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# TERTIARY KINEMATICS OF THE TADJIK DEPRESSION (CENTRAL ASIA): INFERENCES FROM FAULT AND FOLD PATTERNS

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## ABSTRACT

The Tadjik depression, situated West of the Pamirs (Central Asia), is a wide intermontane compressive basin. Its overall structure is that of a fold-and-thrust belt, made of alternating basins and ranges striking N-S to NE-SW. Basins are filled with Cenozoic and Quaternary sediments up to 6 km thick. Major reverse fault zones verge westwards and eastwards in the eastern and western parts of the depression, respectively, the central domain forming a pop-down basin. From fold and fault patterns throughout the area:

(a) The direction of regional shortening is sub-horizontal or gently plunging and trends NW-SE to WNW-ESE.
(b) Thrusting is generally accompanied by significant wrenching along the ranges.
(c) The sense of shear is sinistral in the depression and dextral at its E-W striking northern boundary (Ghissar range). Inferred kinematics are consistent with the northward displacement of the Pamirs with respect to Asia during Himalayan tectonics.

At a larger scale, they are consistent with NE-SW directed sinistral wrenching along the Pamirs-Baikal zone, as a result of the India-Asia collision. Our observations are further compatible with the occurrence of counterclockwise block rotations throughout the Tadjik depression, as revealed by paleomagnetic studies.

## INTRODUCTION

For the last 55 Ma, Asia has been deforming, as a result of collision and indentation by India. Crustal thickening occurs in the Himalayas, Tibet, Tien Shan and Altai, while major strike slip displacements are accommodated along the Altyn Tagh, Red River or Talas-Fergana faults. The way indentation is distributed throughout Asia is somewhat controversial. Tapponnier et al., (1986) and Peltzer and Tapponnier (1988) have suggested that about 50% of convergence has been accommodated by eastwards extrusion of continental blocks. Tapponnier et al., (1990) and Avouac and Tapponnier (1992), have believed that Indochina was extruded towards the South East during the Tertiary. In contrast, England (1982) and Dewey et al., (1989) consider that most part of the convergence has been accommodated by crustal thickening. Cobbold and

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Davy (1988) have suggested that crustal thickening in the Himalayas attenuates laterally across wrench zones, left-lateral in the western Himalayan syntaxis and right lateral in the eastern one. They also argued that a SW-NE band, from the Pamirs through the Tien-Shan and Alai ranges to the Baikal area, has undergone left-lateral wrenching, partially accommodated by a set of NW-SE dextral antithetic faults (Fig. 1). They inferred that wrenching is accompanied by block rotations.

The Tadjik depression is located in the southern part of the Pamirs-Baikal band (Fig.1). It is bounded to the East by the Pamirs and to the North by the South Tien-Shan range. There are various models for the formation of the depression. Leith (1985) suggested that it was a Mesozoic passive margin, reactivated during Cenozoic compression. Tapponnier et al., (1981) considered that it was a Mesozoic marginal basin, which became a foreland basin after the India-Asia collision. Finally, Hamburger et al., (1992) used balanced cross-sections in the North-Western part of the depression to infer that it has been a foreland basin since the Mesozoic. In this paper, we describe faults and other structure developed in Tertiary rocks and we infer principal directions of strain throughout the depression.

## 1. GEOLOGICAL SETTING

### 1.1 Surrounding Ranges

The South Tien-Shan is the southern margin of the Hercynian orogen (Burtman, 1975). This foldbelt was reactivated during the Tertiary (Fig.1). The Ghissar area, north of Dushanbe, is considered to be a major thrust-wrench zone with a dextral strike-slip component (Trifonov, 1978) (Fig. 2a). The South and Central Pamirs consist mainly of accreted island arcs, associated with an active continental margin of Paleozoic to early Mesozoic age. The Pamir block is overthrusted upon Tertiary sediments of the Tadjik depression. South of the Amudarya river is an active reverse fault which probably forms the southern boundary of the depression. Further South is the Herat fault, considered to be a Mesozoic suture zone reactivated as a dextral strike-slip fault during the Tertiary (Tapponnier et al., 1981). Eastwards verging thrusts dominate at the western boundary of the depression, along the South West Ghissar range. Further to the West, Tertiary deformation decreases towards the stable Eurasian platform.

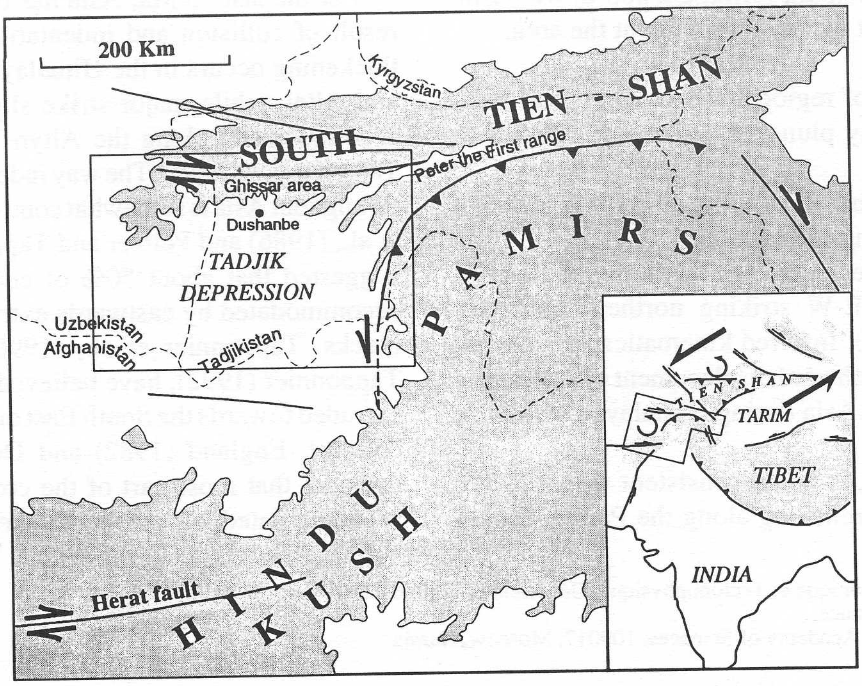


FIG. 1. Simplified map of the Pamirs and adjacent areas (adapted from Leith, 1985). Shaded areas are above 2000 meters.

## 1.2 Sediments

Sediments filling the Tadjik depression range from lower Jurassic to Quaternary in age. The lower and middle Jurassic consists mainly of carbonaceous sediments overlain by massive Kimmeridgian marine limestones. An evaporite horizon marks the top of the Jurassic. The Cretaceous starts with continental redbeds, overlain by a thick sequence of shallow marine to fluvial deposits (Cretaceous Tethyan Seaway). They are overlain, locally with a slight angular unconformity, by massive evaporitic shallow-water Paleocene limestones. The sedimentation became purely continental around late Oligocene time, with deposits of redbeds overlain by Neogene to Quaternary alluvial sandstones, conglomerates and mudstones. The total thickness of the sequence reaches 10 km in the southern part of the depression and near the Pamirs. Tertiary and Quaternary sediments are up to 6 km thick.

## 1.3 Seismicity

Strong seismicity occurs in a narrow band including the Northern Pamirs, the southern margin of Tien-Shan, and the intervening Peter the First range (see location on Fig. 1) (Kristy and Simpson, 1980; Leith and Simpson, 1986; Hamburger et al., 1992). Depths of hypocenters are almost always less than 10 km in the Peter the First range, whereas they can reach up to 70 km in the Northern Pamirs. In the Central Pamirs, another zone of intense seismic activity is present, but

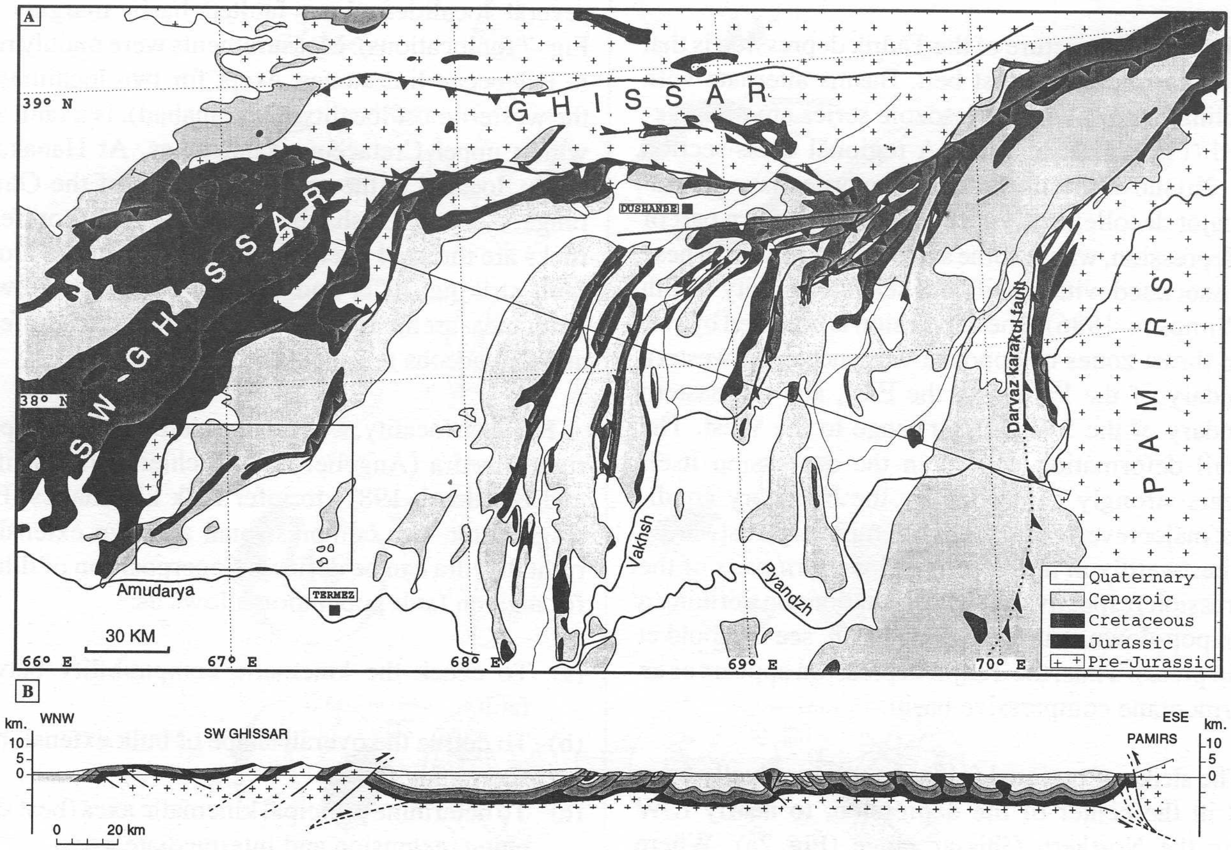


FIG. 2a. Geological map of the Tadjik depression and surrounding areas, showing main faults. Oblique triangles on faults point in direction of underthrusting. Rectangular inset shows location of Fig. 3a.

FIG. 2b. Geological section across Tadjik depression (data from Zaharov 1962, 1/500000 geological map of Tadjikistan, and our own observations). (For section line, see Fig. 2a).

at depths between 70 km and 250 km. This pattern of seismicity is attributed to intracontinental subduction of the Tadjik depression beneath the Pamirs (Roecker et al., 1980; Mattauer, 1986; Hamburger et al., 1992). As in the Peter the First range, seismicity within the Tadjik depression is limited to shallow depths, mainly above 10 km, which is the maximum depth of the Jurassic evaporite horizon (Leith and Simpson, 1986). Fault plane solutions are rather consistent throughout the area, with compressive stress axes clustered around a NNW-SSE direction (Roecker et al.; 1980, Prévot et al., 1980; Leith and Simpson, 1986).

## 2. MAJOR STRUCTURES

The overall structure of the Tadjik depression is that of a wide fold-and-thrust belt. Basins alternate with anticlinal ranges where Mesozoic series are often exposed (Figs 2a, 3[1] and 4a). A regional cross-section (Fig. 2b) shows that the Jurassic evaporites have provided major decollement, especially in the eastern part of the depression, where some salt diapirs crop out. These are associated with significant seismic activity (Leith and Simpson, 1986). The depression is bounded by two main thrust zones of opposite vergences, the western boundary of the Pamirs to the East, and the eastern boundary of the SW Ghissar range to the West. The overall deformation pattern in the depression itself appears strongly controlled by the boundary conditions: major reverse faults verge dominantly westwardly and eastwardly in the eastern and western parts of the depression respectively, the central domain defining a large pop-down structure (ramp basin, see Cobbold et al., in press). Thus, the Tadjik depression appears as an intermontane compressive basin.

The strike of regional folds changes gradually from N-S in the center of the depression, to nearly E-W along the Northern Ghissar range (Fig. 2a). Where exposed, the tips of individual ranges are generally rather symmetric anticlinal hinges, with moderately plunging axes (commonly around 30°-40°) (Fig. 4b)[1]. The degree of deformation varies strongly along the ranges. With increasing deformation, asymmetric box folds become strongly asymmetric folds with steep to reverse short limbs defining basin margins (Fig. 4c)[1], then high-angle thrust zones bringing Mesozoic rocks or Paleocene limestones over steeply dipping to inverted Neogene strata (Fig. 4d)[1]. From such changes in the amount of thrusting along strike, we infer strike-slip components. In fact, folds and thrusts are locally en échelon (Fig. 3) (Leith and Alvarez, 1985).

## 3. SLIP DATA FOR MINOR FAULTS

To better constrain the regional kinematics, we have measured populations of small-scale striated faults at several localities along faulted basin margins (see Fig. 7 for locations). Measurements were mainly made in Paleocene limestones, exept for two localities. At the westernmost locality (Derkanabad), is a fault zone within upper-Cretaceous sandstones. At Hanaka locality, located at the southern margin of the Ghissar range, North of Dushanbe (see Fig. 7), Carboniferous rocks are thrusted over Cretaceous limestones along a fault striking 70°N and dipping steeply northward. Fault measurements were made in both Carboniferous and Cretaceous sediments.

For each locality, we used the method of overlapping right dihedra (Angelier and Mechler, 1977; Pfiffner and Burkhard, 1987) to infer bulk kinematics. For a single fault, two compressional and two extensional right dihedra can be defined. Superposition of dihedra for a given fault population allows us:

(a) To check the kinematic compatibility between faults.
(b) To define the overall shape of bulk extension and shortening fields.
(c) To determine principal kinematic axes (best shortening, extension and intermediate axes).

This latter calculation involves the diagonalisation of the Scheidegger orientation tensor (Scheidegger, 1965) for strain fields deduced from the right dihedra method (Meyer et al., 1991).

1. See color figures.

Except for three localities (Tukaynaron, Kalinabad, and Kafirnigan River), results are mostly consistent, despite the locally limited amount of data (Fig. 5). The main features are as follows.

The direction of principal shortening is generally subhorizontal or gently plunging, and lies between 90°N and 150°N. In contrast, the attitude of the principal stretching direction is much more variable. For several sites (e.g. Aksu, Pulkhakim, Derbent) the extension field defines a great circle, normal to a well-defined shortening direction. For these localities, we infer bulk flattening strains, a feature which suggests that deformation differs from pure thrusting. This is confirmed by:

(a) The highly variable pitch of striations on fault planes with reverse components (Figs 5 and 6).
(b) The locally subhorizontal or gently dipping attitude of the principal extension direction (e.g. Aksu, Pulkhakim, or Hanaka Carboniferous localities).

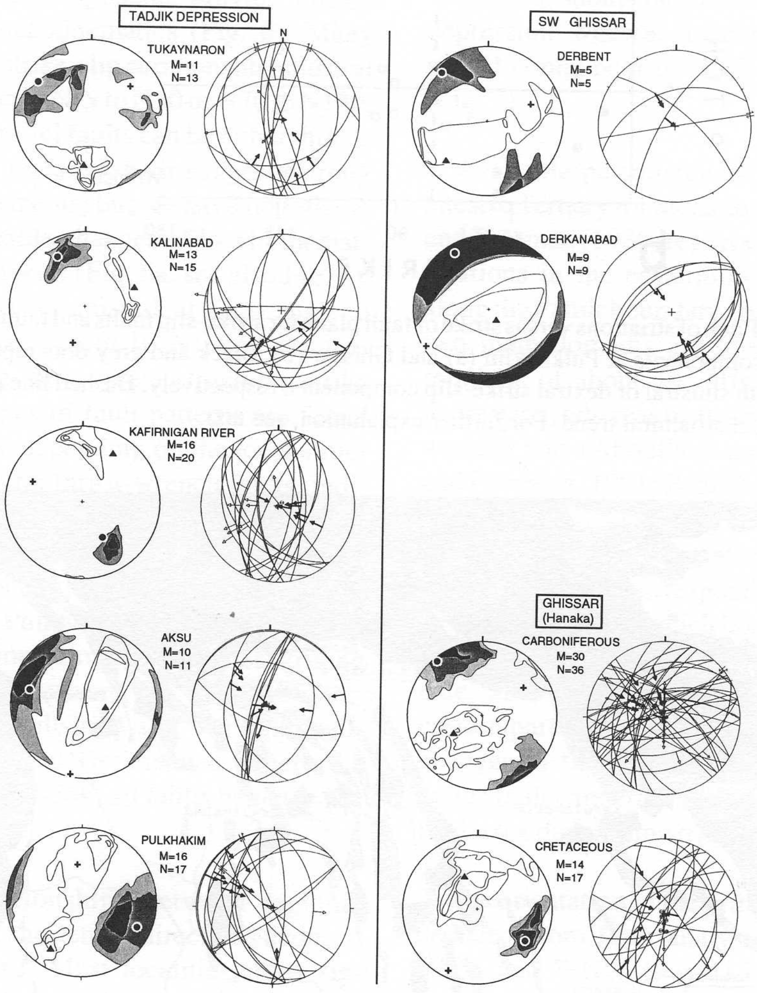


FIG. 5. Equal area stereographic projections (lower hemisphere) of fault-slip data. For each locality, right-hand diagram shows measured fault planes and associated striations. Arrows (bold for reverse faults, thin for normal faults) indicate azimuths of striations. Left-hand diagrams show results of kinematic analysis (method of right-dihedra). Contours are percentages of faults for which shortening dihedra (shaded) and stretching dihedra (white) are compatible. Analysis yields principal directions: shortening (dot), extension (triangle) and intermediate (cross). N is the number of measured faults; M, the number of faults defining a maximum.

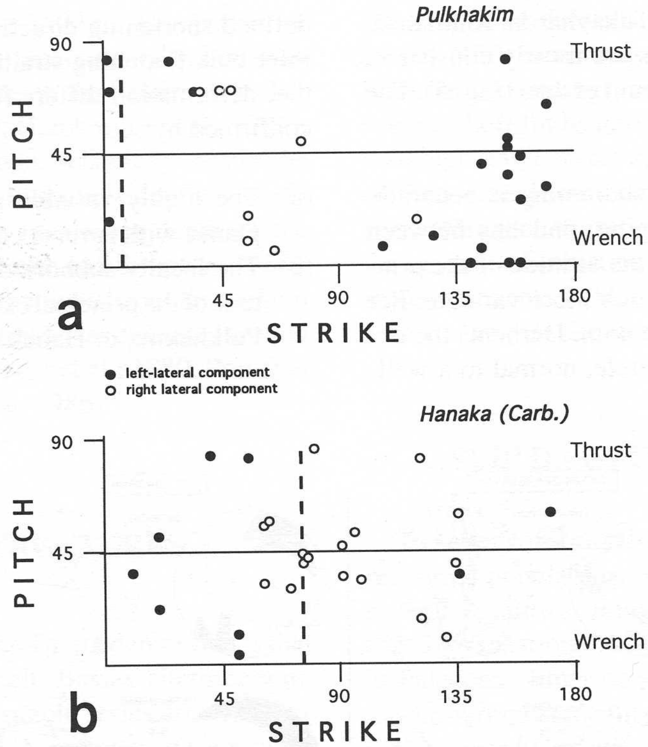


FIG. 6. Pitch of striations versus strike of fault plane for strike-slip faults and faults with reverse components at Pulkhakim (a) and Ghissar (b). Black and grey dots represent faults with sinistral or dextral strike-slip components, respectively. Dashed line shows mean local structural trend. For further explanation, see text.

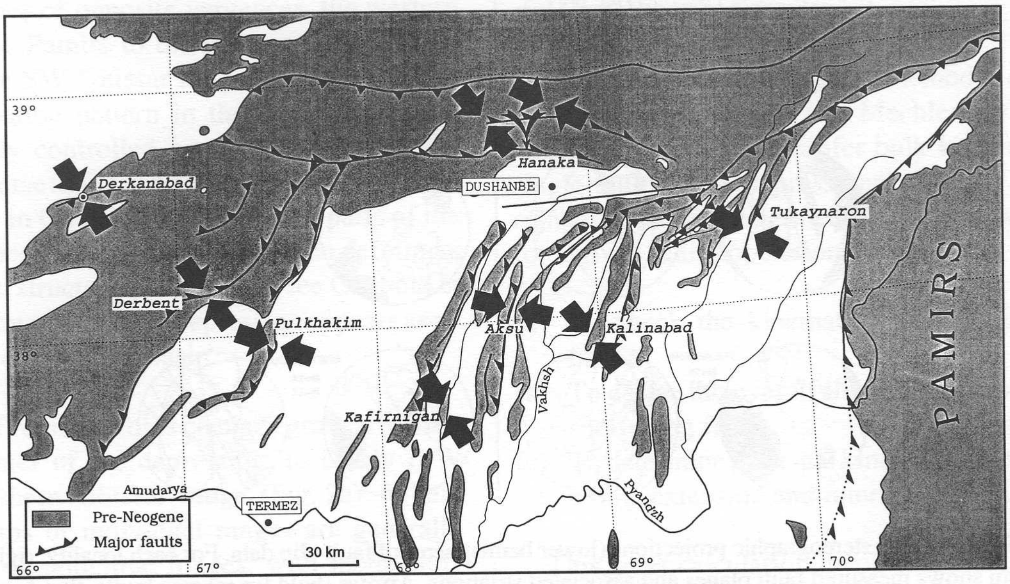


FIG. 7. Relationship between regional structures and principal shortening directions inferred from the analysis of fault populations. For most localities, the shortening direction is oblique to the regional structures, indicating strike-slip components. For further explanation, see text.

At Tukaynaron, Kalinabad and Kafirnigan River, maxima within extension and shortening fields are not orthogonal (Fig. 5). There are problems of compatibility between some faults at these localities. Nevertheless, there is a satisfying agreement between the calculated principal directions and the overall attitude of individual fault planes and striations (Fig. 5). Furthermore, calculated best directions of principal shortening are consistent with those observed at other localities.

For two representative localities, plots of pitch of striations versus strike of individual strike-slip faults and faults with reverse components provide further insight into the regional kinematics (Fig. 6). Many faults show substantial strike-slip components, sinistral or dextral on faults striking N-S to N30 or N70 to N120, respectively. Quasi-parallel faults can be either thrusts or strike-slip faults, a feature which suggests strong partitioning of displacements; but we have no reliable information about possible changes of local kinematics with time. At Pulkhakim (Fig. 6a, see also Fig. 5), the dominant shear sense is sinistral, at a low angle to the local structural strike (about 10°N); whereas it is dextral at Hanaka (Fig. 6b), where structures strike 70°N. In fact, three types of fault patterns are found along basin boundaries, depending on the local structural strike. Thus, sinistral thrust-wrench faults, indicating substantial amounts of bulk sinistral strike-slip along strike, are frequent at sites located within the depression, where regional structures strike NNE-SSW to N-S (e.g. Aksu and Pulkhakim, Figs 5 and 6a). In contrast, fault populations along fault zones striking more E-W (Hanaka and Derbent, Fig. 5 and 6b) indicate components of dextral strike-slip. An intermediate situation is observed at Derkanabad, where the local structural trend is NE-SW, all faults being nearly pure thrusts (Fig. 5).

Figure 7 shows relationships between regional structures and principal shortening directions deduced from local fault patterns. Most localities show significant obliquity between shortening directions and trends of regional structures. These obliquities are consistent with regional sinistral wrenching throughout the Tadjik depression and with dextral wrenching along the northern Ghissar boundary.

## DISCUSSION AND CONCLUSIONS

According to Cobbold and Davy (1988), the Tadjik depression is part of the Pamir-Baikal sinistral wrench zone. In their interpretation, NNE-SSW sinistral wrenching along the stable Eurasian plateform involved antithetic dextral slip along NW-SE faults (e.g. Talas-Fergana fault), with associated anticlockwise block rotations (see Fig. 1). Dextral slip along NW-SE striking faults is well documented throughout the whole area (Burtman, 1975; Cobbold and Davy, 1988; Cobbold et al., this issue). Our structural analysis reveals dextral wrenching along the northern margin of the Tadjik depression, whereas the depression itself shows a regional component of NNE-SSW sinistral wrenching (Fig. 7).

Available paleomagnetic data for the area further attest to Tertiary rotations about vertical axes. Bazhenov and Burtman (1986) report up to 60° counterclockwise rotations in the easternmost part of the depression, along the Pamir boundary. Within the depression itself, two main domains are observed. Counterclockwise rotations of about 50° affect the eastern part of the depression; whereas up to about 20° rotation affects the western part (Abdullaev and Rzhevsky, 1973; Pozzi and Feinberg, 1991; Bazhenov et al., 1993; Thomas et al., submitted). Our analysis also support these observations. Thus, the two paleomagnetic domains found in the depression correspond most probably to the two structural domains which bound the central pop-down. In the the western part, eastward verging faults dominate, and westward verging faults dominate in the eastern part (Figs 2b, 7 and 8). In addition, the strong changes in the amount of thrusting observed along major faults are consistent with rotations around vertical axes during sinistral wrenching.

The orientation of the principal shortening direction deduced from fault analysis, which varies between NNW and WNW (Fig. 7) is further consistent with counterclockwise rotations. Indeed, they are parallel or show apparent counterclockwise rotation with respect to the inferred direction of convergence of the Pamirs, which varies between N-S and NNW-SSE according to the chosen boundary conditions (Minster and Jordan, 1978; Dewey et al., 1989; DeMets et al., 1990). Rotations reported by paleomagnetic studies probably involve basement blocks beneath the décollement level of Jurassic evaporites. Indeed:

(a) The basement is largely involved in the deformation along western, northern, and eastern boundaries of the depression.
(b) The general structural pattern indicates that some major faults within the depression offset the basement (Fig. 2) (Zakharov, 1962).

In summary, the Tadjik depression appears as a wide lozenge-shaped compressive basin, bounded by conjugate thrust-wrench faults, and made of three main domains affected by combined sinistral wrenching and counterclockwise rotations during the Tertiary indentation of the Pamirs (Fig. 8). The triangular topographic shape of the South-West Ghissar range, which widens northward (Figs. 2a and 8), suggests that the amount of basin underthrusting increases toward the North along its western margin . This in turn suggests rotations around an axis located somewhere to the SW of the depression. The above kinematic interpretation implies that the Tertiary deformation of the Tadjik depression has been accompanied by substantial crustal thickening.

## Acknowledgements

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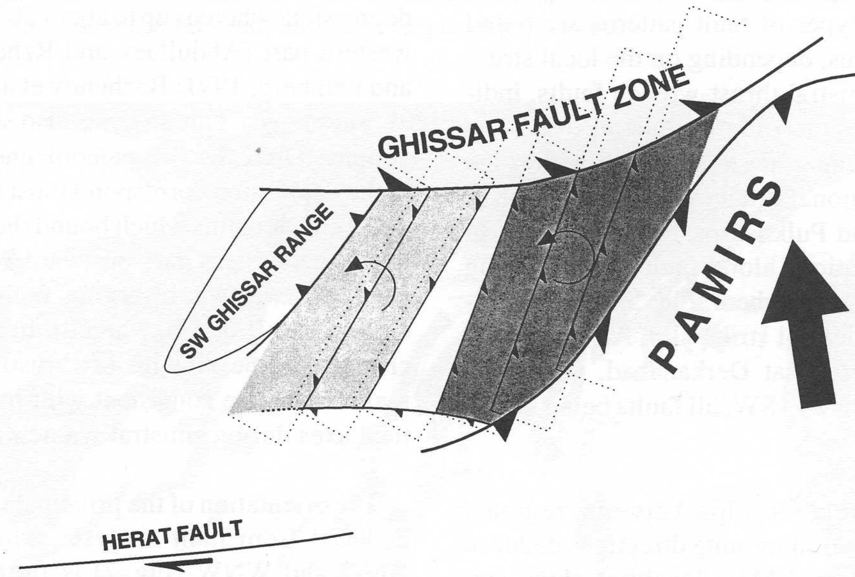


FIG. 8. Inferred Cenozoic kinematics of Tadjik depression due to India-Asia collision. Indentation by the Pamirs (arrow) is assumed to control the deformation. Relative displacement between blocks is taken up by oblique-slip thrusting, dashed boundaries of blocks representing underthrust edges. In the eastern part of the depression (dark domain), there are large counterclockwise rotations; whereas smaller counterclockwise rotations occur in the western part (light-grey domain). Central domain is a pop down basin (white).

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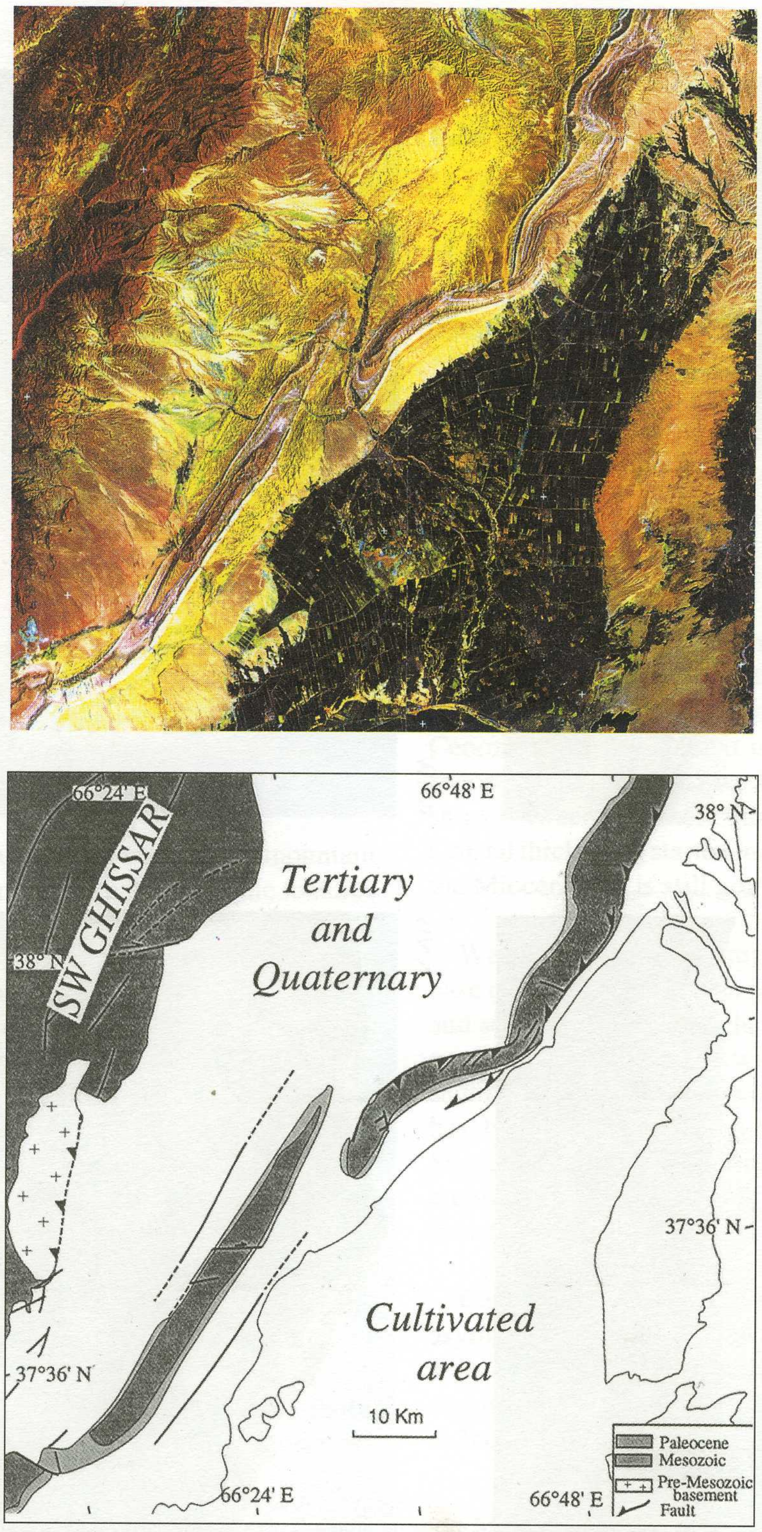


FIG. 3. Landsat TM image of the western boundary of the Tadjik depression (a) and its schematic structural interpretation (b). Oblique triangles on faults point in direction of underthrusting. Total image width is about 80 km. see location on Fig. 2a.

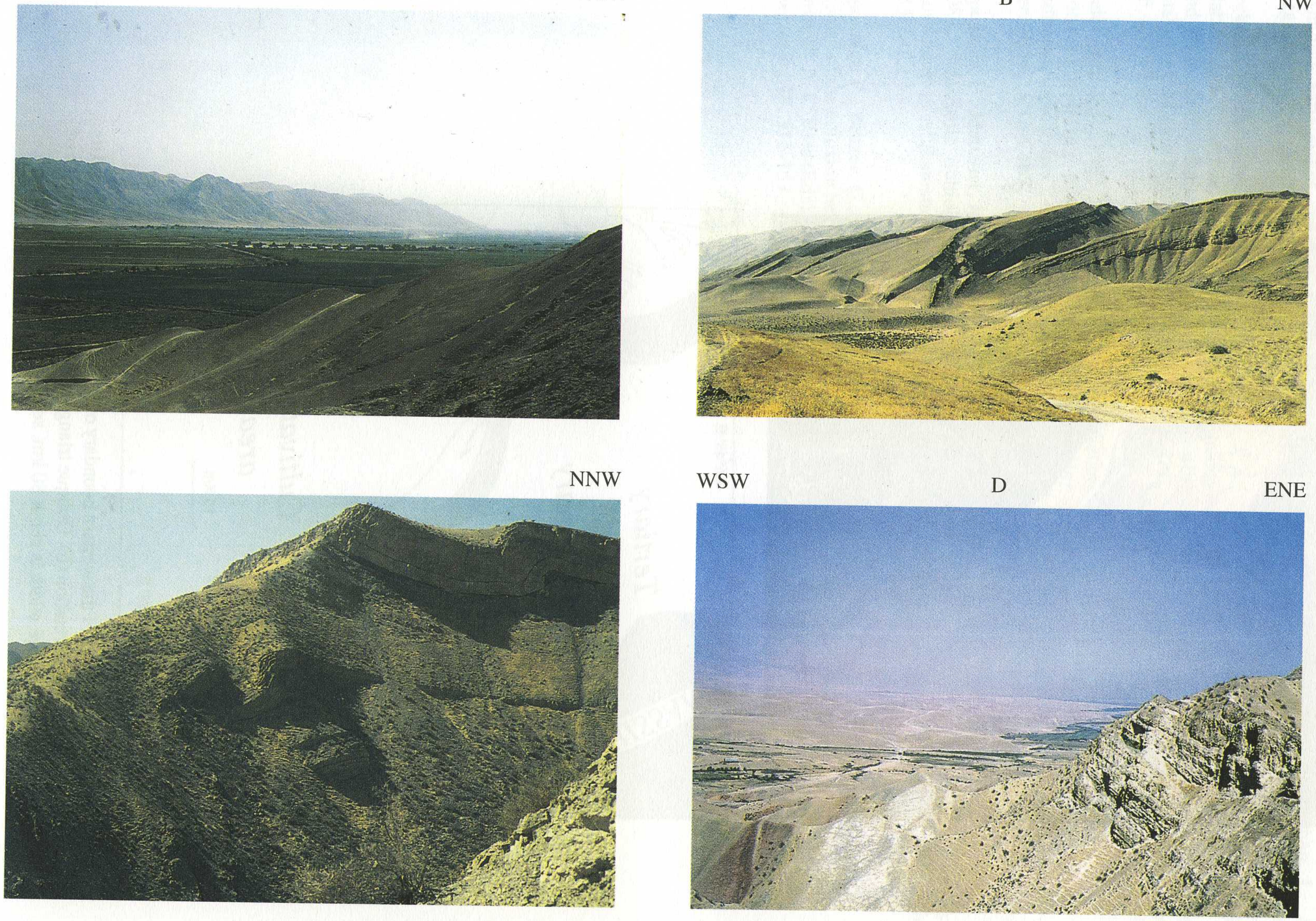


FIG. 4. Photographs showing the general basin-and-range topography of the area and various structural patterns observed at basin margins: A. Aksu area. N-S basin intercalated between ranges; B. Kafirnigan area. Plunging anticline at tip of range; C. Pulkhakim area. Asymmetric fold above thrust; D. Kafirnigan area. Faulted fold with gently dipping Paleocene limestones (right) thrust over subvertical Oligocene series (left) (For approximate locations, see Fig. 7).