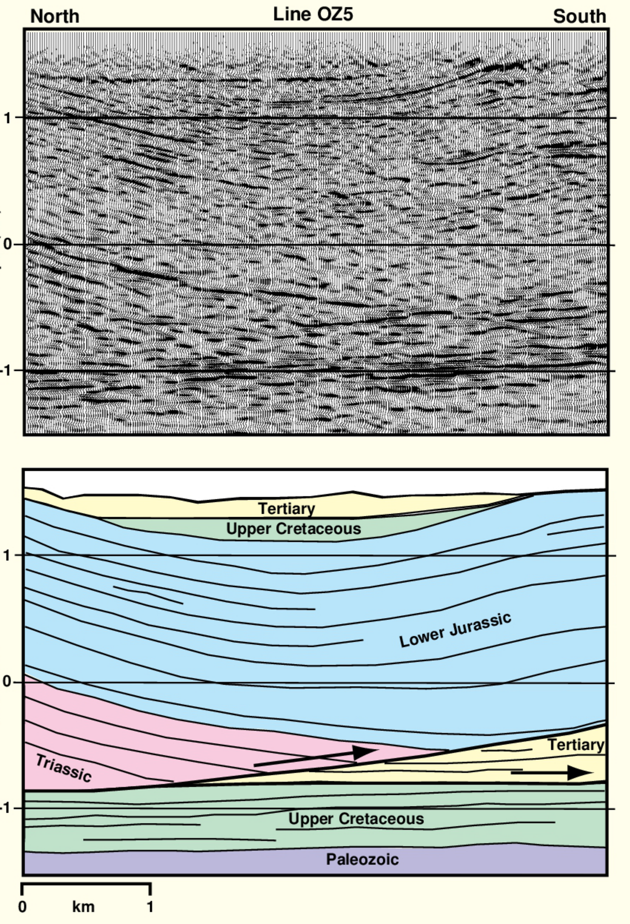
Large scale folding in the central High Atlas north of Jebel Mgoun. Lower Jurassic (Sinemurian/Hettangian) beds are steeply dipping (78°) to vertical along the southern limb of the fold/kink. The Triassic is exposed in the far right of the photo. Lower Jurassic bedding is gently dipping to the north (15-20°) in the left of the photo. Structures such as these are interpreted as forming by fault-propagation and fault-bend folding. The faults that form these structures are believed to propogate from evaporites in the Triassic.

Examples of Tectonic Inversion from Seismic Reflection Data

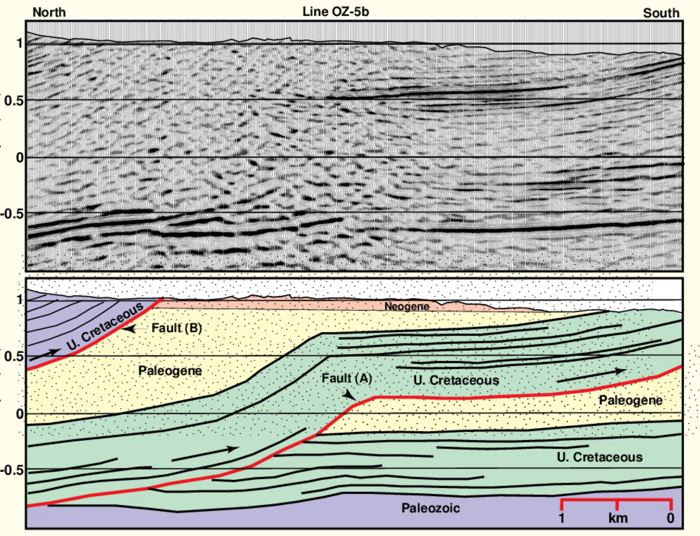




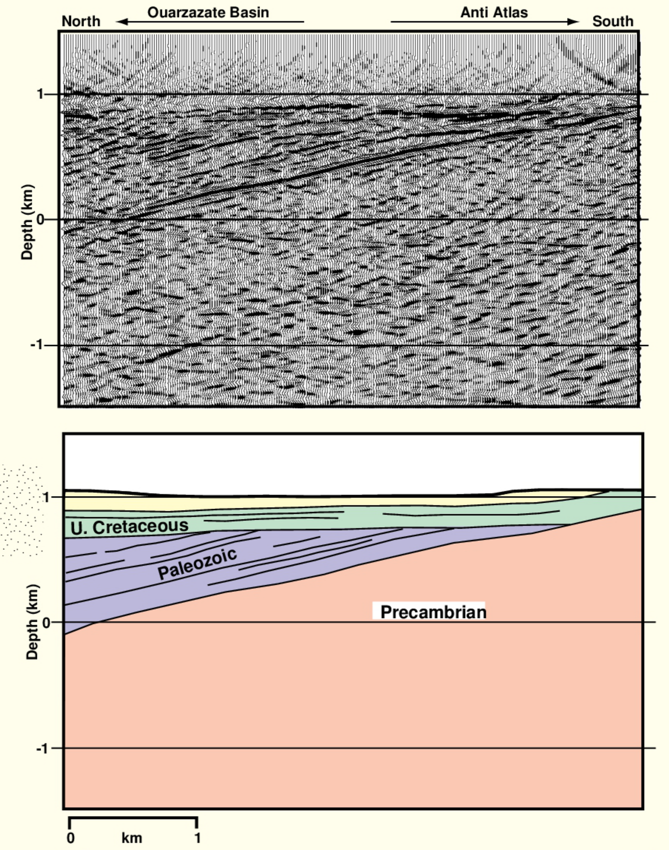
Above) A part of seismic line KT-6 (transect A-A') across the Ait Attab syncline in the northern High Atlas northeast of Marrakech. Reflections from folded syn-rift Jurassic rocks and post-rift Cretaceous show thickening from SE to NW across the syncline. These folded rocks in the syncline lie above a major thrust fault (exposed to the NW) that formed in the footwall of a syn-rift half graben. These folded rocks in the Ait Attab syncline were transported up a reactivated normal fault, and along the hanging wall of a newly formed thrust.



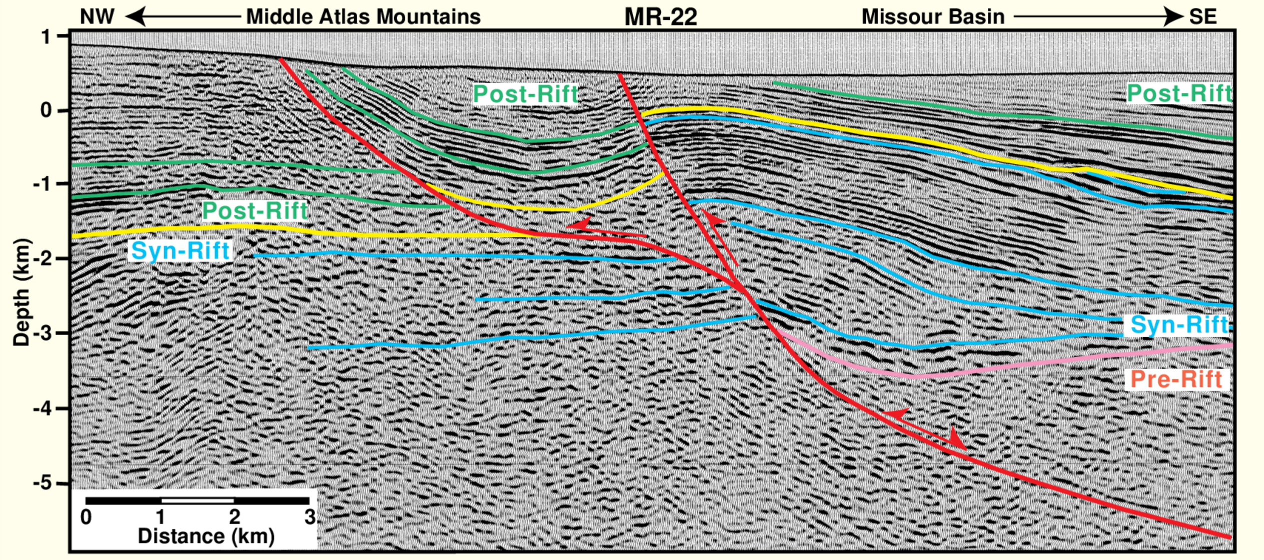
Above) Seismic line OZ-5b located to the north of the line shown to the right) in the Ouarzazate basin. This line shows what is interpreted as syn-rift rocks transported in the hanging wall of a new thrust. These syn-rift strata are thrust out-of-sequence over an earlier thrust formed between the Upper Cretaceous and Paleozoic.



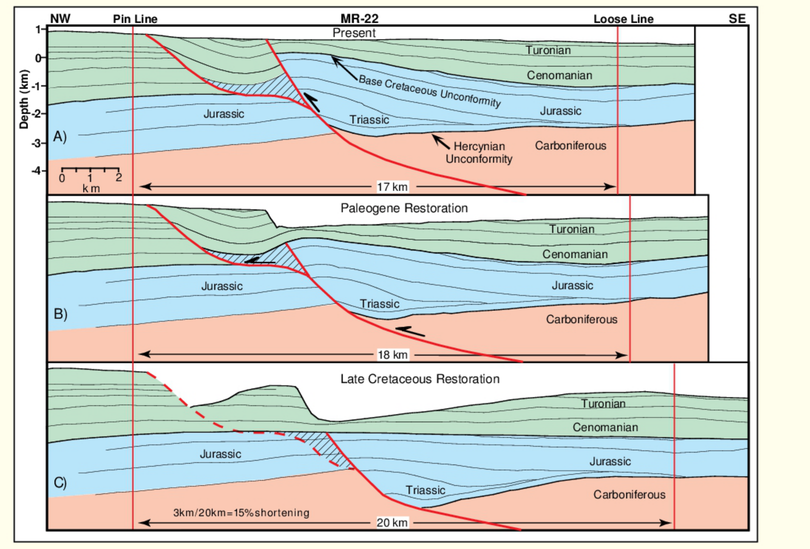
Above) Seismic line OZ-5b located along the southern margin of the High Atlas. This seismic line was shot across several exposed thrust faults which repeat the Upper Cretaceous in the hanging walls of thrusts interpreted as newly formed fault-bend folds developed during the Oligocene. Fault (A) is believed to have occurred first with Fault (B) occurring out-of sequence.



Above) Seismic line OZ-5a located along the southern margin of the Ouarzazate basin and the Anti-Atlas. The high amplitude reflection which dips 15° from the south to north across the section is interpreted as Precambrian basement. The reflectors above the basement are interpreted as Paleozoic rocks which are truncated by the Upper Cretaceous unconformity.



Above) Seismic line MR-22 from the southeastern margin of the Middle Atlas mountains. This line was migrated, depth converted and displayed with no vertical exaggeration to illustrate the structural geometry of a reactivated syn-rift fault and a resulting footwall short cut fault. Reflections in syn-rift age rocks show thickening into a listric normal fault.



Above) Cross sections showing a palinspastic restoration of line MR-22 (C) with the reactivation of a syn-rift listric fault during the Paleogene (B), and the formation of a mechanically more efficient footwall short cut fault. Displacement along these two faults formed a fault-bend fold over the resulting ramp, until a high angle breakthrough occurred along the forelimb (A).