Late Quaternary tectonic movements of western and central Asia

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ABSTRACT

Late Pleistocene and Holocene activity on major faults of western and central Asia are inferred from offsets of young topography. Large active strike-slip faults bound the northward-moving Arabian and Indian plates. The Indian plate moves more rapidly with respect to Eurasia than does the Arabian plate, with the highest rate of young lateral motion (1.2 to 1.4 cm/yr) along the Darvaz fault on its northwestern side. Convergence of these plates on the Eurasian plate produces the north-trending compression of the latter. It results in the creation of northwest-trending dextral wrench faults, smaller northeast-trending sinistral faults, east-west–trending thrust faults, and rare north-trending normal and extension faults. The rates of relative motion are slower here than on the borders of the southern plates, being higher to the north of the Indian plate than to the north of the Arabian. Not all relative motion of the southern plates is accommodated by their boundary deformation and by the compression of the Eurasian plate. This motion and resistance of the Eurasian plate produce squeezing of the rock masses on both sides of the southern plates that results in dextral west-trending wrench faulting on the western side and sinistral on the eastern side of each plate. This pattern can be recognized throughout the Neogene-Quaternary tectonic evolution of the Asian segment of the Alpine–central Asian orogenic belt. This paper is an attempt to correlate synchronous tectonic movements over huge areas of the continent. The author believes it is appropriate to recognize in such correlation mobile and stable zones of different scales. The depth and character of motion in the mobile zones define important features of the structure and evolution of the Earth's crust.

INTRODUCTION

Subject, Terminology, and Methods of Study

E. Argand, N. Pavoni, A. V. Peive and his collaborators, A. Gansser, Li Sy-Huan, H. W. Wellman, A. I. Suvorov, J. E. Dewey and J. M. Bird, L. M. Rastsvetaev, P. Molnar and P. Tapponier, and the other tectonicians have proposed various models of the Cenozoic lateral displacement of large blocks of the Earth's crust in the Asian segment of the Alpine–central Asian orogenic belt. Although conforming in general, these conceptions imply different correlations of individual blocks, because of the difficulty of correct age determinations for the lateral motions along major faults. That is just the most critical information required to differentiate the main blocks of the Earth's crust and to reconstruct the dynamic pattern of each epoch. The most reliable chronological data result from the determinations of the age of sedimentation in associated grabens, folds, and so on (Lukyanov, 1963, 1965). They make it possible to know the trends of the horizontal motions in a given epoch only, however — not the magnitudes and rates.

The difficulty of proving the synchronous lateral movements of the major blocks of the Earth's crust is essentially decreased if one limits the age of displacements under study to the late Pleistocene and the Holocene. The deposits and topography broken and offset by these displacements are readily found and can be mapped very accurately. It is possible to correlate them in detail which is unapproached in studies of older geological features, because one can use for this correlation not only the usual geological and geomorphological methods, but also data about changing locations of old coast lines, climatic changes, stages of degradation of the Late Quaternary glaciations, rates of erosion and accumulation, archeology, and radiological data of C^{14}(Wegmann, 1955). It is possible to make detailed quantitative studies of the tectonic motions of the last glacial and postglacial epochs. The peculiarities of study permitted Yu.A. Meshcheryakov (1961) to differentiate these motions as a special subject for research that he called "young movements" of the Earth's crust.

In the present paper, the author differentiates neotectonics (Neogene-Quaternary), young tectonic motions (the last few ten thousand years; that is, the late Pleistocene and the Holocene), and recent tectonic motions (the last few hundred years).

It is essential for our purpose that records of the young lateral offsets of topographic forms, unlike the older ones, usually have not been destroyed by erosion and are thus found in many areas of neotectonic activity. The magnitudes of displacements during various parts of the Holocene and the late Pleistocene give us average rates of young movements that can be extrapolated to the past, using known data about the trends of the older motions.

Young tectonic deformations in areas of high neotectonic activity affect formations of various size, genesis, and structural significance. Some deformations are caused by landslide processes. Specific forms are created by disturbance of the gravitational balance and action of shock waves during disastrous and strong earthquakes (Bogdanovich and others, 1914; Solonenko, 1965, 1973). Concentric and other kinds of faults and fractures are formed by volcanic and mud volcanic activity. Small (but sometimes numerous) landslides, cracks, and normal faults are developed in the allochthons of major young overthrust faults (Scobelev and Florensky, 1974). All of these deformations are near the surface and secondary to large faults and folds. The latter are the main subject of the present research.

Methods of study of young vertical movements have been widely described (Wegmann, 1955; Meshcheryakov, 1961; Kostenko, 1972; Nikonov, 1970; Morisawa, 1972; Ivanova and Trifonov, 1976). They include: variation in inclination of the longitudinal

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profiles of recent stream channels, the altitudes of low terraces (Fig. 1), the width and form of valleys, the alluvial sediments, and the location and form of deltas. A specific method of determination of young folding is by measurement of the recent altitude of old coast lines; for example, the postglacial levels in the Baltic (Wegmann, 1955) or the late Pleistocene levels in the Caspian (Ivanova and Trifonov, 1976).

Young overthrust, reverse, and normal faults can be rarely observed in the natural or artificial exposures (Fig. 2A). Normally, they are defined by geomorphological methods. For their interpretation, it is necessary to know the dip of the fault and the vertical component of offset. The dip of the fault is found rather easily if the topography is steep (Figs. 2B, 2C, 2D). The strike and altitude of the vertical component can be determined in valleys intersected by the fault.

In some cases, a terrace is formed on one side of the fault, and its height displays the altitude of uplift (Fig. 3C). In other cases, the terrace is formed on both sides, but its height is greater on the uplifted flank than on the downthrown flank of the fault (Figs. 2B, 3D). More often, the terrace is absent. After the uplift of the upper part of a valley, the scarp is partly reduced, and detrital material is accumulated downstream. If the lower part of the valley has been uplifted, the material is accumulated above the scarp as a dam; fine-grained deposits are often produced here, and new channels can be cut through the dam. Sometimes the dam effect can be caused by overthrusting of the upper part of the valley if the uplift of the thrusted side is concentrated near the fault (Kopp and others, 1964, Fig. 3). To sum up, the dip of the longitudinal profile of the channel increases or decreases near the fault with respect to the adjacent segments of the valley (Figs. 2F, 3E), permitting the vertical component of the offset to be determined. In combination with the dip of the fault, it is possible to determine the real displacement and differentiate the young thrust and normal faults.

The methods of determination and examples of young strike-slip movements are described in various areas of high neotectonic activity (Hill and Dibblee, 1953; Wellman, 1955; Rantsman, 1963; Kopp and others, 1964; Rantsman and Pshenin, 1967; Wallace, 1968a; Trifonov, 1974, 1976). They can be recognized by repeated lateral offsets and Z-like bends of channels, terraces, ridges, and other linear topographic forms along the fault independent of the general dip of the area (Figs. 4A, 4B). As a result of the offset, drainage net can be changed, and it becomes necessary to reconstruct the old net to define the magnitude of movement (Figs. 4C, 4D). Sometimes topographic forms of various ages are displaced different distances (Fig. 4E), and this is believed to show repeated motion.

Some papers (Wellman, 1966; Ivanova and Trifonov, 1976; Trifonov, 1976; Molnar and Tapponnier, 1975) examine the use of air and space photos for studies of the young deformations. The best way seems to be to combine air and space data with land observations. On small-scale space images from satellites, large faults and areas of neotectonic activity are recognized. On more detailed space pictures from Landsat, Soyuz, Salut, and Skylab, areas of young folding and the deformation of late Quaternary topography are seen. The interpretation of such zones on the air photos permits mapping of young folds (Fig. 5) and active faults and fractures (Fig. 6) and locating the places where they can be best observed by field methods. The dips of faults and the trend and magnitude of offsets can be first defined from air photos in some places (Figs. 2E; 6, top). In any case, field checking is necessary for the final determination of young deformation, trend, magnitude, and age of displacement.

This paper is devoted to systemization and analysis of data about late Pleistocene and Holocene activity of major faults in the Asian part of the Alpine–central Asian orogenic belt.

LATE QUATERNARY DISPLACEMENTS ON THE MAJOR FAULTS OF WESTERN AND CENTRAL ASIA

The largest active fault of the southeastern Caucasus is the dextral reverse-wrench fault trending along the southeastern segment of the Adjichay fault zone (1 on Figs. 7 and 8). The fault dips about 65° to the southwest. The terrace dating from the beginning of the

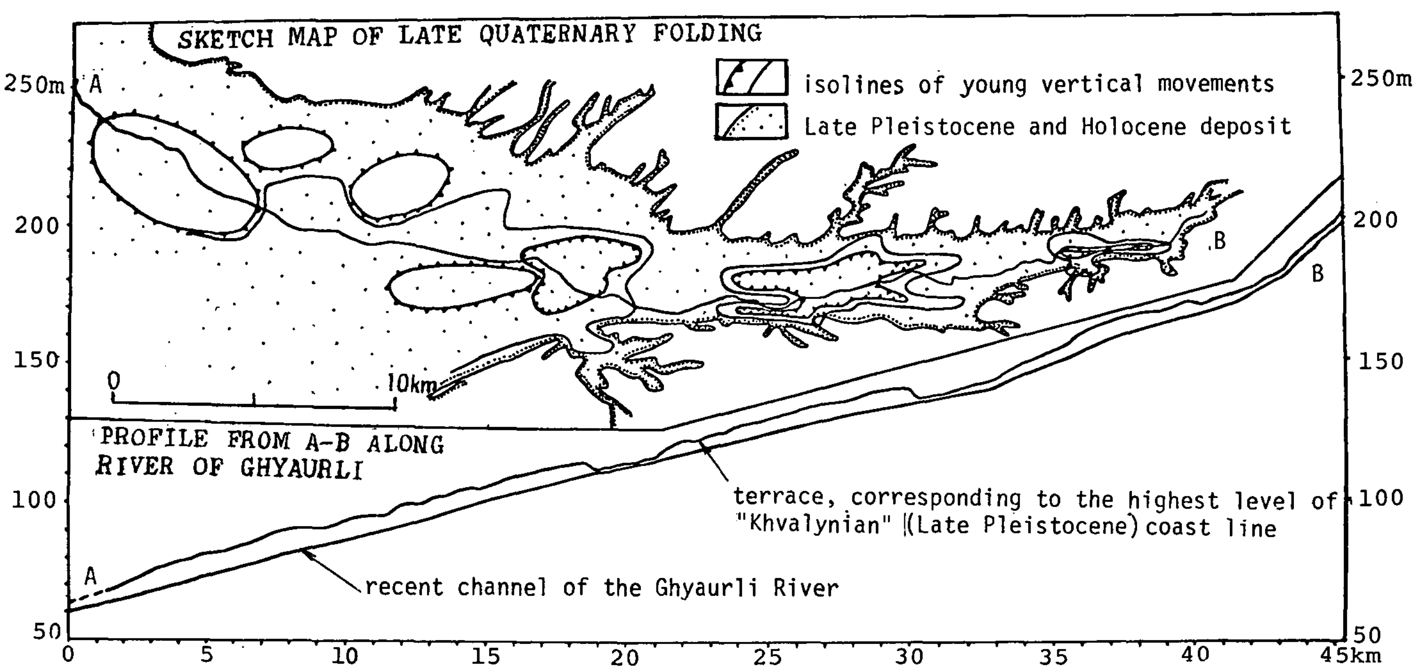


Figure 1. Late Quaternary folding in the Ghyaurli syncline, the Western Kopet-Dagh (Ivanova and Trifonov, 1976).

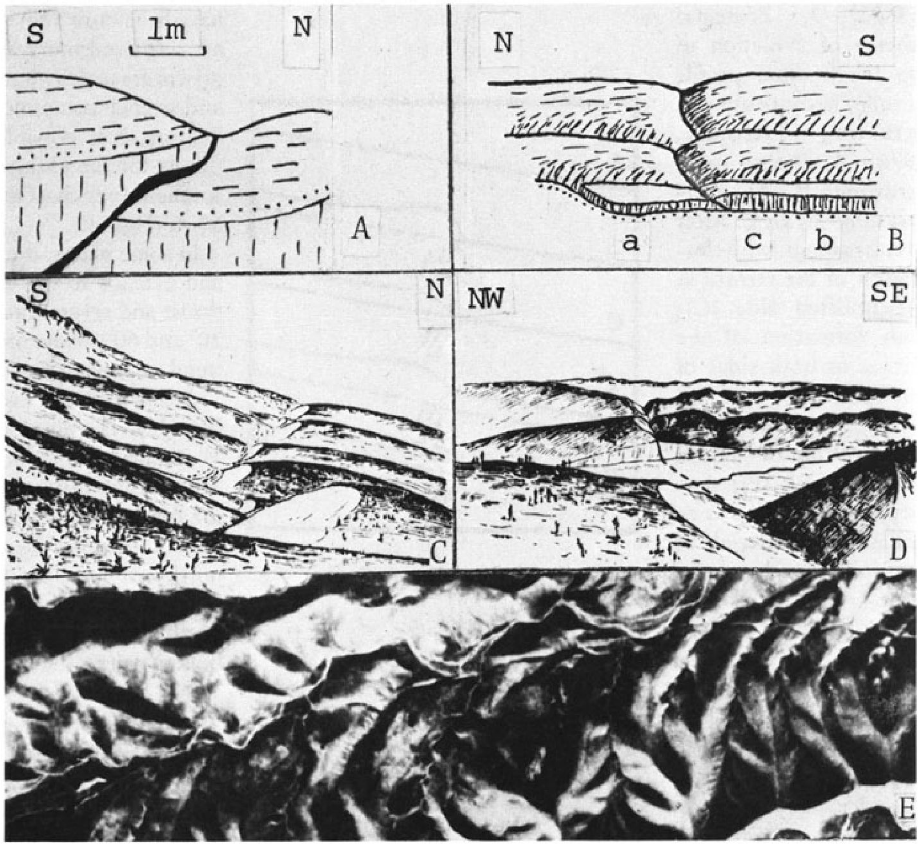
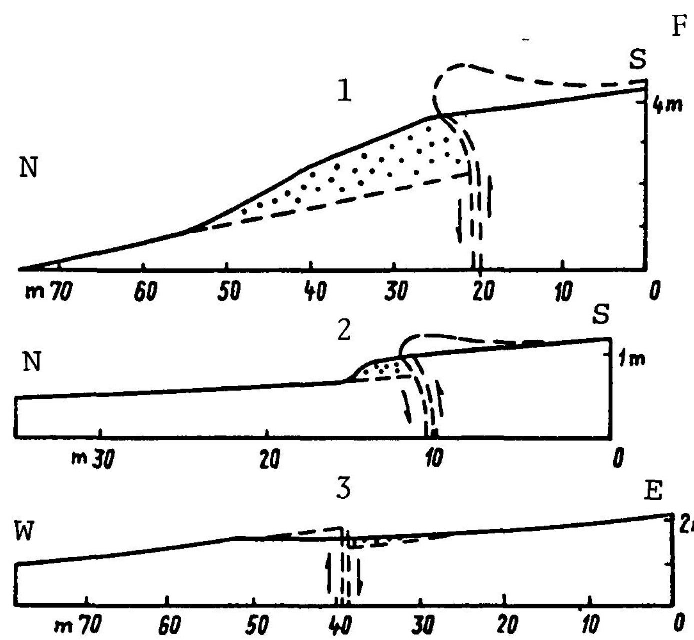


Figure 2. Late Quaternary overthrust and normal faults, the southeastern Caucasus, Big Balkhan, and Kopet-Dagh. A. Artificial outcrop of overthrust fault to the north of the town of Shemakha, Caucasus. Vertical lines are Tertiary argillites; horizontal lines are the late Quaternary sediments; black band is the disturbed rocks along the fault. B, C, D. Late Quaternary faults in the topography of the Big Balkhan (B from Trifonov, 1974) and the central Kopet-Dagh (C, D from Kopp and others, 1964). The faults are differentiated with gentle (B, C) and sharp (D) dip of face. The altitudes of the valley terrace (B) depend on the displacement (a<b<c). E. Young overthrust fault on air photo corresponding to Figure 3C, the Ghyaurs-Dagh range in the central Kopet-Dagh (Trifonov, 1976). F. Deformations of the longitudinal profiles of valleys near overthrust (1, 2) and normal (3) faults, the Ghyaurs-Dagh and the eastern Kopet-Dagh (Trifonov, 1976).

late Pleistocene is displaced 8 to 10 m, with uplift of the southern side of 0.7 to 9.8 m. The offset of the terrace of the end of the late Pleistocene is 3 m, and the Holocene channels are offset up to 2 m. Where strikes of the fault or accompanying ruptures are approximately north-south, the dip-slip component appears and becomes predominant in some places. Where strikes are approximately east-west, the overthrusting develops.

To the north of the Adjichay fault, in the Kobystan and Shemakha region (Fig. 7), the trends of faults are more diverse. The magnitudes of offsets are less than a few metres. Several systems of young faults are mapped. Each system is represented by both overthrust and reverse faults, lateral faults extending about 45° to these, and transverse normal faults and extension fractures. Analysis of the systems shows that the overthrust and reverse faults trend parallel to the axis of many of the modern folds (Makarov and others, 1974, their Figs. 5, 6). The development of such systems seems to be a result of continued folding. In addition, there is a system of rather large faults that extends consistently across the area (overthrust and reverse faults striking 270° to 285° northwest, dextral wrench faults striking 315° to 330° northwest, sinistral wrench faults striking 45° to 60° northeast, and normal and extension faults striking 0 to 20° northeast). The same consistency also characterizes the various segments of the angular and bent faults. Dextral and sinistral strike-slip faults having the same trends are known to the north of the region, in the Limestone Daghestan (Scaryatin, 1963). Many of these faults have been active in the late Quaternary. The young wrench, normal, and extension faults of the system strike parallel to the lineaments that are traced on Soyuz photos and correspond to deep faults (Makarov and others, 1974). Thus, this system of young faults seems to reflect on the surface the active deep deformations of the Earth's crust, but the faults and fractures accompanying the folds do not extend deeper than the sedimentary cover.



Young faults and fractures (Fig. 9) trend more than 500 km along the main Kopet-Dagh fault zone on the northeastern slope of the Kopet-Dagh Mountains (2 on Fig. 8). The majority of them are dextral wrench and reverse-wrench faults that strike parallel to or make a small angle to the trend of the zone. Dextral offsets (as much as 0.3 m) of the walls of the ancient palace are found in remnants of the town of Nissa; of the Wall of Chugundor fortress (Middle Ages), these are up to 2.5 m; of the irrigation systems (lines of "kyarizes"), they are as much as 9 m (Fig. 10). The first such lines were constructed not later than the 5th century B.C. They

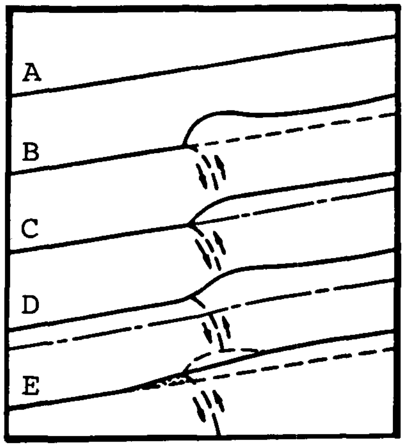


Figure 3. Principal scheme of evolution of the longitudinal profile of valley because of overthrusting (Trifonov, 1976). A. Before overthrusting. B. At overthrusting. C, D, E. After overthrusting: with formation of the terrace in the uplifted side (C); with formation of the terrace in both sides of the fault (D); without terrace, but with increasing of the dip of channel near the fault (E); dots represent the resedimented material of the uplifted side of the fault.

have been built and used over a long period of time. The older lines are displaced more than the younger ones. The Holocene dextral offsets are usually 8 to 10 m along the zone. The ratio of the reverse and wrench components is 1:3 to 1:7. To the west of the village of Beurme, it is possible to measure the magnitudes of the dextral offsets for the Holocene and Holocene–late Pleistocene along the southern branch of the fault. The first is 8 ± m, the second is 55 to 60 m (Fig. 4E).

In some places, the main Kopet-Dagh zone forms step-like bends and extends to the east or east-northeast. There are young overthrust and reverse faults in these bends. They dip 25° to 50°, rarely 20° and 60°. There are also sinistral lateral faults in the zone, which trend to the northeast.

Active folds are especially numerous in the western Kopet-Dagh (Fig. 11). The altitudes are 7 to 8 m for the local young folds (Fig. 1) and up to 50 m for the regional vertical bends. The strikes of the active faults vary more here (as in the eastern Kopet-Dagh) than in the central Kopet-Dagh because of the presence of faults and fractures caused by the folding. The northwest-trending and north-northwest–trending dextral lateral faults and the east-trending and northeast-trending sinistral faults predominate. The young northwest-trending reverse-wrench faults are observed on the Big Balkan range.

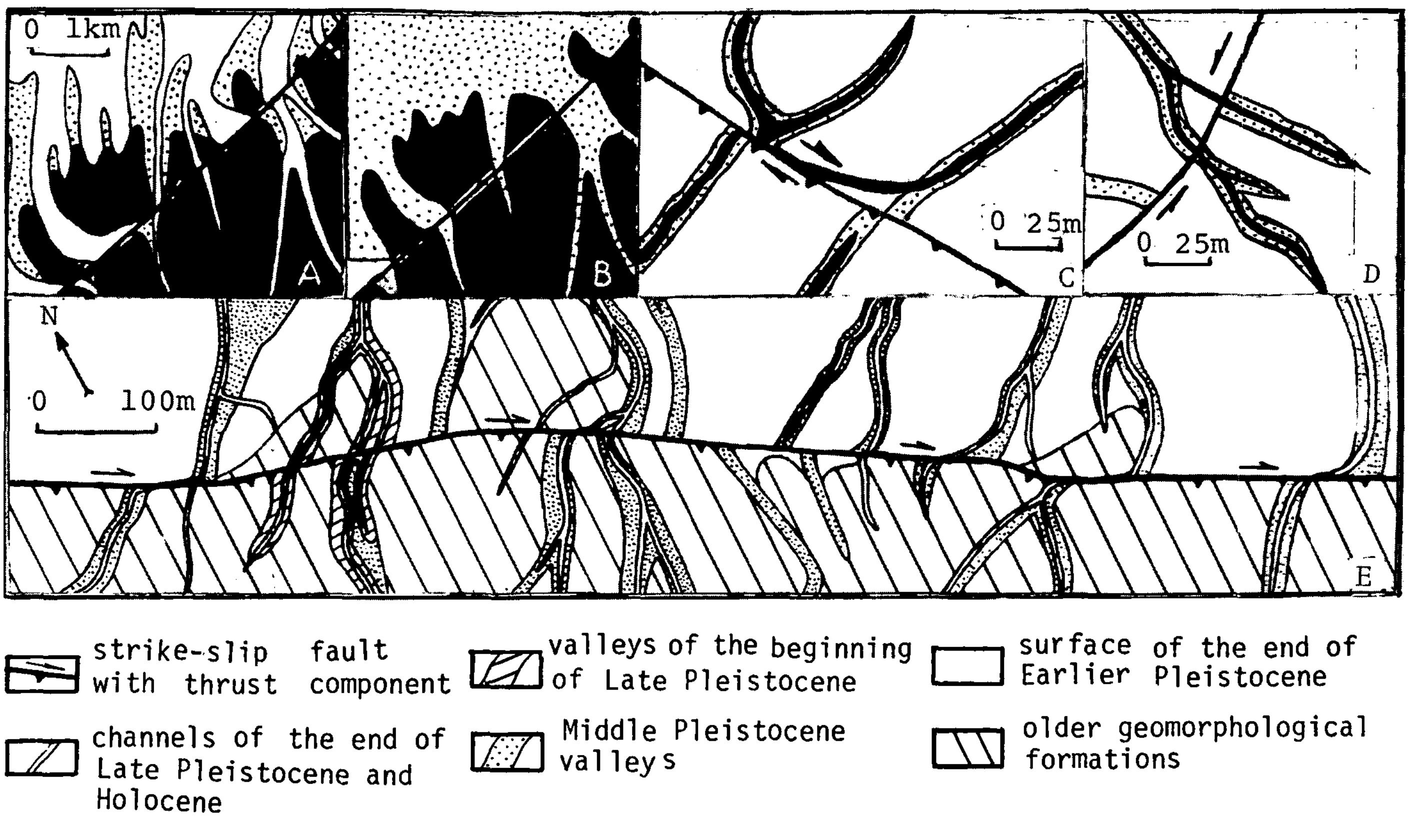


Figure 4. Active strike-slip faults. A, B. Sinistral lateral offset of valleys along the Darvaz fault to the southwest of the village of Saghirdasht, according to the data of Kuchay and the writer (1977): (A) recent pattern of the topography; (B) reconstructed pattern of the topography before the late Pleistocene (zones of sedimentation of the end of the late Pleistocene and Holocene are white; the same zones of the beginning of the late Pleistocene are dotted; the older geomorphological formations are black). C, D. Captures of streams because of the lateral displacements in the southeastern part of the Adjichay fault, 10 km to the northwest of the town of Kazi-Mahomed, the Caucasus (C); and along the Darvaz fault to the northeast of the Vozghina Pass (D). Recent channels are black and older valleys are dotted. E. Different offsets of the topogrpahic features of the different ages along the main Kopet-Dagh fault zone to the west of the village of Beurme (Trifonov, 1974).

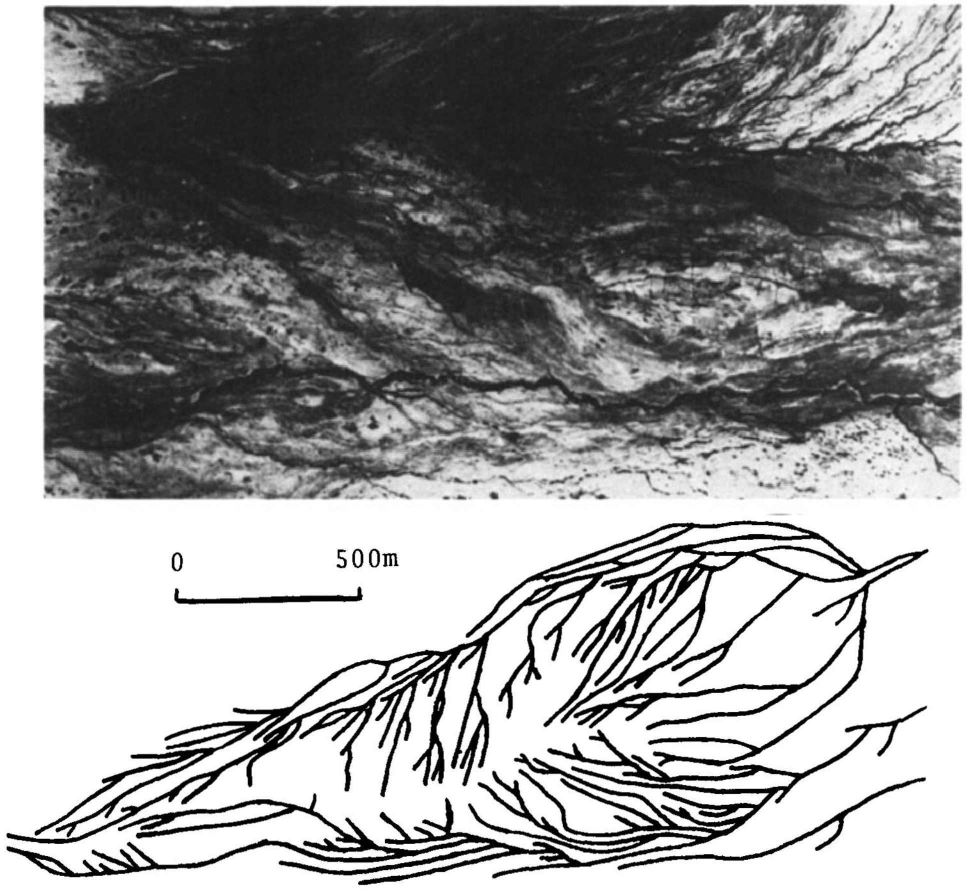


Figure 5. Young folds on air photos of the western Kopet-Dagh (Ivanova and Trifonov, 1976). On top: living and dead Holocene streams curved around the small active anticlines, the Ghyaurli valley. On bottom: interpreted stream pattern on the active anticline to the east of the Lesser Balkhan range.

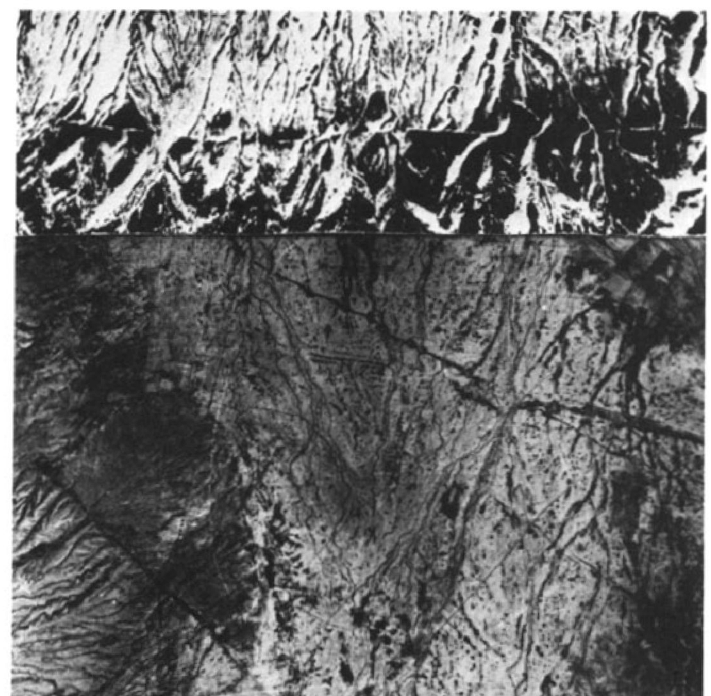


Figure 6. Active strike-slip faults on air photos of the main Kopet-Dagh fault zone (Trifonov, 1976). On top: to the west of the village of Beurme (corresponding to Fig. 4E). On bottom: to the southeast of the village of Parou. The main active fault and some small faults to the northeast of it are seen. The small black dots are the irrigation line displaced by the movements along the main fault (see Fig. 10-III).

Records of late Quaternary activity are displayed along the 150 km of the Talass-Fergana fault to the north of the Soviet-Chinese boundary (3 on Fig. 8). According to the data of Burtman (1963), dextral offsets of the small Holocene valleys are 30 to 35 m, rarely 50 m here, but near the Kyldau River, dextral displacement of a small ridge can be as much as 100 m. Rantsman and Pshenin (1967) published data about the older dextral strike slips. The offset of the third terrace in the southwestern part of the Toguz-Torou basin is from 200 to 250 m (for Holocene and perhaps the end of Pleistocene time); the offset of the middle Pleistocene moraine in the upper part of the Eastern Karasu River is 750 m (from the end of middle Pleistocene). The common dextral displacement from the middle Pleistocene is believed to be not less than 1,200 m (Gerasimov and Rantsman, 1964).

East-trending and east-northeast–trending young overthrust and reverse faults are exposed in various parts of Tien Shan. V. I. Makarov observed overthrusting of the older rocks on formations

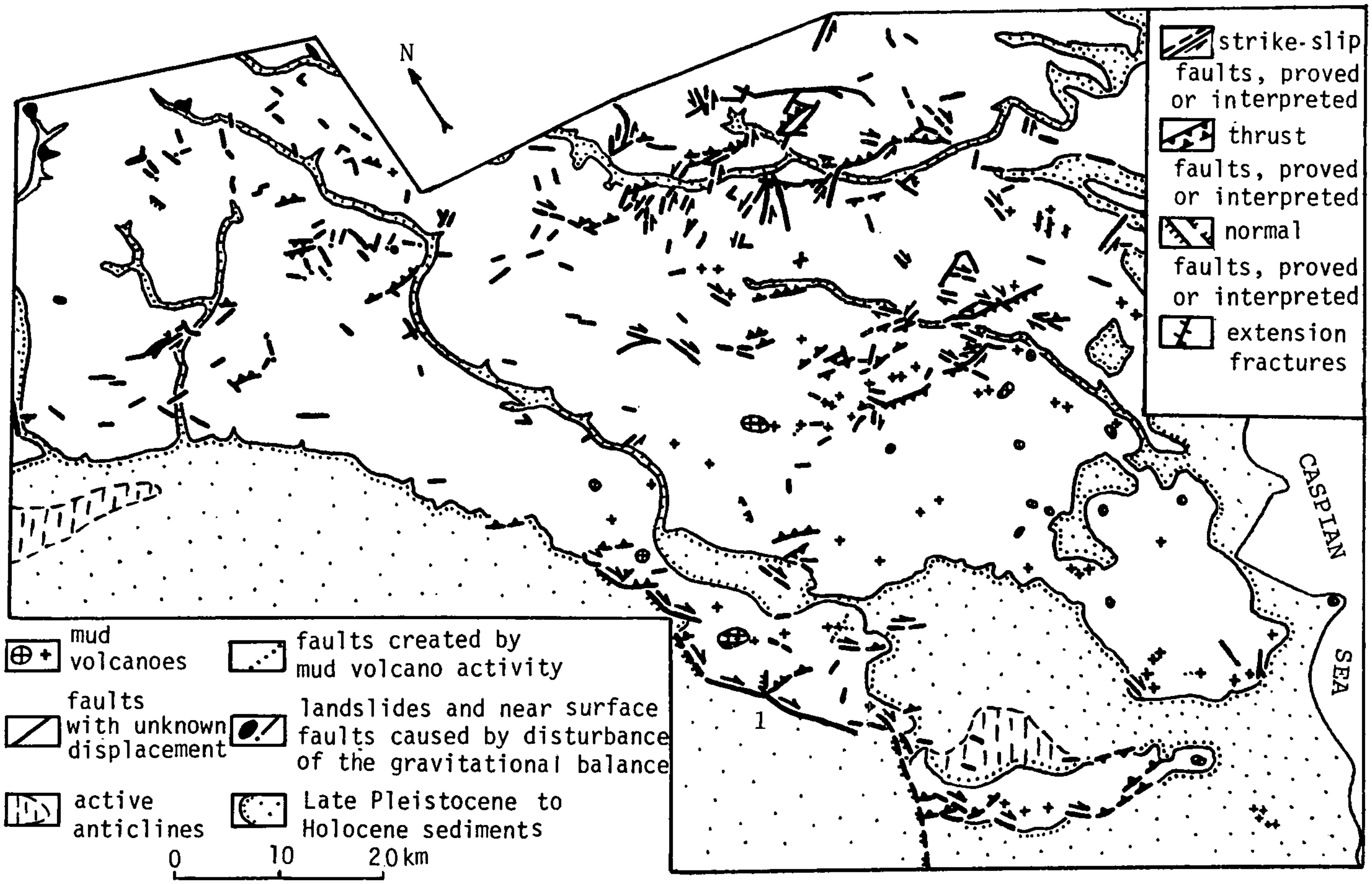


Figure 7. Late Quaternary deformations of the southeastern Caucasus (reduced from Makarov and others, 1974).

formed at the end of middle Pleistocene, late Pleistocene, and Holocene on the southern side of the Kochkor basin, and on the northern sides of the Atbashi, Naryn, and Upper Naryn basins. Late Quaternary displacements seem to take place, according to the data of B. V. Senin, along the Zaamin reverse fault. B. E. Akinin described Holocene reverse faulting in the upper part of the Zeravshan River. There are young overthrust and reverse faults on the southern slope of the Ghissar Mountains to the West of the town of Dushanbe. Overthrusting took place during the Kebi earthquake of January 4, 1911 (Bogdanovich and others, 1914; Kuchay, 1969).

Records of young dextral lateral movements are described for the 100 km of the Dzungar fault near Dzungarian Gates (4 on Fig. 8). Voytovich (1968) believes the dextral displacements for the late Pleistocene and Holocene occurred in two stages and that they measured 500 m — the first of 300 m, then of 200 m. According to the data of K. V. Kurdyukov and V. S. Voytovich, the offsets of the small valleys on the late Pleistocene surface near the mountain front are as much as 35 m near the Rgaity River. In 1970, A. V. Dolitsky and the writer defined two magnitudes of dextral displacements here: the first 40 to 50 m from the end of the late Pleistocene and the second 20 to 25 m (only 10 m in some places) during the Holocene. The young fault dips very sharply to the southwest. The reverse component of offset is up to 7 m. To the northwest, the fault is separated into a few en echelon branches. The Holocene dextral offsets are not more than 10 to 12 m along each branch and decrease to 0 to the northwest.

To the southwest of the Dzungar fault, Kurdyukov (1956) described the east-west–trending late Quaternary Lepsy reverse fault. A. V. Dolitsky and the writer observed a few east-west–trending and west-northwest–trending young reverse and dextral reverse-wrench faults in the Dzungar Alatau Mountains. The sinistral reverse-wrench fault was found on the southeastern slope of the Altyn-Emel range (5 on Fig. 8). It dips sharply under the range. The sinistral offsets are 2.5 to 3 m for the end of the Holocene; 5 to 7 m for the Holocene; 15 to 20 m for the Holocene and the end of the late Pleistocene; and 30 m for the Holocene and the late Pleistocene. Middle Pleistocene forms are displaced to 50 m; it is not clear if this displacement is only Late Quaternary or includes the middle Pleistocene also. The reverse component is 1/6 to 1/8 of the strike-slip component.

All of the young faults under consideration belong to the northern front of the Alpine–central Asian orogenic belt and have constant trends: northwestern for the dextral wrench faults, northeastern for the sinistral ones, east-west for the overthrust and reverse faults. The faults with intermediate displacements have intermediate trends. A more complicated pattern is found to the south. On the southern front of the belt, there are two plates with ancient crust: the Arabaian and the Indian. They cut deeply into the belt and are essentially rebuilt by neotectonic movements in the frontal parts. The most extensive movements have taken place in the Indian plate. Both of the plates are bounded by zones of young activity.

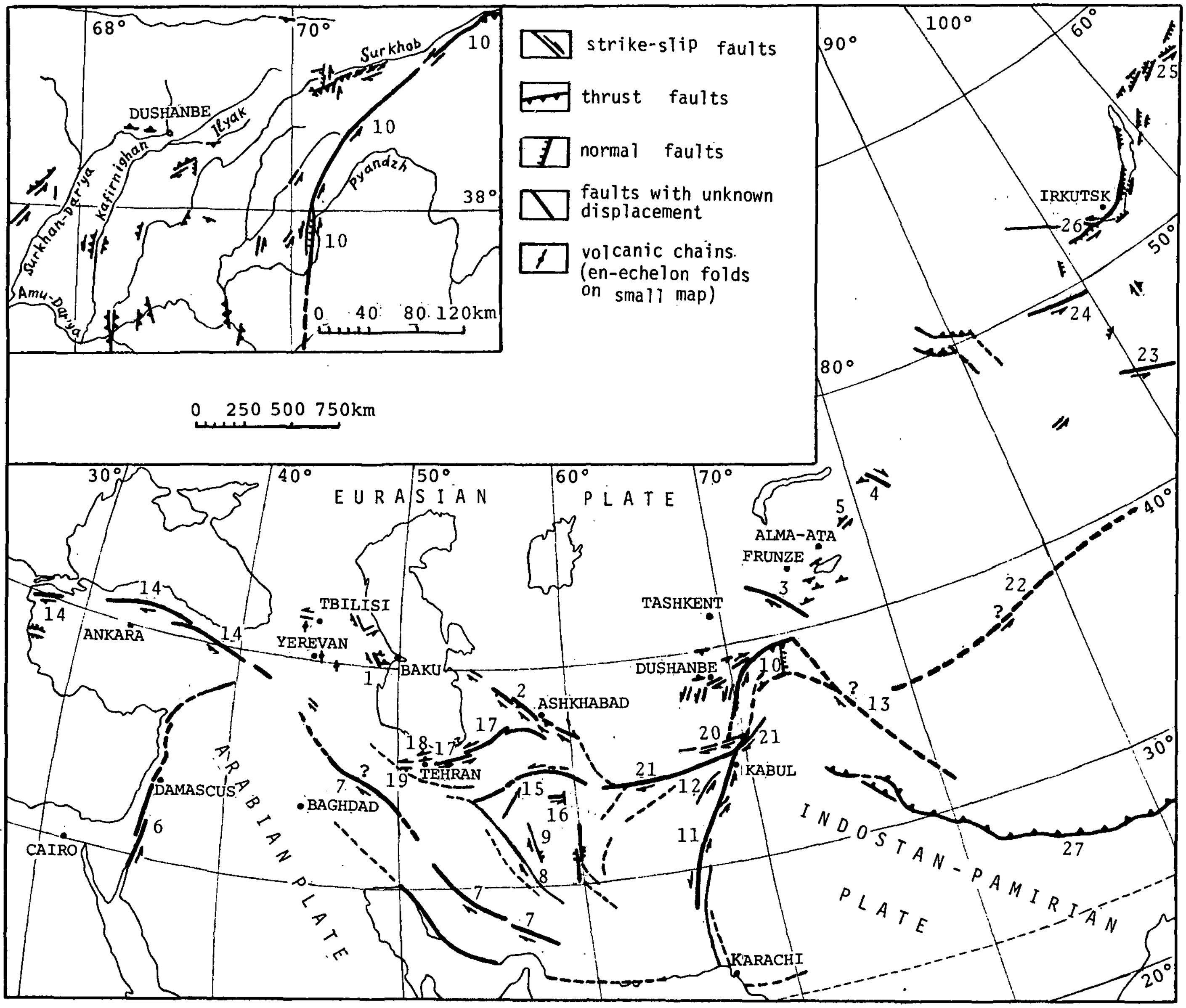


Figure 8. Major faults of western and central Asia that have been active during late Pleistocene and Holocene time. The faults of the Afghan-Tadjik depression are also shown on the small map (the data of A. A. Nikonov, 1970, are used here about the Amy-Dar'ya-Pyandzh Valley).

Numbers denote localities of the faults: 1. Adjichay; 2. main Kopet-Dagh, 3. Talass-Fergana, 4. Dzungar, 5. Altyn-Emel, 6. Dead Sea, 7. Zagros, 8. Kuhbanan, 9. Naibandan, 10. Darvaz, 11. Chaman, 12. Darafshan, 13. Pamir-Karakorum, 14. North-Anatolian, 15. Doruneh, 16. Dasht-e Bayas, 17. Shahrud, 18. North-Tehran, 19. Buyin-Zara, 20. Talemazar, 21. Herat, 22. Altyn Tah, 23. Lake Valley, 24. Khangay, 25. Muya, 26. Tunka, 27. Himalayan Boundary Fault.

The north-trending Dead Sea rift system extends close to the eastern coast of the Mediterranean Sea from the Gulf of Aqaba to the Taurus Mountains (6 on Fig. 8). There are several main en echelon faults and many smaller ones. In addition to vertical displacements, sinistral lateral displacements of about 100 km have been determined along the system (Quennell, 1959; Freund, 1965). The Dead Sea graben corresponds to the extension zone between two en echelon main wrench faults. A compressional component appears in the Lebanon and Hermon-Anti-Lebanon ranges, where the system strikes to the north-northeast.

Quennell (1959) stated that the last phase of the lateral movements was in Quaternary time. The northern Dead Sea basin has not yet been filled by deposits, and the mouths of the permanent and temporary streams have not built deltas. These indicate the young age of the motion. Holocene sinistral offsets of about 10 m (Quennell, 1959) are determined in Wadi Araba (the south). The

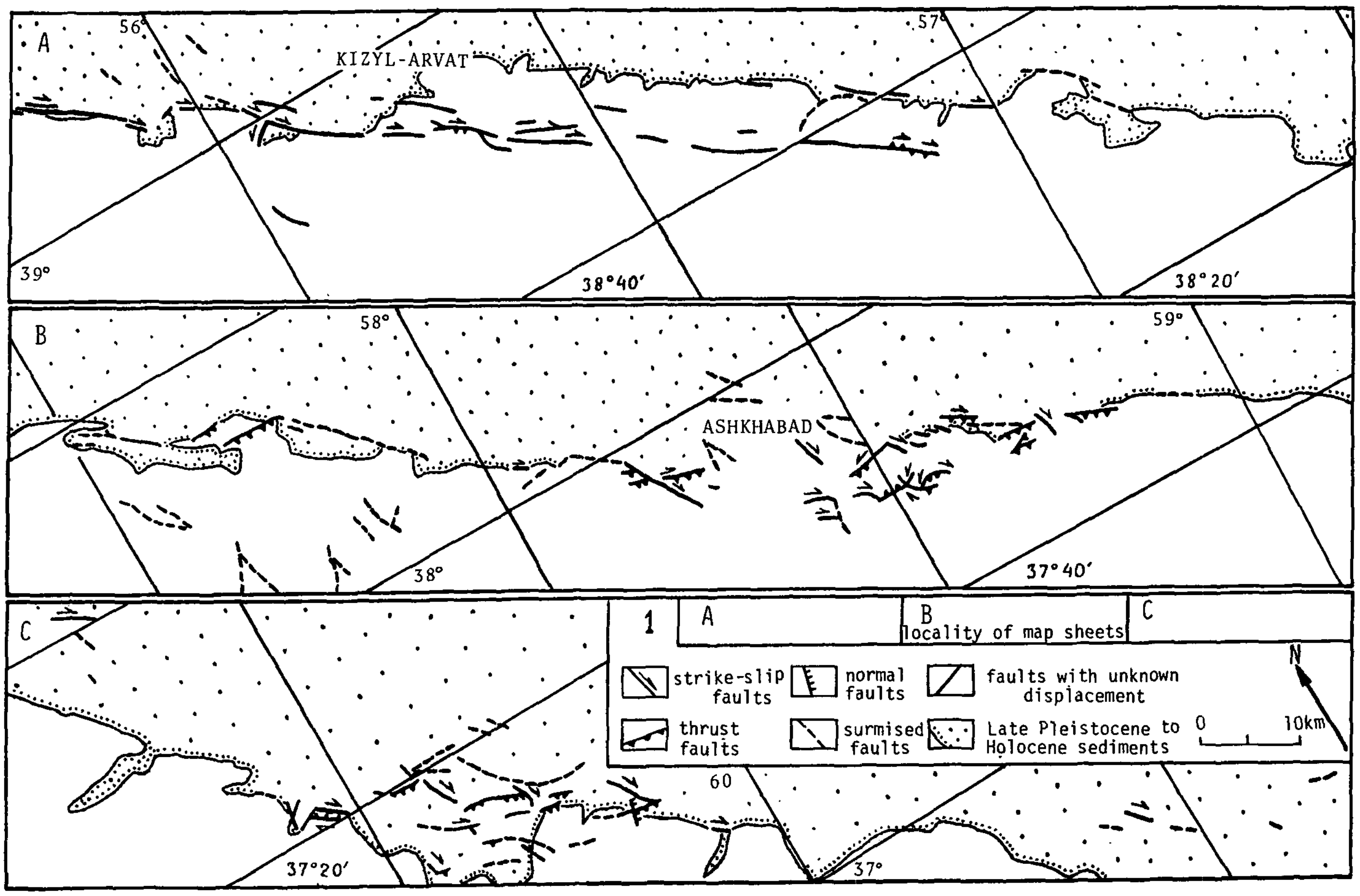


Figure 9. Active faults of the main Kopet-Dagh fault zone (reduced from Trifonov, 1976).

faults of the system are often expressed by scarps on Late Quaternary surfaces. The records of the vertical displacement of 31 B.C. are found in the Essenes monastery in Khirbet-Qumran (Zeuner, 1955).

There have been extensive young movements on the northeastern coast of the Persian Gulf and on the Mesopotamian plains. Lees (1955) demonstrated local and regional folding during historical time. The axis of the modern northwest-trending Shaur anticline between Shush and Ahwaz has been lifted as much as 18 m during the last 1,500 yr (more than 1 cm/yr). Wellman (1966) found the records of the late Quaternary activity of large segments of the Zagros fault (7 on Fig. 8) and mapped dextral offsets of the intersected valleys of up to 100 m. To the northeast, the Kuhbanan and Naibandan young faults (8 and 9 on Fig. 8) were mapped with dextral bends of valleys (Wellman, 1966). The faults strike to the northwest and bend to the north in their northern parts.

The Darvaz fault (10 on Fig. 8) bounds the Indian plate on the northwest. The system of the extensive young deformations trends here from its east along the southern margin of the Alay Valley. Westward it strikes to the southwest between the village of Lyakhsh and upper part of the Obi-Miniou River, and continues southward, striking south. It intersects the Pyandzh River and joins with young deformations of the western Indian border which extend along the Sulaiman-Kirthar sinistral shear belt that was traced by Abdel-Gawad (1971) using space photos. It is a sinistral en echelon row of faults. The largest of these is the Chaman (11 on Fig. 8), active in late Quaternary time (Wellman, 1966). The zone continues to the south, following the north-south faults of the Arabian Sea floor.

On the west-trending segment of this giant system, in the Alay Valley and westward between the villages of Karamyk and Lyakhsh, there are young overthrust and reverse faults. On the northeast-trending segment of the Darvaz fault, between the village of Saghirdasht and the Vozghina Pass, the late Quaternary sinistral offsets were described by Zakharov (1969) and Nikonov (1975). Kuchay and the writer (1977) observed this area in 1974 and defined the magnitudes of the displacements of different ages. In some places, small valleys are offset 5 m or 20 m. The same magnitudes of the offset of the Sogdian (6th to 12th centuries) and the later fort walls show that both of these displacements have taken place during the last 1,500 yr. The general displacements reached 60 to 95 m during the late Holocene, 150 to 160 m during the Holocene, 300 to 350 m (up to 500 m?) during the end of the late Pleistocene and the Holocene, and about 800 m during the late Pleistocene and the Holocene as a whole (Figs. 4A, 4B). The single measurement of the offset from the end of the middle Pleistocene is of 1,200 m. The fault dips sharply to the southeast. The reverse component varies, but is many times less than the lateral.

To the south, along the north-trending part of the fault zone, the sinistral offsets are predominant. The individual young faults and fractures may locally spread the belt for a few tens of kilometres. The main young faults produce the late Quaternary graben along the Pyandzh River and in the valley near the villages of Yol and Porvor (small map on Fig. 8). In some places, the faults are located en echelon and form sinistral rows.

Late Holocene channels are displaced sinistrally up to 20 m; earlier Holocene terraces and deltas are displaced up to 120 m, rarely up to 140 to 150 m (with uplift of the western side of 3 to 4 m); the valley slopes of the beginning of the late Pleistocene are displaced up to about 300 m along the western boundary of the graben between the villages of Khirmandjo and Yol.

Sinistral offsets and bends of the valleys take place along the Chaman fault (Wellman, 1966). It is possible that there are sinistral offsets of 800 m and 1,100 m to the north of the town of Chaman. To the south of the town, two magnitudes of sinistral offsets have been determined for the different valley systems (20 m and 120 m). Sinistral displacement of the railroad of 1 m took place in the town of Chaman during the earthquake of 1892 (Griesbach, 1893). The small late Quaternary uplift of the western side is revealed in the northern part of the fault; to the south, the vertical component varies. To the west of the northern part of the Chaman fault, there are sinistral offsets of valleys of up to 150 m (Wellman, 1966) along the Darafshan fault (12 on Fig. 8.).

There may be large young displacements on the northeastern front of the Indian plate, along the Pamir-Karakorum fault (13 on Fig. 8) described as a Cenozoic dextral wrench fault with a magnitude of up to 270 km (Burtman and others, 1963). As seen on the space imagery, the fault intersects late Quaternary formations. Young activity is recorded along the Aksu-Murgab dextral wrench fault zone (Ruzhentsev, 1963) which is a branch of this fault.

On both sides of the Arabian and Indian plates, in the inner parts of the Alpine–central Asian orogenic belt, there are many west-trending young faults. Pavoni (1961) described dextral offsets of up to 4 m along the North Anatolian fault (14 on Fig. 8). These displacements took place along almost the entire 1,300-km length of the fault and were caused by the series of earthquakes of 1939–1953. The southern side of the fault was uplifted to 1 m at the same time. The same offsets were formed during the earthquake of August 19, 1966 (in the area of the village of Varta), and in the early stages of late Quaternary time (Wallace, 1968b).

Young faults are also found to the northeast of the Zagros fault. Sinistral offsets of valleys of 75 and 200 m (Wellman, 1966) are determined along the west-trending segment of the arched Doruneh

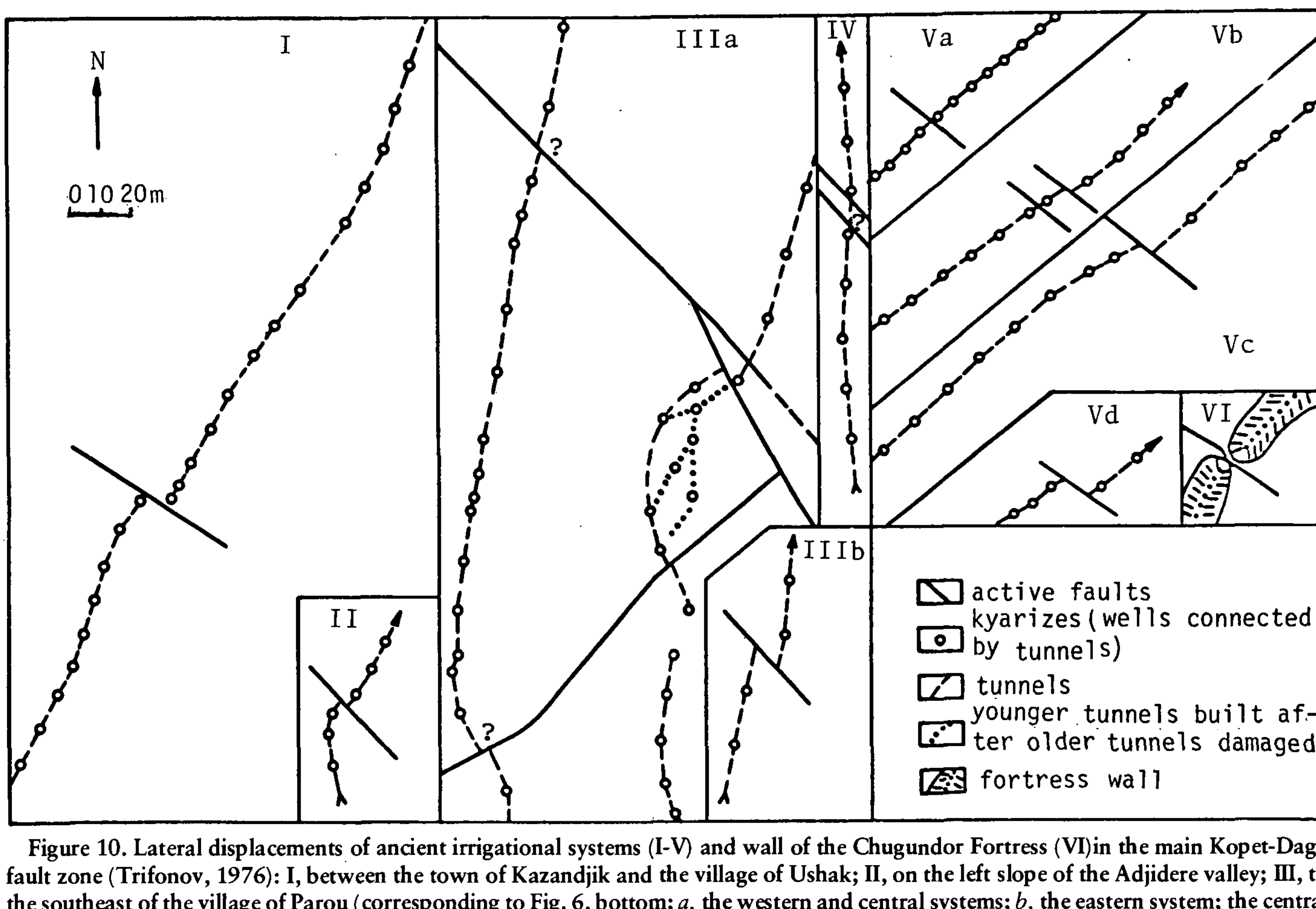


Figure 10. Lateral displacements of ancient irrigational systems (I-V) and wall of the Chugundor Fortress (VI)in the main Kopet-Dagh fault zone (Trifonov, 1976): I, between the town of Kazandjik and the village of Ushak; II, on the left slope of the Adjidere valley; III, to the southeast of the village of Parou (corresponding to Fig. 6, bottom; *a*, the western and central systems; *b*, the eastern system; the central and eastern systems are older than the western one); IV, to the east of the village of Pyrnuar; V, near remnants of the ancient town of Old Nissa (*a* is younger than *b* and *c* and all are younger than *d*). All faults strike northwest-southeast, and offsets are right lateral.

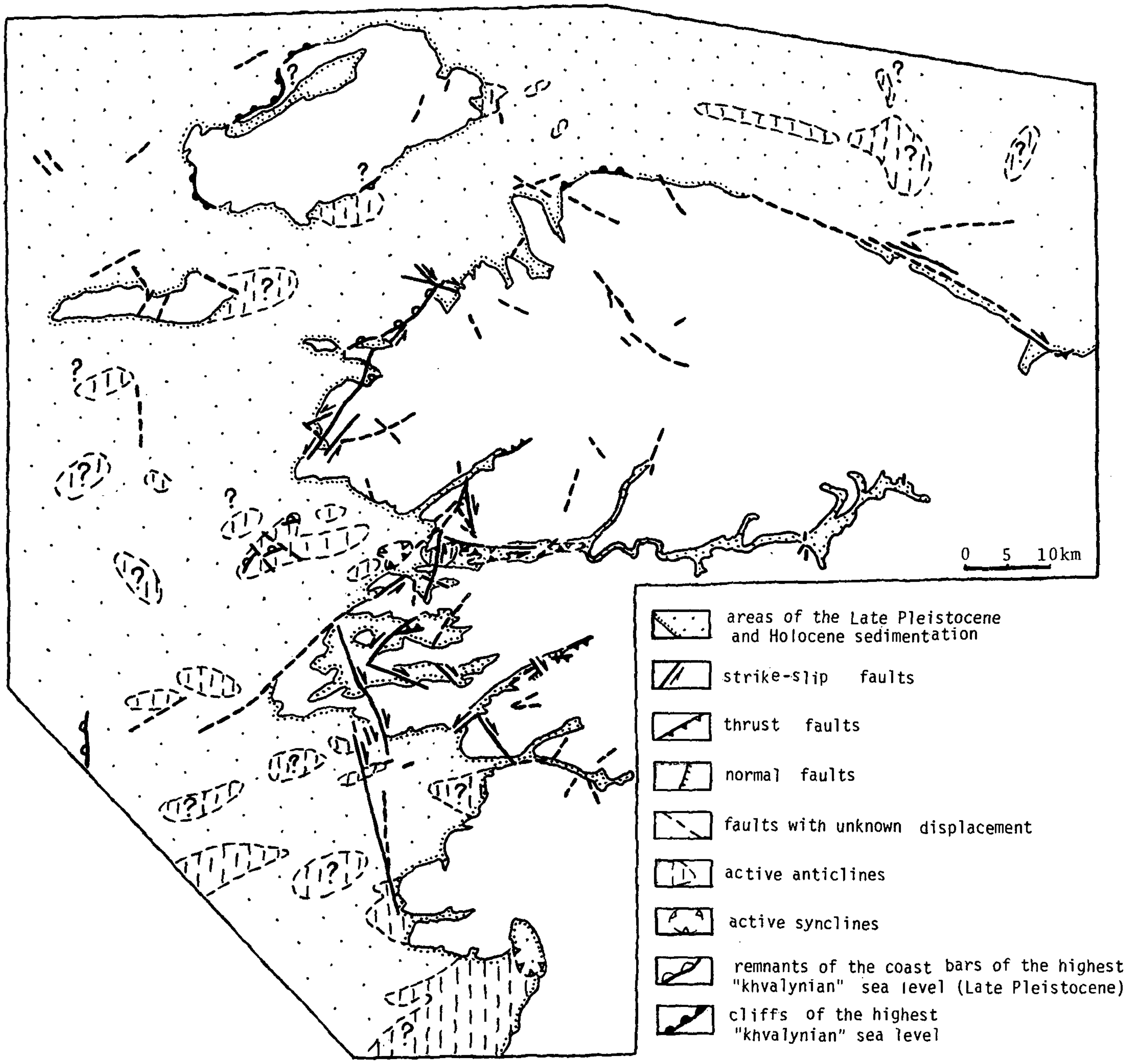


Figure 11. Late Quaternary deformations of the western Kopet-Dagh (reduced from Ivanova and Trifonov, 1976).

fault (15 on Fig. 8). A west-trending fracture zone was created during the Dasht-e Bayas earthquake of August 31, 1968 (Gansser, 1969; Tchalenko and Ambraseys, 1970). The zone has a length of 80 km and a width of up to 3 km (16 on Fig. 8). Sinistral offsets of up to 4.5 m are measured along the zone; the vertical component varies, but reaches 1.6 m in some places. Sinistral offsets of valleys of 35 and 100 m (Wellman, 1966) are defined along the east-northeast–trending Shahrud fault (17 on Fig. 8). To the west, along the North Tehran fault, which has an azimuth of 70° northeast (18 on Fig. 8), young reverse displacements are found, but en echelon location of the fault segments shows the presence of the smaller sinistral lateral component (Tchalenko and others, 1974). To the south, in the town of Tehran, several small west-trending and northwest-trending young overthrust faults are defined (Tchalenko and others, 1974). The west-trending sinistral reverse-wrench fracture zone (19 on Fig. 8) was created during the Buyin-Zara earthquake of September 1, 1962, 150 km to the west of Tehran; the lateral component reached 0.1 m, with the southern side lifted up (Ambraseys, 1963).

Kogoshvili (1970) gives examples of young folding and vertical offsets on the faults of Georgia. S. S. Shulz, Jr. observed the young west-trending sinistral wrench-fault near the town of Gori. North-trending late Quaternary volcanic chains are known on the Abul, Ghegam, and Sinyuk volcanic plateaus of the Caucasus. They seem to mark extension zones of this age.

There is a complicated system of young deformations to the west of the Kirthar-Sulaiman-Darvaz shear belt. On the northern side of the Afghan-Tadjik depression, Zakharov (1964) showed that the Surkhob zone of the seismically active modern dextral wrench faults continues to the west as the Khanaka, Ilyak, and Kokshaal branches of the Southern Tien Shan fault. The Ilyak branch is the most seismically active. Holocene vertical displacements (Pevnev and others, 1968; Finko, 1970) and overthrusting (Scobelev and Florensky, 1974) are described in the Surkhob Valley (small map on Fig. 8). According to the data of T. P. Ivanova and the writer, the east-northeast–trending young overthrust and reverse faults are predominant here on the northern slope of the Peter the First range. North-trending sinistral wrench faults and the west-northwest–trending dextral wrench faults are connected with them. Normal and extension faults strike to the north-northwest and become quite important in some places. All faults showing young deformation are attributable to northwest-southeast compression with a dextral component of motion along the Surkhob zone. The latter is confirmed by the en echelon location of the late Pleistocene faults and folds on the left slope of the Surkhob Valley near Tadjikabad (upper right corner of small map on Fig. 8). On the Ilyak zone (central part of small map on Fig. 8), there are young faults that show only reverse offsets; but along the major young northeast-trending fault to the northwest of the town of Yavan, the dextral component is greater than the reverse component by many times. Lateral offsets on this fault have reached 13 to 15 m during the Holocene and 80 to 90 m from the middle of the late Pleistocene.

To the south of Ilyak zone, the modern folds of the Afghan-Tadjik depression are oriented north-northeast to north in the southern parts. There are modern reverse faults along the flanks of the anticlinal ranges.

Nikonov (1970) shows that development of the folds and vertical movements of the faults have continued into the Holocene. According to the author's observations, some of these Holocene faults are sinistral reverse-wrench faults with a predominance of lateral component (on the western slope of the Surkhan-Dar'ya valley; in the Kafirnighan valley; see small map on Fig. 8).

The west-trending Talemazar and the larger Herat faults (20 and 21 on Fig. 8) are mapped to the south of the Afghan-Tadjik depression (Wellman, 1966). Dextral offsets of the Holocene(?) valleys of 25 m are found along the Talemazar fault. The same bands of valleys can be interpreted along the Herat fault. Records prove right-lateral movements along the northeastern continuation of the Herat fault, to the east of its intersection with the Chaman fault. The Holocene(?) valleys are displaced 60 to 100 m here. The vertical component is essentially less (Wellman, 1966). P. Molnar (1976, personal commun.) reviewed data of H. W. Wellman. He found young dextral offsets of 3 to 4 m only along the Talemazar fault and no young offsets along the Herat fault.

To the east of the Indian plate, Molnar and Tapponnier (1975) mapped the Cenozoic east-northeast–trending fault along the Altyn Tagh range (22 on Fig. 8); they interpret the movement as sinistral because of similarity of the fault with known wrench faults and because of earthquake first motions. Their conclusion is supported by the en echelon location of modern horst-anticlines to the south of the Altyn Tagh. On the space imagery, the fault line cuts the late Quaternary deposits and topography.

Sinistral lateral displacements of up to 8 m took place along 270 km of the Lake Valley fault in the Mongolia (23 on Fig. 8) during the Gobi-Altay earthquake of December 4, 1957 (Solonenko and Florensov, 1963; Lukyanov, 1963, 1965). The vertical component varies; it is usually not more than a few metres, but it increases in some places because of secondary deformations. According to the data of Lukyanov, the sinistral displacements during the Gobi-Altay earthquake followed the same earlier motion. Sinistral lateral offsets of up to 6.5 m took place along more than 320 km of the Khangay fault (24 on Fig. 8) during the Tannu-Ola earthquakes of July 9 and 23, 1905 (Voznesensky, 1962).

The majority of investigators (Obruchev, 1922; Lamakin, 1955; Florensov, 1968) consider the Baykal and smaller adjacent basins to be grabens created by the extension. Many of the longitudinal normal faults of this system have been active in the Holocene; seismic ground deformations with normal faulting are recorded along them (Solonenko, 1968). Another pattern is seen on the northeastern and southwestern continuations of the Baykal rift system. Here, the west-trending reverse-wrench and normal-wrench faults were created to the northeast of Baykal, near the southern side of the Muya basin (25 on Fig. 8) during the earthquake of June 27, 1957 (Solonenko, 1965; Solonenko and others, 1966). The bent (but as a whole, west-trending) Tunka fault extends to the west of the southern end of Baykal (26 on Fig. 8). The dip-slip component is defined by geomorphological and geological methods as 300 to 400 m and is accompanied by a sinistral offset of 300 to 1,200 m; the displacements have taken place for the Pliocene and Quaternary (Sherman and others, 1973). Obruchev (1950) determined the young dip-slip offset on the fault of 30 to 40 m. There are young seismic ground deformations with records of the sinistral normal-wrench displacements in the fault zone (Khromovskikh and others, 1975).

DISCUSSION AND INTERPRETATION

The data about young displacements on the major faults of Western and Central Asia vary in kinds of evidence and completeness. Some conclusions are supported by detailed studies, but others (for example, the data of H. W. Wellman) are based on the interpretation of air photos only. The magnitudes of the displacements for the different parts of the late Pleistocene and Holocene are defined for some faults, but a single record of earthquake movements during the past 100 yr is all that is known for the other ones. The age of motions cannot be determined precisely in some places. In addition, data are absent for many areas. However, the data under consideration seem to be sufficient bases for the determination of the main tendencies of young movements of the Earth's crust in the studied part of the Alpine–central Asian orogenic belt.

The largest magnitudes of the late Quaternary displacements are found in the Darvaz fault zone. The average rate of the sinistral movement is 1.2 to 1.4 cm/yr here. It seems to be the same in the southern part of the Kirthar-Sulaiman-Darvaz system. This system and the Pamir-Karakorum fault bound the Indian lithospheric plate which moves to the north relative to Asia. This motion, meeting resistance from Tien Shan (a margin of the Eurasian lithospheric plate) seems to be the origin of the rapid late Quaternary uplift of Pamir, Karakorum, and Himalayas (Gansser, 1964; Loskutov, 1969; Molnar and Tapponnier, 1975; Belousov, 1976) and the overthrusting along the Main Bounding Fault of the Himalayas (27 on Fig. 8). Gansser (1964) believes the overthrusting to have followed the early middle Pleistocene folding of the Siwalik formation. Similar, but slower motion has taken place in the Arabian lithospheric plate, bordered by the Dead Sea and the Zagros fault zones. These zones are not limited to the margins of the two plates, but encroach to tens, sometimes hundreds of kilometres beyond the main bounding faults.

The approach of the Indian and Arabian plates to the Eurasian plate has created compression of the Eurasian plate. It has resulted in the uplift and warping of the plate margin (strongest of all in Tien Shan) and in late Quaternary activity of the faults. The strikes of fault displacements are similar throughout the large area that displays the consistent trend of the compression. The rates of motion are lower at the southern part of the Eurasian plate than at the southern front of the orogenic belt (that is, on the borders of the Arabian and Indian plates) and are higher to the north of the Indian plate than to the north of the slower moving Arabian plate. The average rate of lateral displacements along the main Kopet-Dagh fault, therefore, seems to be about 1.5 to 2 mm/yr; along the Talass-Fergana fault, it is apparently not lower than along the Darvaz fault.

More complicated young motions have taken place between the Indian and Arabian plates and the Eurasian plate. They are seen best of all between Pamir and Tien Shan where the rock masses have been squeezed out of the area of the closest approach of the plates. Because of it, dextral reverse-wrench faults have been produced along the southern border of Tien Shan, in the Surkhob-Ilyak zone, and the transverse normal and extension faulting have been created in the squeezed rocks of the Peter the First range. West-trending dextral lateral movements also have taken place farther south (the Talemazar fault and probably the Herat fault). Perhaps they have been caused by differential squeezing of the rock material out of the moving Indian plate under conditions of resistance from the North (Zakharov, 1958; Molnar and Tapponnier, 1975).

Young motions along the west-trending faults to the east of the nearest area of approach of the Indian and Eurasian plates have mirror-image symmetry. Sinistral wrench, reverse-wrench, and normal-wrench displacements are found along the Altyn Tagh, Lake Valley, Khangay, Tunka, and Muya faults.

These symmetric west-trending lateral movements were shown and explained by Zakharov (1958) and later by Molnar and Tapponnier (1975). Molnar and Tapponnier connect the formation of the north-trending and northeast-trending Baykal and other extension zones with the sinistral motions along the west-trending faults.

The same axial symmetry takes place on both sides of the Arabian plate. To the west of the plate, there is the west-trending North Anatolian dextral fault, but to the east, there are Dasht'e Bayas, Doruneh, Shahrud, North Teheran, and other sinistral wrench and reverse-wrench faults.

East-west–trending wrench faults seem to be the important element of the late Quaternary tectonics of the inner part of the Alpine–central Asian orogenic belt. They are caused by the unequal drift of the rock masses in the southern front of the belt. Here the Arabian and Indian plates move toward the Eurasian plate more rapidly than adjacent segments of the front.

Related to the movements along the major faults, secondary faults are produced by bending of the blocks (Afghan-Tadjik depression) or folding of the cover deposits (southeastern Caucasus and western Kopet-Dagh). Landslides and other structures produced by the disturbance of the gravitational balance are the result of large uplifts. Thus, the rather simple pattern of the main fault movements becomes more complicated.

Older motions are revealed on some major active faults which strike similarly to the Late Quaternary movements. Many kilometres of Cenozoic lateral displacements are proved or surmised along the Darvaz (Zakharov, 1958, 1969), Sulaiman-Kirthar (Abdel-Gawad, 1971), Dead Sea (Quennell, 1959; Freund, 1965), and Pamir-Karakorum (Burtman and others, 1963) fault zones. Many modern thrust faults are known in Tien Shan.

Dextral reverse-wrench movements are interpreted from the analysis of the neotectonic structural pattern of the main Kopet-Dagh fault zone (Krymus, 1966; Rastsvetaev, 1966, 1972). There are structural arguments for modern lateral motions along the Lake Valley (Lukyanov, 1965) fault. Multiphase sinistral movements can be inferred along the Altyn Tagh fault from the presence of protracted (Neogene-Quaternary) en echelon horst-anticline ranges to the south of the Altyn Tagh Mountains. Data have been published about the older dextral motions along the Talass-Fergana fault (Burtman, 1963; Ranstaman and Pshenin, 1967) and the Dzungar fault (Voytovich, 1968). Thus, there is a real possibility that the features of the late Quaternary movements may be extrapolated to the Neogene-Quaternary tectonic evolution of western and central Asia.

There are several methods of estimating Cenozoic lateral displacement by using the data about the young movements. First, it is possible to estimate the average rate of the young motions (by using the magnitudes of displacements during various parts of the Holocene and the late Pleistocene) and extrapolate it to the total time of fault activity. Second, it is possible to extrapolate the late Quaternary ratio of the vertical and lateral components in this way; one can obtain the rates of the vertical motions for the different epochs by using thicknesses of the deposits and variations of the altitudes of the geomorphological levels and use these rates to calculate the lateral component. If the ratio of the young horizontal and vertical components is not known, it is possible to use slickensides, striations and other records on the fault face for the estimation. Of course, these techniques are inaccurate because the rate of movements, as well as the ratio of the components, can vary during the fault evolution. However, if the results of estimations from different methods are similar, they can be believed to be real. Such hypothetical estimations give general Neogene-Quaternary magnitudes of 20 to 30 km of lateral displacements along the main Kopet-Dagh fault zone, of up to 15 km along the Dzungar fault, and of more than 150 km along the Darvaz fault. The last value is comparable with the estimate of Zakharov (1958, 1969) of about 200 km of Cenozoic sinistral motion along this fault.

The present studies are an attempt to correlate the geologically synchronous tectonic movements over a very large area and can be used for the same correlations of the tectonic events of various epochs. It seems to be reasonable to propose dividing the Earth's crust into mobile and stable areas for these correlations. The mobile areas are characterized by the high gradient of the tectonic movements, the stable areas by the low gradient, although they can move rather rapidly as a whole. The Alpine–central Asian mobile belt is located between the large stable plates (the Eurasian, Arabian, and Indian), but it extends across their margins. It is possible to find relatively mobile and stable zones of various orders in the mobile belts, as well as in the stable plates. For example, in the Alpine–central Asian belt, there are mobile zones with major faults and accompanied deformation. These zones divide the stable blocks, such as the Lut and the Tarim.

Following the ideas of A. V. Peive (1960), it is possible to represent some subhorizontal lithospheric boundaries (such as the Moho surface, the Conrad surface or surface of basement in some areas) as mobile zones. The inconformity of the structural patterns of the various lithospheric horizons (Makarov and others, 1974) is perhaps related to them. It can be explained not only by different strikes of stress or different reaction of the horizons to the same stress, but by the shearing of the horizons relative to each other.

Mobile zones vary in size, depth, evolution, strike, and magnitude of tectonic movements. They define topography, sedimentation, structure, magmatism, and some metamorphic processes in the mobile zones, as well as in the adjacent stable blocks — that is, they define the important features of the Earth's crust.

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