COMBINED REMOTE SENSING AND FIELD INVESTIGATIONS
OF MAJOR LITHOSPHERIC COMPRESSION
IN THE TURKMENISTAN-IRAN
REGION OF CENTRAL ASIA

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“Better is one day in your courts than a thousand elsewhere; I would rather be a doorkeeper in the house of my God than dwell in the tents of the wicked. For the Lord God is a sun and a shield; no good thing does he withhold from those whose walk is blameless”
Psalm 84:10, 11
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CHAPTER I

INTRODUCTION

The folded Kopet Dag Mountains of Southern Turkmenistan (Figure 1) are generally regarded as the tectonic boundary between the Turanian Platform of the European plate and the Iranian microcontinent (e.g., Berberian, 1981). They extend from the eastern edge of the Caspian Sea to the Iranian-Afghan border and are linked in similar orientation across the Caspian Sea to the Caucasus. The Kopet Dag Mountains are bounded by the Kopet Dag Fault to the north and the Binalud Fault to the south. The Kopet Dag and Binalud Mountains are also generally regarded as the region representing the suture zone from the closure of the Paleo-Tethys Sea (Figure 2) (Allen and Sengor, 1993; Natal’in and Sengor, 1994; Nowroozi and Mohajer-Ashjai, 1985; Sengor, 1976, 1979a, 1979b, 1984; Sengor and Kidd, 1978, Sengor and Dyer, 1979).

The Kopet Dag Mountains have also been regarded as a world-class example of foreland-fold and thrust tectonics with a foreland basin to the north (Sengor, 1984). To provide a sense of the scale for the plate-boundary interactions, a comparison with the western United States (Figures 3 and 4) is provided to help illustrate the distances and the relationship to plate boundaries using the much better known western United States tectonics. Because the Kopet Dag Mountains are strategically located on what has been widely considered the boundary region for both ancient plates like those that bounded the former Tethyan Sea and the boundary of current plates, studying the region should provide insight into the large-scale structure of the region. The formation of the Kopet Dag mountain range
Figure 1. Regional map of Turkmenistan. Red outline is the approximate location of field area and Landsat coverage on which this study is focused. Blue outline is the approximate limit of the regional Landsat 7 browse mosaic used to gain a sense for the regional geometry.
Figure 2. Regional tectonic map of Central Asia. Black arrows delineate current plate motion (After Lyberis and Manby, 1999).
Figure 3. Comparison of digital elevation models showing the relative size of collision zones of the Zagros and Kopet Dag to the Rocky Mountains from subduction zone to mountain front. Images are of nearly the same scale. Note that Miocene extension of Nevada essentially doubled the east-west width of the state. If Miocene extension is excluded, the relative size of the two collision zones is nearly the same.
has been interpreted in many different ways varying from strike-slip faulting to compression. Discerning the most likely origin of the regional deformation that formed this range is the focus of this thesis. Figure 2 shows the present-day tectonic provinces and significant ranges that are considered in this study.

Within the region of Turkmenistan and Iran, Mesozoic rocks were deposited in an oceanic environment that was created as vast seaways opened up in the region (Senger, 1984). Figures 5 through 8 are a generalized progression through time from Jurassic through Miocene illustrating the location of these seaways and the relative position of major continental masses as located by most modern-day plate reconstructions. These seaways are referred to as the Paleo-Tethys and Neo-Tethys that were present from the late Permian through the early Eocene. The details of these seaways and which exact ranges and rock units were formed in them are not well known. This is in part because of the remoteness of the region and the difficulty of interacting with workers in this region because of the past political boundaries that transect the area.

Most present models for the Kopet Dag Fault define it as a right-lateral, strike-slip dominated fault with a lesser extent of shortening directed to the northwest in the eastern Kopet Dag and northeast in the western Kopet Dag (Jackson and McKenzie, 1984; Tchalenko, 1975; and Trifonov, 1978). Other models advocate oblique convergence across this boundary with high-angle thrusting as the dominant mechanism of the Kopet Dag Fault (Lyberis and Manby, 1999). The nature of this specific fault is commonly taken as the nature of the boundary for the entire region; in other words, a strike-slip fault equals a strike-slip boundary or a thrust fault equals a compression boundary.
Figure 5. Late Jurassic tectonic reconstruction. Paleo Tethys encompasses the entire eastern hemisphere. Lut Block and Iran are colored red (After Müller and others, 1993, 1997).
Figure 6. Early Cretaceous tectonic reconstruction. Paleo Tethys encompasses the entire region. Closure of the Paleo Tethys is beginning as Gondwanna begins to break apart (After Müller and others, 1993, 1997).
Figure 7. Middle Eocene tectonic reconstruction. Remnant block of the South Caspian begins to collide with Iran and the subsequent formation of the Talesh and Alborz Ranges (After Müller and others, 1993, 1997).
Figure 8. Early Miocene tectonic reconstruction. Lut block has finally collided with the Turan Platform resulting in the closure of the Paleo Tethys (After Müller and others, 1993, 1997).
The folded Kopet Dag Mountains stand in stark contrast to the apparently undeformed Karakum platform to the north, which is almost totally covered by the sands of the Karakum Desert. The boundary between the covered desert and the highly deformed mountains has led to the widespread interpretation that these two regions are located on opposite sides of a plate boundary (Berberian, 1981). This interpretation has been incorporated into many figures and drawings synthesizing the plate tectonics of the world and is often shown as a strike-slip boundary because of the presence of major strike-slip faults in the region and the active seismicity that is occurring here. Alternative interpretations invoking the compressional nature of the region and considering it as a world-class example of foreland-fold and thrust tectonics with a foreland basin to the north have also been made (Sengor, pers. comm., 1999).

The dominant component of motion in the Kopet Dag has been interpreted by earlier workers (Jackson and McKenzie, 1984; Tchalenko, 1975; and Trifonov, 1978) as a northwest-trending, strike-slip fault with oblique, right-lateral motion. Active compression in the northward direction with essentially little deformation in the foreland basin is also the widespread interpretation of this region (Berberian, 1981; Lyberis and Manby, 1999). The Kopet Dag fault is commonly thus assumed to represent a strike-slip plate boundary, based on observed strike-slip faults. The assumption is made that because there are strike-slip faults in the area that this is therefore a strike-slip boundary.

What is not considered is that strike-slip faults do not necessarily infer a strike-slip plate boundary, but can be secondary to a much larger-scale, thrust system. Strike-slip faults commonly appear in extensional and compressional systems in the form of accommodation zones and transfer faults. Their role as secondary, rather than first-order features is one of
the concerns of this study. Major compressional features are also present in this region. Compressional features can obviously form as secondary features in a strike-slip setting, as is interpreted in many regions around the world such as in California and Indonesia (e.g., Wilcox and others, 1973). Trying to discern what the dominant structural style is, whether it is strike-slip or compressional, and which is the secondary component in the regional deformation is the focus of this study.

Discerning between these two major types of regional deformation was done using numerous spatial and spectral data sets coupled with field investigations of structural features. By seeking to gather regional information that showed the deformation in three dimensions and on both large and small scales, it was hoped that the many existing questions based on the widespread use of two-dimensional (compressional and strike-slip) mechanical models for the Kopet Dag could be resolved. Trying to also evaluate the presence of strain partitioning, whereby both strike-slip and compressional deformation are present and are collectively an expression of oblique motion, was also a focus of the work.

The difference between the two models has major significance in suggesting whether low-angle shortening would likely extend out into the Karakum platform, buried beneath the sands of this desert. Strike-slip faulting, or strain partitioning with both strike-slip and compressional features present, would suggest different tectonic models for the region. These different geometric models for the deformation of the Kopet Dag Mountains have major implications for both the seismic safety and risk analysis in the region and for hydrocarbon exploration. As an example, if low-angle compressional deformation is occurring in the region and underlies the capital city of Ashgabat with its 400,000 plus people, these people are significantly more at risk than if the fault is a high-angle, strike slip
or reverse fault located south of the city. Similarly, if the fault represents a region whereby the mountains are folded into structures that could trap hydrocarbons, but the desert does not, then the potential region for oil and gas exploration is far smaller in the vast desert region of Turkmenistan. A regional structural framework that helps provide the understanding of how strike-slip and compressional features can be present in this region can thus be very important for the people of Turkmenistan. This importance is both for evaluating the earthquake risk in the region and the potential for hydrocarbon traps and source rocks, which will have a major effect on the economy of the country and the ability of the people to succeed.

One of the most attractive models for interpreting the structural geology of this region is in linking the strike-slip and compressional structures with each other and trying to see how they interrelate. Field studies and analysis of remote sensing images focused on the geometries and interrelationships of the different deformational features and determining if the strain is being transferred from the large-scale thrust faults to dextral strike-slip faults at regional and local scales. In particular, fault-bend fold models (e.g., Shaw and Suppe, 1994, 1996) appear to be a powerful means of interpreting structural geometries based on the relationship between folds and faults. The geometry of structures associated with strike-slip faults provides clues into their role in the structural framework and their three-dimensional character. The thrust fault and fold-related models of Clark and Suppe (1988), Shaw and Suppe (1994, 1996), Suppe (1983, 1985), and Rouby and Suppe (1996) match the observed surface geometries and provide insight into the development of this Kopet Dag orogenic system. The lithologic control on structural framework (mechanical stratigraphy) is interpreted here as a primary control on the geometries of the folds and faults.
Historically, seismic activity has brought great loss to the people of Turkmenistan. In 1948 an earthquake of magnitude 7.3 claimed the lives of approximately 19,000 people (Ishankuliev, pers. comm., 1999) although other estimates of the loss are much greater. This earthquake occurred before the building of the Karakum Canal, leakage from which has significantly increased the current seismic risk. Standardized, pre-manufactured apartment buildings with tilt-up walls were completely leveled in the earthquake. Immediately after the destruction of these buildings, the same inadequate style of buildings was reconstructed. Today the building construction has improved to modern European standards in terms of laws, although enforcement of these laws is difficult to assess. Many of the geotechnical problems neglected in the last 200 years still exist in the region. Many new geotechnical factors have been added to the seismic hazard equation with the onset of large-scale development over the last century for the major population center of Turkmenistan, which is located near the trace of the Kopet Dag Fault.

In addition to the natural seismic risks associated with major fault zones, much of the infrastructure of the region was constructed with little thought to potential natural disasters. As an example the Karakum Canal is an extensive aqueduct system subparallel to the topographic front that carries water that once drained to the Aral Sea via the Amu Darya. The canal was built in the Soviet era as part of a major project to develop southern Turkmenistan into an agricultural heaven much like the Salton Trough was thought to be. This canal is lined with concrete in only a few places, and the lining is only along the sides of the canal, not in the center where more water can seep into the strata and out into the desert. Major leakage from the canal and extensive agricultural use of the water by flooding the
desert region parallel to the mountain front has greatly intensified the potential liquefaction hazards of the region.

The canal runs to the north of most of the populated areas such as Ashgabat and the direction of groundwater movement is to the north as well, downslope away from the mountain front. There is therefore less risk to the city interior than in the canal were in the middle of the city. However, many of the business and governmental regions of the city are still underlain by high groundwater levels. These levels decrease within the alluvial fan regions that form much of the residential parts of the city, upslope from the city center, but are still quite high (Ishankuliev, pers. comm., 1999).

Previous work has shown that at present the groundwater levels near the city range from the very near surface to 1-meter depth (Kissin, Belikov and Ishankuliev, 1996; Ishankuliev, 1994). This significantly increases the risk for liquefaction in a seismically active region. The regional setting is much like that of the Salton Trough with a semi-arid climate and seismically active terrane. Cotton is a major crop in southern Turkmenistan and requires an enormous amount of water. Much like the Salton Trough, the Karakum Desert is a prime candidate for geologic hazards associated with anthropogenic changes to the substrate. These environmental issues coupled with potentially low-angle fault geometry, beneath the city pose a severe risk to the people of Turkmenistan. The mountains south of Ashgabat, which have formed the historical boundary of Central Asia and Iran for thousands of years, were produced by motion on this very active fault system. Other earthquakes will unquestionably take place; the only question is when and how great the loss will be.
CHAPTER II

METHODS

The structural analysis of the Kopet Dag began with a regional approach, on the scale of hundreds of kilometers, and then a more localized synthesis at the scale of tens of kilometers. The structural style of the region was evaluated by composing regional mosaics of Landsat-7 browse imagery to gain a sense of the large-scale deformation fabric, as the Lut block impinges on the Turan platform (Figure 1). Detailed work was centered on a smaller region, specifically on the area around the city of Ashgabat, Turkmenistan, in an area the size of one TM scene Path 160, Row 34 (185 x 185 kilometers) (Figure 9 and Plate 1, back pocket). Folds and faults were examined in detail, as was their relationship to each other.

The actual shapes of the large-scale folds were determined using the remote sensing images. This analysis included characterizing spectral units to trace them throughout their outcrop. Spectral units were picked using a variety of reflective characteristics and their continuity throughout the imagery. Several different band combinations were used to map highly reflective and distinctive units. Spectral units were defined on the basis of consistency throughout several band combinations. Spectral units normally should mimic lithologic units with respect to outcrop pattern and distribution, so that the mapping using spectral units will mimic a normal lithostratigraphic geologic map.

Major faults were picked on the basis of duplicated, truncated, offset or missing spectral strata. Smaller-scale faults that did not offset spectral units and were not resolvable in the imagery were picked on locally known criteria or field discovery. The spectral
Figure 9. Landsat 741 image showing regional coverage (185 x 185 kilometers). A. Dushak Anticline. B. Markou Anticline. C. Vanovskova Syncline. D. Gaurs Dag Anticline. E. North limb of a rabbit-ear fold with complimentary fault. F. Karakum Canal. Main Kopet Dag Fault is colored in yellow with the bright green segment being a major thrust that has prominently broken the surface. Red faults are sigmoidal strike slip faults that are the actual sidewall ramps that tip out into imbricate thrust sheets. Projected bedding-parallel thrust shown in light blue. Imbricate thrust sheets can be drawn at the frontal edge of the north-verging folds.
mapping of folds, faults, and lithologic units was then compared to both high-spatial resolution data and field studies. Declassified Corona satellite photography acquired in September 1964 was the principal high-spatial resolution data that were used to validate the folds and faults that were discerned with the high-spectral resolution information.

The typical method of dividing formational boundaries in the traditional Soviet style of mapping is to separate the units based on fossil assemblages and not necessarily lithology. In essence, most published Soviet geologic maps are composed of chronostratigraphic units based on the known fossils at the time of the mapping. This proves to be quite difficult in the field when trying to use a chronostratigraphic geologic map as a base map. The use of spectral units is more consistent with field mapping and interpretation of lithologic units. Most Soviet-era geologic maps in the area were constructed on the basis of both chronostratigraphic and lithostratigraphic units. This makes it difficult to interpret stratigraphic and structural relationships because the map units do not always reflect the complete depositional and deformational history as displayed by the lithostratigraphic units. A major advantage to using spectral units to determine the fault and fold geometries is that the remote sensing images differentiate the lithologic units much better than the visible light field color and textures of different rock units, which are quite subtle. A differentiation of the rock units on the basis of field observations alone is very difficult, so that the images greatly assist in structural mapping. Accurate field mapping over a huge area in a relatively short amount of time is nearly impossible without using remote sensing data focused on spectral signatures of the different rock units.

Besides imaging the rock identities very well, the Landsat imagery also faithfully delineates the water content in the soil. The dendritic patterns of darker colors (Figure 9 and
Plate 1) represent high water content in the soils. The high water content results from water streaming out of the Karakum Canal for distances of 30-50 km in some areas. In most band combinations, water content appears as a dark pattern in a typically arid soil. Field observations show that the average groundwater levels in the city and surrounding area near the Karakum Canal have risen in the past 10 years and is now up to only 1 meter below the surface (Ishankuliev, pers. comm., 1999).
CHAPTER III

FIELD INVESTIGATIONS

Field investigations were conducted in order to discern the overall structural style, to identify the major lithologic units, and to relate them to the imagery. By doing detailed investigations of small-scale faults, it was hoped that they would provide insight for larger-scale interpretations. The major question in the process was to determine the stratigraphic control on structural style. Field data were collected in two forms. The first was done through analyzing of raw data of Landsat 5 (Path 160 Row 34) and Landsat 7 browse imagery (Paths 162-160 Rows 34-32) to best delineate stratal subtleties and distinguish definitive fault features that could be visited in the field. The latter was accomplished by five weeks of fieldwork centered on the correlation of the spectral information and field observation. Landsat scenes represent an enormous area (185 km x 185 km), so that it was physically impossible to traverse the whole region. Special consideration was therefore given to simply resolving what the stratigraphic units on a large scale and determining how they have responded to tectonic forces. The purpose of systematically tracking down unit boundaries in the field was to determine exactly how the rocks were behaving within the units and what the physical unit boundaries represented. A unit in the imagery is of little value unless it is also possible to determine what the lithologic, rheologic and deformational character of the unit is. Predictions can then be made as to how major deformation will occur in the unexposed rocks beneath the Karakum Desert.
Description of Mapped Lithologies

Stratigraphic units in the greater Gaur's Dag area exposed 20 kilometers south-east of the capital city of Ashgabat consist of a coarsening-upward sequence of limestone, marl, fossiliferous sandstone, terrigenous sandstone and conglomerate. Spectral units are displayed on Figure 10. Top and bottom of units are defined by an abrupt change in a spectral signature that corresponds to a lithologic boundary in the field. At the core of Gaur's Dag Anticline, the bottom of the mappable units (unit A) is a unit of Lower Cretaceous limestone of unknown thickness. Individual limestone beds are typically 2 to 4 meters thick with some units nearly 8 meters in maximum thickness. Paleontological data from Soviet publications indicate an age of Lower Cretaceous (Turkish Petroleum Inc., 1998). Ammonite fossils were found lying on this unit, but none were found in place. Throughout Sherwok Valley, which dissects the core of Gaur's Dag Anticline, brachiopods were abundant in thin lenses of shale, also supporting this general age of Lower Cretaceous.

Conformably overlying the limestone core of the Gaur's Dag Anticline is a 1000-m thick chalk and marl sequence (unit B). The base of the chalk/marl sequence is defined as the last occurrence of dense limestone beds a thickness of 2 meters. The chalk/marl unit is a rhythmically bedded package of syn-depositional chalk and shale. The unit as a whole is whitish tan to medium brown. Individual layers range from 7 to 15 cm in thickness and often contain fossil shell fragments. The contact between the two units is a gradational contact as individual 15-cm thick fossiliferous limestone beds are more abundant near the bottom of the chalk/marl unit. This contact is easily imaged in a 7,4,1-band combination as the stark contrast between cliff-forming strata versus the whitish colored marls (Figure 11).
Figure 10. Image crop from 741 scene of Gaurus Dag Anticline. Letters indicate spectral units chosen to lithologically describe the anticline. Arrows indicate significant features that are continuous throughout the scene relevant to be picked as marker beds.
Figure 11. Photo looking to the east taken at the location shown by the red dot in the image below it. Slope forming unit is the marl/shale sequence, which is light blue/purple in the image. The close correlation of spectral units to lithostratigraphic units is shown here. Cliff-forming bottom of unit C is shown on the right of the photograph.
The chalk/marl sequence gradationally coarsens up to a cliff-forming abundantly fossiliferous, silty, sandstone-sandy limestone sequence (unit C). This package of ammonite-bearing strata is a ridge-forming unit (Figure 11) and is approximately 250 meters thick. This unit is extremely rich in ammonites ranging from 5 cm to 20 cm in diameter (Figure 12).

Overlying the chalk/marl sequence is an interbedded, fossil-bearing sand-shale package that covers most of the accessible area (unit D). The sand units in this sequence are coarse-to medium-grained marine sands with an average sand package thickness of 10 to 20 meters, with shale bed frequency decreasing up section. Individual stratigraphic units in this package are difficult to separate since most of the area is inaccessible from the Turkmen border. Common trace fossils in this section are worm burrows indicative of a marginal to shallow marine environment.

The Upper Paleogene and Lower Neogene section (unit E) is characterized by striking spectral signature in the imagery and can be easily identified in the field. This section is dominated by a coarsening-upward sequence of iron-oxide cemented sands and conglomerates. These deposits are indicative of channel-fill deposits and fanglomerates. In some places this unit is in conformable contact with the unit D. In the northern limb of Gaur's Dag, unit E is in fault contact with unit A indicating major deformation to eliminate the intervening units. Unit E composes the northern limb of Gaur's Dag Anticline and core of the syncline south of Gaur's Dag Anticline.

Correlation of lithologic units to spectral units proved to be an easy process in the region as the contacts between continuous lithologic units were easy to distinguish at the 30-meter (image scale) and outcrop level. Validation of spectral units served the purpose of distinguishing the structural level at which faulting was occurring, whether faults were
Figure 12. Ammonite fossils ranging in size from 5 to 20 centimeters in diameter are extremely abundant in the limestones of the south limb of Gaurs Dag Anticline.
breaking through the surface and whether units were being duplicated or truncated. It appears that much of the deformation appears to be occurring in the chalk/marl sequence (unit B). On a larger scale, it appears that this section is duplicated on the south limb of the anticline and is faulted out of exposure on the north limb. Finding the actual detachment is nearly impossible since much of the deformation is taking place between the thinly laminated individual shale beds.

**Nature of Faulting and Folding**

The general structural style can be easily depicted from the imagery. However discovering detailed small-scale structures below the 30-meter pixel size must be carried out in the field. Fault and fold patterns were examined to delineate the direction of fault motion and to demonstrate how strain was being transferred throughout the thrust sheet. Fault rupture from previous earthquakes was examined to provide important data to answer this question. Brittle rock behavior observed in the field was observed as secondary faults such as synthetic and antithetic thrusts and back thrusts, bedding plane interactions and joint patterns.

Deformation from historic earthquakes was observed on the south limb of Gaurs Dag Anticline (Figure 13) where slip direction could be directly interpreted from secondary faults, slickensides, and striations. Numerous small-scale strike-slip features, which are secondary to the preserved main fault rupture (Figure 14) are oriented N 20° W, 87° SW. Features such as these are indicative of slip direction at the moment of the earthquake and as a thrust sheet as a whole. Epicenter depth is not known, but is estimated as being very shallow, perhaps only 5 kilometers (Ishankuliev, 1994).
Figure 13. Epicenter data showing the location of three major earthquakes in the last century. The specific location and depth of 5 to 10 kilometers suggests that these earthquakes occurred on thrust faults. The 1987 earthquake may have occurred on a lateral ramp or the terminal end of the ramp as it tips out into a major thrust. This illustration conveys the notion that the uplifted rocks between the Karakum platform and the Binalud fault zone are a compressed package between two major, oblique thrusts. Exact locations of epicenters are subject to location errors of unknown size that are inherent in the still generalized velocity structure for the region.
Figure 14. Surface rupture from the 1987 M 5 earthquake 1 km from the village of Manish. Fault surfaces are oriented N 20° W, 87° SW or near vertical. Surficial talus shown in photo A depicts the brittle and homogeneous manner of deformation that is characteristic throughout the area. Faulting is typically dispersed throughout units and is entirely masked by less resistant units. Photo B illustrates well preserved striations (15° N rake) and serves as a representative model for oblique, lateral ramps.
Faulting within the dense limestone units typically occurs along bedding planes and thin, weak layers of shale. Joints within these units are perpendicular to bedding. They are interpreted to have formed as the thrust sheet rides up over the thrust ramp. Figure 15 illustrates the horizontal nature of faulting at an outcrop scale. The fault in Figure 15 is in the core of Gaurus Dag Anticline and is oriented N 65° W, 35° SW. The fault is indistinguishable from bedding until it breaks through a limestone bed and continues along bedding planes. Layer-parallel shortening appears to be the dominant mechanism throughout the field area. Much of the deformation appears to be plastic deformation in weak shale units where actual deformation is almost impossible to quantify. Most thrusts are nearly indistinguishable from bedding planes. Large-scale thrusting is observed on the north limb of the anticline as well as within the core of the fold. The main mapped fault is easily identifiable in the field as Paleogene limestone is juxtaposed against Neogene conglomerates. However a more subtle, unmapped fault was discovered at the axis of the anticline. Figure 16 is an east/west-looking view at a duplicated shale section at the core of Gaurus Dag Anticline. The shale unit is completely disrupted and bedding is nearly impossible to distinguish. The fault is subtle and would not have been discovered except for a limestone fault breccia (Figure 17 and 18) at the top of the shale unit. The 1 to 2-meter thick fault breccia consists of boulder-to sand-size clasts and is cemented by non-crystalline calcite. The fault appears to tip out to the east and west as coherent bedding can be traced over the axis of the anticline in the west-looking photograph. This heterogeneous type of deformation is evident throughout the field area and serves as a template for larger-scale interpretations.

Small-scale faulting and fracturing between differing lithologies at the bedding plane level were also evidence of heterogeneous deformation throughout the area. The rigid
Figure 15. Small-scale thrust fault in the south-dipping limb of the limestone core of Gaurs Dag Anticline. Thrusts are largely localized parallel to bedding and cross structures at slight angles as shown here. Individual beds are about 1 to 2 meters thick.
Figure 16. West and east looking views at a major thrust breaching the crest of Gaurs Dag Anticline. The thrust is bedding parallel and is contained within the duplicated shale unit at the left of the photo. Bottom photo is an east look at the same fault. Fault breccia was discovered on the area shown at the middle right of the photograph.
Figure 17. Photo of fault breccia in the Sherwok Valley thrust. Thrust strikes N 75° W and dips parallel to bedding to the south. Limestone is completely pulverized and cemented with post-deformational calcite. Directly underlying the breccia is an intensely fractured shale unit of which the depositional thickness is unknown.
Figure 18. Fault breccia in a bedding parallel thrust, illustrating localization of much of the strain parallel to bedding. Such layer-parallel deformation leads to significant changes in unit thickness across the region.
mechanical character of the limestone appears to focus the location of the strain. This is especially evident in close observation of bedding plane interactions between “rigid beam” limestone beds and soft, easily deformed shale. Figure 19 shows the nature of the bedding plane interaction between units whose shear strength varies. In this figure, the limestone is fractured in an east-west orientation by the result of flexural folding as the rigid beam is flexed. The shale takes up almost all of the strain and original bedding is completely overprinted by the fractures in shale. The shale shown in photo A apparently absorbs all of the deformation since the joint does not break through the rigid limestone bed below the shale unit.

Major thrust features are best observed in the imagery since observation of the actual contact in the field is difficult due to limited access and the proximity to the Iranian border. The north limb of the Gaurs Dag Anticline is truncated by a major east-west trending reverse fault. Bedding on the north limb of the anticline is slightly overturned to the north (Figure 20 and 21).

Twenty kilometers west of Ashgabat, in the Chuli and Pöweruza (pronounced Fıruza) area, the structural style is exposed as the surficial expression of kilometer-scale anticlines and synclines that appear to have low-angle faults beneath them. Although the actual detachment could not be visited, several smaller features were discovered that support the interpretation of a fault-bend fold geometry and lateral ramps controlling the structural style. Three specific structures were visited in the field east of the Gaurus Dag Anticline, Dushak Anticline, Vanovskova Syncline and Markou Anticline (Figure 9). Along the road to Pöweruza and Chuli the road passes directly through the core of the Markou Anticline where
Figure 19. Photographs showing the relationship between rigid limestone and less competent shale. Penetrative deformation within the shale layers appears to have accommodated much of the strain, while more rigid carbonates have acted as rigid beams. A. Carbonate overlying uniformly fractured shale. Sense of motion is normal but micro-fractures are the result of northward compression. B. Micro-fractures strike east-west and dip to the north and south and are separated by 45°.
Figure 20. North limb of the major Gauers Dag Anticline 30 kilometers southeast of Ashgabat looking east. Deformation appears to be localized within shales between more resistant carbonates. Building for scale is unlikely to withstand significant seismic shaking of the region. Along strike, this fold is overturned to the northeast.
Figure 21. West-looking photo of the slightly overturned north limb of the Gours Dag Anticline. Bedding appears as to have behaved plastically. Most deformation throughout has been taken up in bedding-plane slip.
The large-scale nature of deformation is visible on the other side of the canyon. Figure 22 shows the intense nature of this deformation.

Thrusts are observed to be parallel to bedding and break through rigid layers at a relatively low angle. Figure 23 shows a view from the western part of the field area at the nose of Dushak Anticline. This fault is typical of thrusts in the study area in that it is constrained within bedding planes. The fault here is easily recognizable as it breaks cleanly through the limestone units, but is parallel to bedding planes in a short distance above the carbonate units and it is relatively untraceable in the upper right of the photograph. It appears that much of the shortening is transferred by bedding plane thrusts. In contrast to Lyberis and Manby’s (1999) interpretation of the same outcrop, it appears that these faults do not approach near vertical at the surface but remain low angle. Similar fault and fold geometries are also seen in the Canadian Rockies (Figure 24). It is not uncommon to have significant deformation and faulting extending several kilometers beyond the frontal folds and faults exposed at the surface and continue into the subsurface into the foreland basin (Dahlstrom, 1969; Price, 1988).

Strike-slip faulting plays a major role in the strain observed in the Kopet Dag Range. Large-scale, northwest-striking strike-slip faults are imaged by the right-lateral separation of spectral units (Figure 25). By measuring offset of the spectral units it can be seen that the deformation is heterogeneous throughout the system. Strike-slip faults appear to be tipping out into thrust faults, becoming more shallowly dipping and actually becoming part of the thrust sheet (Figure 26). The schematic figure of an oblique, lateral ramp is a generalization of what may be going on at the fault-plane level. What this schematic diagram does not show is that much of the deformation is contained within bedding planes at a small scale.
Figure 22. West-plunging Markou Anticline 25 kilometers west of Ashgabat showing overall structural style. Resistant units are limestone and sandstone. Less resistant rocks are marls and shale. Field of view is about 2 km across.
Figure 23. Photo of a low-angle thrust on the south limb of Dushak Anticline depicting the near bedding plane nature of deformation near the village of Chuli. Fault can be traced to the top right of the photo but is lost in the bedding planes. Total offset unknown. Murad Ishankuliev pictured for scale.
Figure 24. Subsurface structures east of the Canadian Rockies near Calgary showing thrust imbrication and fold development beneath the plains as derived by multiple seismic cubes and drill core. Similar structure is thought to be present beneath and NE of Ashgabat, Turkmenistan. (Price, 1988).
Figure 25. Cropped image from 741 Landsat scene illustrating the sigmoidal geometry of lateral ramps. Each right lateral strike-slip lateral ramp (outlined in red) tips out into another thrust sheet. Offset along the ramps is heterogeneous as evidenced in the center of the image. Here a ridge marked by the blue lines is offset by approximately 30 kilometers, yet lateral offset is negligible as the fault tips out. Deformation of folds is also heterogeneous on either side of the strike-slip faults suggesting fold compartmentalization.
Plunging Fault-Bend Folds reflect underlying lateral ramp

Figure 26. Three dimensional block diagrams showing the geometric nature of fault-bend fold systems. A. Top diagram delineates the lateral ramp nature of strike-slip faulting in the Kopet Dag hinterland. B. Exposed geology will dictate underlying ramps, Gaur’s Dag, Dushak and Markou structures are represented by this type of geometry as in the Mist Mountain Analogue. (Dahlstrom, 1969)
This model does, however, explain the way in which strike-slip faults tip out into the thrusts. Components of strain are represented in the strike-slip faults as they represent lateral sidewall ramps within the thrust sheet; strike-slip fault planes are near vertical at the center of the fault and near horizontal as they tip out into the thrust. In the western Kopet Dag, the same lateral ramp geometry is occurring but at opposite orientations (i.e. northeast striking). Strike-slip faults are observed at an angle of approximately 120 degrees from adjacent thrusts measured at the center of the strike-slip fault and projected to the thrust. Most strike-slip faults consist of heterogeneous offset and strike to the northwest. The rigid indentor model for the Lut block portrays this interaction eloquently (Figure 27).

Compartmental deformation is also occurring on either side of the strike-slip faults seen in Figure 25. Compartmental deformation occurs as thrust sheets on either side of the strike-slip fault deform at different rates. This observation is reinforced by the fact that folds on either side of the fault do not match those on the other with the exception of the fold marked in Figure 25 and the faults themselves have finite ends.

Rabbit-ear geometries were discovered northwest of Gaurs Dag Anticline. Rabbit ear folds and complimentary faults are the result of a space problem as rocks in an anticline-syncline pair are folded like a deck of cards (Kluth, pers. comm., 2000). The resultant escape mechanism is a back-thrust or reverse fault antithetic to the main thrust and is usually parallel to and often truncates the adjacent verging limb. A small (10 km long) ridge exposed at the northwest corner of Gaurs Dag Anticline (Figure 9, Plate 1) appears to be the eroded north limb of a rabbit ear fold. The reverse fault associated with it is near vertical and is possibly shallow, perhaps only to about 3 or 4 kilometers.
Figure 27. Rigid Indentor model for the Kopet Dag illustrates the rigid beam deformational style of the entire region. Lut Block interaction with the dense South Caspian depression causes rocks to behave like a car hood crashing into a telephone pole. Sinistral and dextral strike-slip faults are observed to heterogeneously offset units by several kilometers and tip out into thrust sheets. Areas of compression are denoted with (+) and extension with (-). (Borissoff, and Rogozhin, 1981).
Strong earthquakes of M 7.3, 5.6 and 4.4 in 1948, 1968 and 1987 gave an approximate hypocenter depth of 5 to 8 km near the Gauers Dag Anticline (Ishankuliev, 1969, 1994). Given the structural features observed on the surface and the placement of the epicenters (Figure 13), it appears that the earthquakes occurred on shallow-dipping thrusts that potentially lie beneath the densely populated city of Ashgabat. Given fault plane solutions from the 1948, 1968 and 1987 earthquakes, it is possible interpret a ramp-and-flat geometry for the Central Kopet Dag. Although the fault mechanism is not well known, it can be inferred given the observed structures, ground rupture and depth. After visiting various epicenter locations in the field and comparing lithologic units and their spectral signature, the evidence seems to support the near-horizontal thrust fault model. Depth-to-detachment calculations of Gauers Dag Anticline based on field mapping and cross-section balancing rendered a depth of 6.7 kilometers, which also suggests a shallow, near-horizontal detachment. The observed fault geometries coupled with previous work done in this region suggest a new model for the development of the Kopet Dag Fault. These earthquake locations occurred on what is interpreted, based on the data presented here, to be a shallow, near-horizontal thrust instead of a high-angle oblique strike-slip fault. This study suggests that bedding-parallel faulting is present in the subsurface of the foreland basin to the north of the Kopet Dag.
CHAPTER IV

STRUCTURAL STYLE

Field observations and analysis of the imagery suggest that there is a dynamic interplay of strain mechanisms throughout the central Kopet Dag Range. The central Kopet Dag has generally been interpreted as representing the leading edge of the deformation. Surficial rocks in this region contain a complex package of northwest-striking, strike-slip faults and east-west striking thrusts. The region north of the exposed rocks is covered by the Karakum Desert. This apparent tectonic boundary is widely interpreted to consist of oblique convergence in the central Kopet Dag and pure strike-slip in the western Kopet Dag (Lyberis and Manby, 1999). The geometric interpretations by Lyberis and Manby exhibit either a deep-seated detachment or a very steep reverse fault as the model for the Kopet Dag (Figure 28). However, the geometry seen in the field does not support the two-dimensional model of Lyberis and Manby, but rather suggests that the overall geometry of the faults and folds in the Kopet Dag resemble fault-bend fold type systems. In this interpretation of the structural style, lateral ramps are displayed at the surface as strike-slip faults and appear to tip out into thrusts (Figure 29). Bedding-parallel thrusting, which is so well developed at the outcrop level, is interpreted to be occurring at the regional scale. It has been widely documented that there is a close relationship between the geometry of the fault and the geometry of the fold (e.g., Mitra, 1988). Therefore, fold geometries can help define the probable details of fault geometries quite well.
Figure 28. Upper-crustal cross section in the region of Ashgabat showing inferred structure. Thrust faults are thought to be shallower in dip and to be related to fold development like in the Canadian Rockies. Ashgabat fault in this usage by Lyberis and Manby is actually the Kopet Dag of Turkmen usage. Subsurface condition of thrust in ramp and flat geometries is interpreted to be more accurate geometry of imbricate thrusts. Third dimension added by regional interpretation of TM image helps to suggest the location and geometries of these ramps and flats. (Lyberis and Manby, 1999)
Figure 29. Fault-bend fold with lateral ramp. Strike-slip faults act as a lateral ramp with dextral slip in the central and eastern Kopet Dag and tip out into thrusts as shown here. Fold geometry is governed by lateral ramp, not heterogeneous compression along the thrust sheet. (After Shaw and others, 1994)
In a fault-bend fold system, folds are a product of underlying fault geometry. The shapes can lend clues into what types and geometries of faults that underlie them. Folds can form either by ramp-and-flat geometry or by heterogeneous deformation across the thrust sheet. Figure 30 illustrates the fact that fold geometry can be the result of different subsurface geometry.

As discussed earlier, major strike-slip faults in the Turkmenistan-Iran study area appear to represent the sidewall ramps of the three-dimensional thrust sheets. This geometry is much like the Pine Mountain thrust system of the Appalachians. In this well documented example, thrusts and related strike-slip faults are closely interconnected as strain is transferred via tear faults, accommodation or compartmental deformation from one thrust sheet to the next (Mitra, 1988). Regional-scale, strike-slip faults represent the sidewall ramps as they tip out into the thrust sheet and are near vertical at the center. Their heterogeneous offset is imaged in Figure 25. Oblique motion on this system will therefore produce an oblique ramp-and-flat fault geometry that can be observed at the outcrop and interpreted to be present at the regional level (Figure 31). Strain partitioning can be observed in compressional bends and pressure ridges truncated by the strike-slip faults. The Turkmenistan-Iran region is interpreted as having the same geometries as the Pin Mountain system. Understanding the transfer of strain from shortening to shear within the Central Asia thrust sheet provides a better understanding of the behavior of small-scale faults at depth and the role they play in estimating seismic risk and petroleum potential.

Strain partitioning as described by Priestley, et al. (1994) along the Kopet Dag Fault is observed in compressional and shear packages along the frontal fault zone. The Kopet Dag Fault is not a completely straight line as it is commonly mapped, but is clearly broken up
Figure 30. Fault-bend fold showing the plunging nature of Gaur's Dag. Heterogeneous deformation along thrust sheet can produce varying structures, some controlled by lateral ramp geometry. (After Shaw and others, 1994)
Figure 31. Schematic diagram of an oblique lateral ramp system similar to that of the Central and Eastern Kopet Dag. Dextral Strike-slip faults act as sidewall ramps that tip out into thrusts.
into strike-slip and thrust components. Young alluvial sediments are intensely folded west of Gook Tepe (40 km west of Ashgabat) revealing shortening related movement on the Kopet Dag Fault. Most studies in the area have been regional in extent, so that the heterogeneous character of the Kopet Dag fault has been synthesized into a single strike-slip fault.

Strain partitioning along the Kopet Dag Fault appears to be divided into packages of shortening and shear strain. The truncation or the duplication of spectral units indicates that motion is transferred from compressional features to strike-slip. Regional structures documented in the imagery indicate that there is a preferred orientation of faults and folds along the frontal Kopet Dag. Anticlines in the eastern and central Kopet Dag are oriented northwest-southeast but in the western Kopet Dag, they are oriented northeast-southwest and east-west. There are young structures throughout the frontal Kopet Dag that appear to be both the results of shortening and strike-slip. The strike-slip component, however, is not thought to be independent, but is interpreted to be part of a larger strain pattern of fault-bend fold geometries with the strike-slip faults acting as lateral ramps between imbricate thrust sheets.
CHAPTER V

DISCUSSION

The structural response of crustal-scale rigid blocks is interpreted to play a large role in the deformation displayed in the Kopet Dag, Alborz, Talesh and Zagros mountain ranges. Fold axes orientations in the Talesh, Alborz and Kopet Dag Mountains reveal the clay-like nature of response to these rigid blocks as they outline the large-scale rigid indentors around which they are draped. The interplay between two of these rigid indentor blocks, the South Caspian oceanic crust and the Lut block, is expressed in the surrounding folded rocks. Plate motion vectors show that the Lut block is continuing to provide north-directed principal compression (Lyberis and Manby, 1999; Sengor, 1984; Berberian and Berberian, 1981, Berberian 1981, 1983, Berberian and King, 1981).

The shape of the Lut Block also appears to be the controlling mechanism of the conjugate fault geometries that resulted in its collision with the Turanian Platform (Figure 27); yet deformation observed in Nebit Dag and Chelekin (Figure 1) do not conform entirely to a solid indenter model. There is a possibility that the Lut is not a solid, rectangular-shaped beam that is bounded by border faults, but that it is an irregular-shaped object (Sengor, pers. comm., 1999). The interpretation that pieces of it may even extend beneath the Kopet Dag is quite possible. The original Lut block may consist of multiple pieces represented by solid blocks from the South Caspian to Central Iran. These irregular-shaped bodies may well control the shape of the Kopet Dag Fault from Ashgabat to Chelekin on the eastern shore of the Caspian Sea (Sengor, pers. comm., 1999). The complex interaction of the Lut block and
dense oceanic crust of the South Caspian Sea appear to be the principal control mechanisms for the overall geometry of the Alborz and Kopet Dag Ranges. The actual shape and lateral extent of the Lut Block is not entirely known and is probably responsible for heterogeneous deformation across the Turan Platform and responsible for the shape of the frontal Kopet Dag Fault.

Relative plate motions (Figure 2) in this region involve continued north-directed motion from the Arabian plate at a rate of 18-25 mm/yr relative to the Eurasian plate (DeMets and others, 1994). Active subduction in Persian Gulf and offshore Makran is represented by subduction-related rocks in the Zagros and Makran fold belts. The Kopet Dag and Binalud Mountains are interpreted to have formed as the resultant ranges separated by the collision and closure of the Paleo-Tethys. The relative motion of the Lut block and Iranian platform is generally to the northwest resulting in a major, oblique compressional regime in the Kopet Dag (Lyberis and Manby, 1999). Numerous workers have deemed the Binalud fault zone as the Paleo-Tethyan suture between the Turan platform and the Iranian platform (Figure 2) (Allen and Sengor, 1993; Natal' in and Sengor, 1994; Nowroozi and Mohajer-Ashjai, 1985; Sengor, 1976, 1979a, 1979b, 1984; Sengor and Kidd, 1978, Sengor and Dyer, 1979). The actual three-dimensional geometry of this boundary is not yet known and therefore its extent into the Turan platform is only inferred.

The Kopet Dag Mountains are generally placed on the southern border of the Turan platform by most workers. The common mistake is to imply that deformation ceases at the northern topographic front of this range. The Kopet Dag Fault is traditionally interpreted as a straight line on a map and even is implied to be boundary of the two provinces and that the rocks on either side of this boundary are of completely different structural regimes. The
results of this study and the application of three-dimensional models suggest, however, that
deformation of the Turan platform may quite possibly extend out into the relatively flat
Karakum Desert into the Turan platform. This study also suggests that the exposed folds and
thrusts of the southern Turkmenistan-northern Iran region are only taking up shortening
within a heterogeneous collage of rigid an relatively soft rock units that once formed portions
of the Tethys and Paleo-Tethys region.

The Kopet Dag fault is typically drawn as a straight line on most geologic maps. Physically
drawing the boundary between the Turan and Iranian plates at the frontal Kopet Dag does not appear to be a correct interpretation of the plate boundary because the rocks
that exist buried out beneath the Karakum Desert are the same rocks that are exposed in the
Kopet Dag. Plate or geologic province boundaries are typically drawn separating genetically
different rock units. Along the Kopet Dag, drawing a provincial boundary is difficult
because collision and deposition are interpreted to have been occurring at the same time on
both sides of the fault during much of its history. In this interpretation, the Kopet Dag Fault
would not represent a major provincial boundary, but is thought to be a major fault within a
continuous structural system; of the foreland fold and thrust belt produced by continental
collision. The three-dimensional structural behavior of this fault system is still not well
known in terms of the horizontal extent of deformation out into the Karakum platform.

An analogous region to southern Turkmenistan-northern Iran is represented by the
Canadian Rockies, where major imbricate thrust sheets and associated folds are beautifully
displayed. Seismic profiling of relatively flat topographic areas out on the platform regions
of Alberta are thought to provide a model similar to the Karakum platform, and show major
fold and fault features beneath the flat topography. On the seismic reflection profiles, the
geometries of the thrust faults generally have a predictable geometry and that, by imaging the exposed fold geometries, interpretations can be made of subsurface fault geometries (Bally and others, 1966; Dahlstrom, 1969; Price, 1988; Snelson, 1978). Geometries similar to the Jumping Pound gas field west of Calgary, Alberta, are thought to be present beneath the Karakum Desert (Figure 24) based on this study. The present model for the Kopet Dag as interpreted by Lyberis and Manby (1999) shows the Kopet Dag as being the end of the deformation. They do not extend the folding and faulting out into the Karakum platform. By synthesizing what is known of the fault geometries exposed in the Rocky Mountains and applying them to the Kopet Dag, a much different model is proposed in this study. This model suggests that folding land faulting continues out into the desert and suggests that there may be significant exploration potential for structural traps to the north of the Kopet Dag fault. However, the seismic risk for the people of Ashgabat also seems to be significantly greater because of the continuation of low-angle motion beneath the city as interpreted in this study.
CHAPTER VI

CONCLUSION

Combining satellite imagery with field observations to map and interpret structural geometries of faults and folds has proven to be a remarkable tool in unraveling the progressive deformation of the Kopet Dag Range. Interpreting the Kopet Dag as a deformational zone and not the simple dividing boundary between a highly deformed hinterland and undeformed foreland allows the construction of a three-dimensional model of crustal deformation and the deformational style. The Kopet Dag Fault is generally regarded as the representative southern extremity of the Turan platform. The traditional interpretation also includes drawing a straight line as the Kopet Dag Fault, but this does not appear to be correct. Major components of compression and shear are represented in the surface expression of the Kopet Dag Fault with conjugate strike-slip faults that tip out into thrust sheets. These strike-slip faults appear to be the surface expression of lateral, ramp-and-flat geometries as strain is partitioned across it.

The overall movement of the Kopet Dag Fault is generally interpreted as being oblique slip. In this traditional approach, a common error, however, is to assume that no further deformation occurs out into the topographically flat region of the foreland. In the interpretation of this study, the exposed rocks of the Kopet Dag Mountains are thought to represent the type of structures that may be present beneath the Karakum Desert. Extending the observed deformational style out into the seemingly undeformed Karakum platform is interpreted to be analogous to the deformation beneath the plains east of the Canadian
Rockies. A three-dimensional model of the exposed folds and faults in the Kopet Dag produces a fault-bend fold interpretation whose features closely match those of the exposed rocks. This model suggests that similar deformation is likely to be present beneath the Karakum Desert.

The implications of these interpretations imply that fold structures exist beneath the Karakum Desert and that these may have hydrocarbon potential, north of the currently inferred plate boundary (Figure 24). In the case of the Canadian Rockies, previous interpretations of the poorly exposed rocks left little reason to explore out beneath the flatland east of the mountain front. It was not until a new look was given at an old problem using the ideas of regional thrust sheets that large discoveries were made. The potential for similar crustal deformation being present into the Karakum Desert is thought to be great.

Seismic activity is also clearly present out in the Karakum foreland. The model presented in this study suggests that there are extensive bedding-parallel faults underneath the city of Ashgabat, thus posing a much more severe danger than would exist with the traditional high-angle interpretation of the faults. Historically, devastating earthquakes have claimed the lives of tens of thousands of people in this region. Planning for the next earthquake starts with an accurate understanding of present structures. Understanding how strain is being partitioned and where to expect major ground acceleration is important for minimizing loss of property and lives. Geotechnical problems related to liquefaction of the substrate during significant shaking is a major problem in the region. The development of the Karakum Canal and the subsequent leaking of water through the canal into the desert has raised the groundwater table to potentially dramatically increase liquefaction during the next earthquake. The need for an accurate deformational model for this region is of importance.
for planning, earthquake preparedness and disaster response. The new interpretations presented here provide a template for future investigation into the structural style and seismic hazards of the region.
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ABSTRACT
ABSTRACT

The Kopet Dag Mountains are a northwest-trending range that formed during the closure of the Tethys Sea and represent the boundary of the Turan and Iranian plates. The Central Kopet Dag is an example of world-class, fault-bend folds that are beautifully displayed on Landsat, Corona and space shuttle imagery. The imagery can be used to determine exactly how strain is being transferred from strike-slip faults to imbricate thrust sheets and fold systems. Understanding this complex array of fault and fold mechanisms offers a suitable platform for extending subsurface geometries out into the topographically flat Karakum Desert to the north. The "rigid indentor" style interaction of the Lut block with the 3-D, wedge-shaped fold and thrust belt into which it impinges provides an array of regionally plunging structures that expose an inclined structural view through the orogenic belt. Field studies reveal a three-dimensional, heterogeneously distributed amount of overall horizontal shortening.

The Kopet Dag represents a three-dimensional model of the oblique convergence of two continental plates. The Kopet Dag fault as normally viewed in a two-dimensional map representation has been thought by most workers to be purely a strike-slip fault in the western Nebit Dag area. When viewed in a three-dimensional or four-dimensional model, however, an alternative model involving strike-slip faults as sidewall ramps in an imbricate thrust stack being differentially deformed by the Lut block appears more attractive. The incredible exposure of plunging structures allows a more sophisticated reconstruction than is traditionally done with most two-dimensional studies of orogenic belts. The Kopet Dag fault thus appears to represent the frontal boundary of oblique fault-bend fold tectonics between
the Iranian plate and Central Asia. Major implications of this study apply to petroleum exploration and overall seismic safety for the densely populated city of Ashgabat, Turkmenistan.