TECTONIC ASPECTS OF THE 1983 KUM-DAG EARTHQUAKE, WEST TURKMENIA

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Translated from "Tektonicheskiye aspekty Kumdagskogo zemletryaseniya 1983 g. v Zapadnoy Turkmenii," *Izvestiya AN SSSR, seriya geologicheskaya,* 1986, No. 5, pp. 3-16. The authors are with the Institute of Geologic Sciences, USSR Academy of Sciences, Moscow. Features of the surface trace nicely match the character of the fault zone as indicated by regional geology and by seismologic data. Kum-Dag is in the Nebit-Dag oil producing district.

This paper treats the tectonic aspects of the Kum-Dag earthquake of 1983 in western Turkmenia, particularly the morphology and kinematics of its surface expression, as well as its geodynamic features, its setting in the Late Quaternary structure and in the current tectonic pattern.

This magnitude M_{LH} = 5.7 occurred on 14 March at 12 h 12 min 54 sec at 40 km southeast on Nebit-Dag. A seismogenic rupture occurred, by which we mean emergence of the focal rupture on the surface, which we examined in detail in 1983. We used the seismograms from the Turkmenian station network and the preliminary catalog for the Kum-Dag earthquakes of 1983 compiled by N. V. Petrova and her colleagues at the Institute of Seismology, Turkmenian SSR Academy of Sciences.* According to these data, the coordinates of the epicenter for the main shock were: $\varphi = 39.20^\circ$N and $\lambda = 54.66^\circ$E (error of determination ±25 km), hypocenter depth H = 7-8 km).

*Only the stations in the Turkmenian SSR Academy of Sciences permanent network were working at the time of the main shock, with the Nebit-Dag station closest to the epicentral zone providing recordings of shocks with $K \geqslant 8$; on 17 March temporary stations set up by the Institute of Earth Physics, USSR Academy of Sciences, and the Institute of Seismology, Turkmenian SSR Academy of Sciences.

The focus of the Kum-Dag earthquake has been seismically active from the beginning of March 1983. The first foreshock with K = 12 was recorded on 1 March, and the last with K = 13 on 12 March. This was a very strong foreshock directly preceding the main shock that occurred at 11 h 55 min 15 sec and had hypocenter coordinates φ = 39.20°N, λ = 54.60°E, and H = 1-2 km.

The aftershock activity was low. Up to the end of May 1983, there were 37 aftershocks with $K \geqslant 8$ (52 aftershocks with $K \geqslant 7$). The strongest aftershock, with K = 12.3, occurred on 18 April. The aftershock zone had a length of ~40 km; the hypocenter depths ranged from 1-2 up to 5 km. The errors in measuring the epicenter coordinates for the Kum-Dag earthquakes (usually not better than ±10 km) did not enable us to determine the configuration of the aftershock region accurately or the relation to surface faults.

The Seismogenic Rupture

The system of ruptures and cracks arising in the earthquake extended in a west-northwest direction for ~20 km through the settlement of Kum-Dag. The system consisted of a main rupture the entire length of the fault trace, and faults parallel to it or diverging from it (Fig. 1A).

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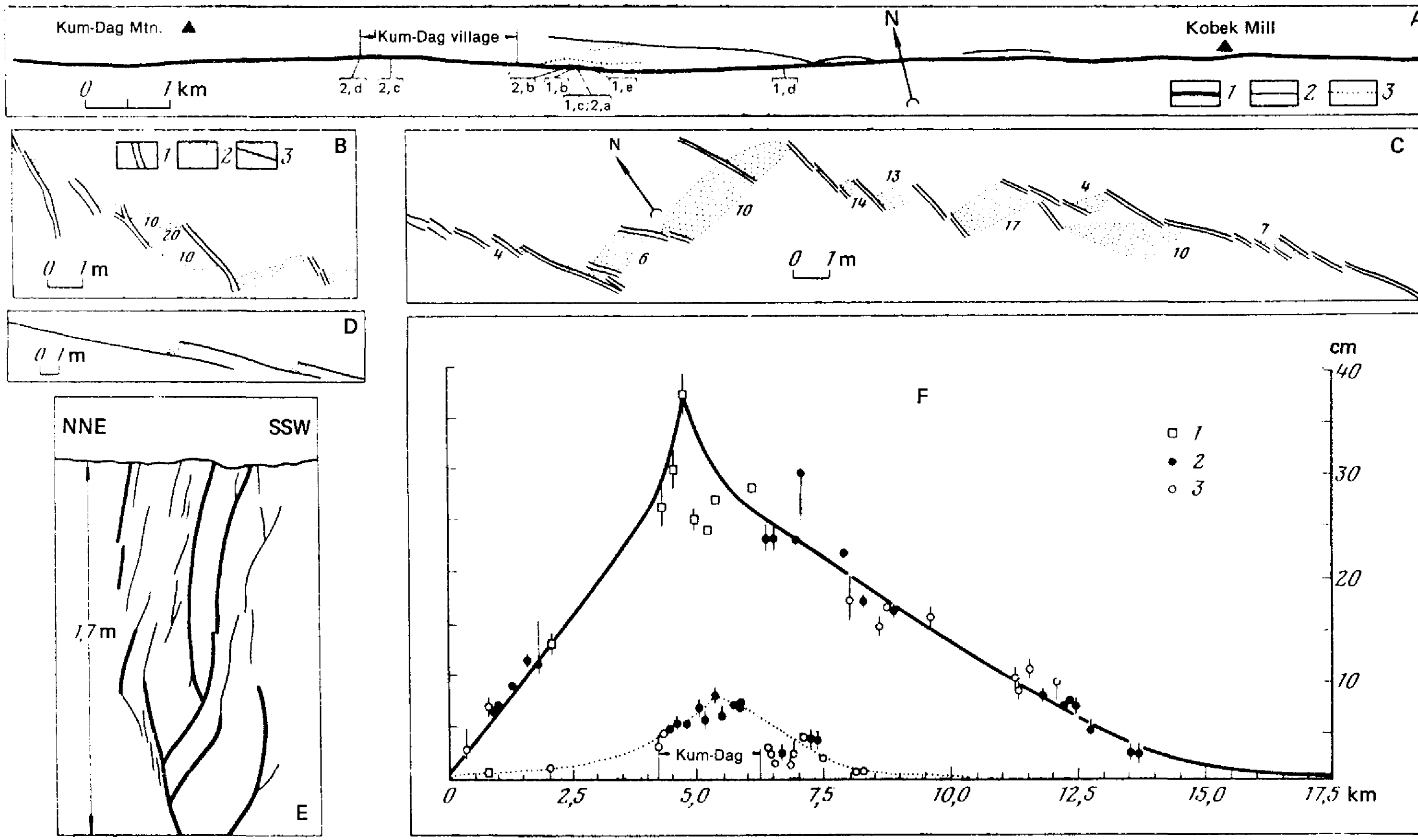


FIGURE 1. Tectonic damage from the Kum-Dag earthquake of 1983: A) seismogenic rupture and fissure map: 1) main rupture, 2) secondary rupture, 3) small fissures; B and C) trace of seismogenic rupture on the surface of a takyr 0.7–0.8 km southeast of the edge of Kum-Dag village: 1) zigzag fissures and cracks, 2) bulges and micro-ridges, heights indicated in cm, 3) shears; D) trace of seismogenic rupture on the surface of Lower Pleistocene sandstone 3.3 km southeast of the edge of Kum-Dag village; E) expression of seismogenic rupture in the wall of an excavation 0.9 km southeast of the edge of Kum-Dag village (main fault lines indicated by bold lines); F) change in right-lateral displacement (in centimeters on the ordinate axis) along the seismogenic rupture (in kilometers along the abscissa). Observed displacement: 1) in walls and other artificial structures, 2) in automobile and tractor tracks, 3) relief microforms; the vertical lines indicate the permissible errors, while the points show the analogous curve for the seismogenic rupture in the Burun earthquake of 1984.

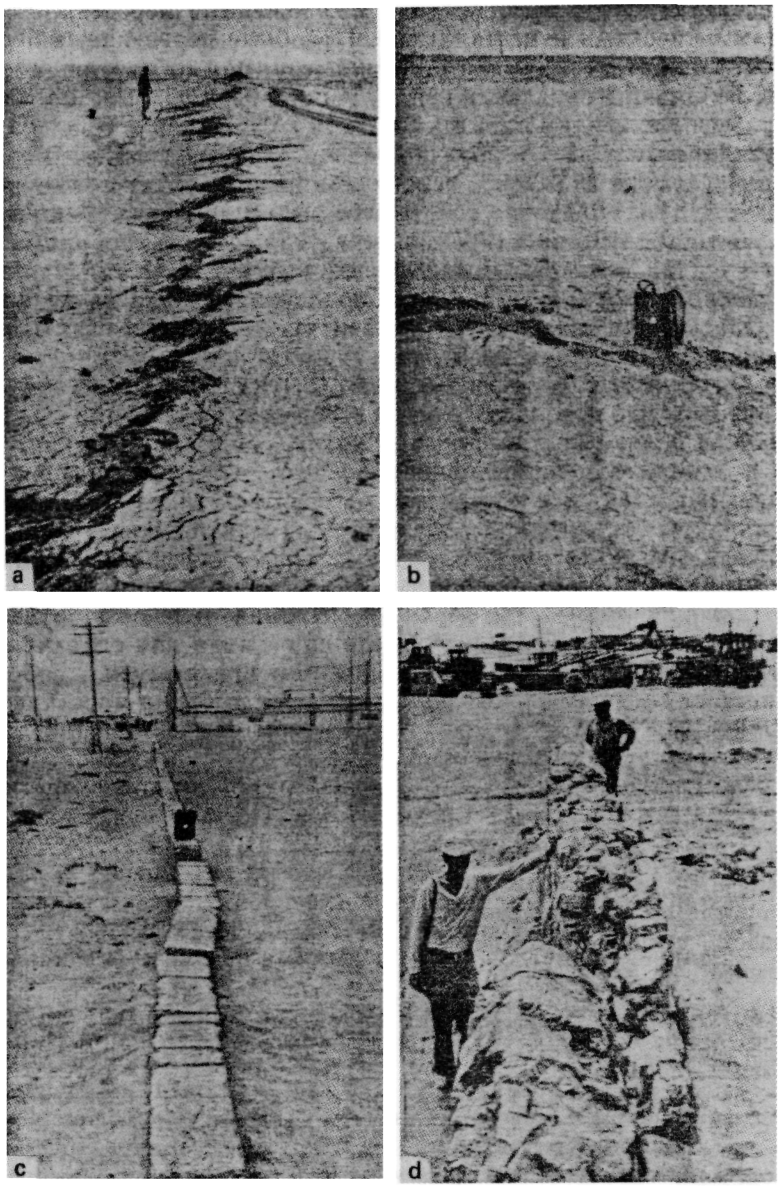


FIGURE 2. Seismogenic rupture photographs: a) kinked trace of rupture in a takyr 0.8 km southeast of Kum-Dag village; b) right-lateral displacement by 23 cm in an automobile track 0.7 km southeast of the edge of Kum-Dag village; c) right displacement by 37 km and possible right deflection by 10 cm in a wall in the western part of Kum-Dag village; d) right-hand displacement by 26 cm and possible right kink by 10 cm in a wall at the western edge of Kum-Dag village.

The main rupture extended on an azimuth of 285-290°, locally with smooth bends to 280° or less often 300°. The trace of the rupture could be followed either from the hummocky surface of the bedrock (weakly cemented Lower and Middle Pleistocene sandstones) or cut through the level surface of the current takyrs [playas] and saltpans composed of Late Pleistocene-Holocene beds deposited by ephemeral streams or the coastal sediments of the Khvalyn Sea. Sand ridges up to 1 m high composed of wind-blown Pleistocene sands and sandstones occur in the takyrs, and also on bedrock, where they formed individual ridges or small barchans and ridges. The trace of the rupture was interrupted in these. The patterns were different in the bedrocks and at the surfaces of the saltpans and takyrs.

The rupture showed a kinked pattern on the surfaces of the takyrs and saltpans (Fig. 1B and 2a), formed by a combination of open fissures and sinuous cracks of northwest strike (320 ± 10°) with bulges and microfaults in the disturbed ground. These positive forms were equant or elongated in the east-northeast direction (65 ± 15°). The lengths did not exceed 1 m. The outlines varied from compact, often curved ridges up to 0.4 m wide and 5-15 cm high to broad ridges (1 m) and smooth uplifts. These uplifts may be accompanied by local bulges, which raise the level above the surrounding surface by 5-10 cm. These bulges and ridges are compressional structures.

The open fissures and sinuous cracks had uneven and frequently ragged edges. They were sometimes curved. Their lengths varied from tens of cm to 2-3 m, and they were usually greater than the lengths of the associated ridges and bulges. The widths of the zigzags usually did not exceed 4 cm, but occasionally they attained 10 or even 20 cm. Funnel-shaped expansions up to 10 cm in diameter occur along some of the sinuous cracks. The widths of the open fissures did not usually exceed 10 cm. These arose from swelling or settling in the soil, mainly in the sinuous cracks. Some of them consisted of regular serrated series of short cracks extending in a 320-330° direction (Fig. 1C). In general, these fissures and sinuous cracks are tensional structures.

The seismogenic rupture zone had widths up to 1.5 m or occasionally 3 m on the surface of a saltpan or takyr. However, shallow drilling by the Institute of Earth Physics, USSR Academy of Sciences, on the trace 900 m from the southeast edge of Kum-Dag village showed that at a depth of 1.7 m the individual faults in the zone converge to 0.4 m (Fig. 1E). Therefore, the zigzag pattern is strictly a surface feature characteristic of the Late Quaternary alluvium.

At some points, particularly at ends of the rupture, the trace is marked only by a regular echelon of tension cracks, which extend in the 315 ± 5° direction and have zigzags of up to 2-3 cm.

The bedrock surfaces in the region of Kobek Hill southeast of Kum-Dag village and south and west of the Kum-Dag range itself also have areas where the fault trace is marked by a zigzag combination of depressions and hummocks or en echelon tension cracks with northwest strikes (315-320°). However, the fault trace is usually different here, with extended straight vertical cracks trending 280-300° and forming regular en echelon series. Usually, the strike of the individual cracks is so close to that of the overall trend that the ends are separated only by 0.3-1 m. At the junctions between such cracks, bulges and microridges often occur, sometimes fairly compact and curved, but more often equant, although generally elongated in a northeast direction (20-70°) (Fig. 1D). Cracks with azimuth 280-290° tend to be straight or have zigzags of not more than 1 cm. They may give rise to short zigzag cracks and fissures, as well as to pressure hummocks, and may run continuously for tens of meters. In contrast, cracks running at azimuths of 290-300° are usually only a few meters in length, while some of them (azimuth 300°) have zigzags of up to 5 cm.

There is no persistent vertical component in the displacement along the seismogenic rupture. The morphology is similar in plan to known seismogenic shears [9] and definitely indicates right-lateral shear displacement during the earthquake. Direct evidence for such motion is the displacement of fairly sharp microrelief forms, road surfaces, and automobile and tractor tracks, as well as the walls of houses, sidewalks, and paved surfaces in Kum-Dag itself (Fig. 2b–d). All of these displacements are regular, with the displacement amplitudes increasing from 3 cm (the least displacement that could be measured reliably) at the northwestern and southeastern ends of the break towards the center (Fig. 1F). The largest displacements were measured in the western part of Kum-Dag village, where displacements up to 37 cm directly along the trace* may also be accompanied by bending in the flanks in the same direction by 10 cm (Fig. 2d). This spread of deformation decreases rapidly away from the fault trace, becoming inappreciable within a few meters. The distributions of the displacements along the rupture are not asymmetrical: the maximum is almost three times closer to the northwestern end than to the southeastern end.

The largest rupture branching from the main one started 3.5 km southeast of Kum-Dag and ran at 290° for 3.3 km, dying out at the eastern edge of the village. Other diverging and parallel lines had lengths of <1 km. All were regular series of comparatively short tension cracks (azimuth 315 ± 15°), often associated with shorter ridges (up to 0.5 or occasionally 0.7 m) and heaving, equant or elongated in the 60 ± 10° direction. The heights of the ridges did not exceed 5 cm. Therefore, the parallel and divergent cracks are morphologically similar to the main one and are also regular shears, but displacements >3 cm, which is the measurement accuracy, never occur on them. It appears that the displacements on these divergent and parallel cracks are extremely small and cannot substantially alter the displacement distribution along the main rupture.

The peak movement distribution in the Kum-Dag earthquake differs considerably from the distributions of the displacements in recent catastrophic earthquakes along the Khangai and Kobda faults in Mongolia (magnitudes $M > 8$ [18]), where the maximum rupture amplitude occurred over extended lengths of the faults, perhaps due to the much greater extent of the foci.

The Kum-Dag earthquake of 1983 had an extensive seismogenic rupture and considerable displacement on it in spite of its comparatively small magnitude. At the same time, the extent of the surface damage decreased rapidly away from the fault trace.

Dynamic Parameters of the Main Earthquake Focus

The dynamic parameters include the seismic moment of the focus M_0, the released stress $\Delta\sigma$, the mean dislocation on the rupture surface $\overline{U}$, and the seismic energy E. The rupture at the focus itself can be characterized by the length L, width W, and area S. We estimated these parameters not only from the field measurements but also from the seismological observations. For example, the field measurements indicated $L = 20$ km and $\overline{U} = 10$ cm, while the width of the failure area is estimated from the maximum depths of the aftershock foci ($W = 5$ km) or the focus depth for the main shock ($W = 7.5$ km).

The seismic moment is defined as

$$M_0 = \mu \overline{U} S. \tag{1}$$

The shear modulus μ is related to the density ρ and the velocity V_S by $V_S = \sqrt{\mu/\rho}$.

DSS data [2] indicate that the V_P velocity in the region of the Kum-Dag focus is 4.0–4.5 km/sec; taking $V_P/V_S = 1.7$ and $\rho = 2.5$ g/cm^3, we get $\mu = 1.75 \times 10^{11}$ dyn/cm^2 for $V_P = 4.5$ km/sec or $\mu = 1.15 \times 10^{11}$ for $V_P = 4.0$ km/sec.

*We examined the fault trace and measured the displacements in July 1983. Members of the Institute of Earth Physics, USSR Academy of Sciences, and of the Institute of Seismology, Turkmenian SSR Academy of Sciences, made analogous measurements directly after the earthquake, and they give smaller displacement amplitudes: under 20 cm [16]. It is possible that this discrepancy is associated with creep and additional displacements in the aftershocks.

TABLE 1. Basic Data on the Aftershocks in the Dagestan and Markansu Earthquakes

Date	Time	Coordinates, deg		H	M_{LH}	K
		φ	λ			
8.VI .1970	12 h 32 min 59 sec	43.00	47.04	10		12
15.VI .1970	6 h 22 min 13 sec	43.00	46.49	12		12
27.VI .1970	00 h 46 min 5 sec	42.59	47.05	13		12
11.VIII.1974	20 h 5 min 25 sec	39.6	73.8		5.8	14
	21 h 21 min 35 sec	39.4	73.6		6.6	15
27.VIII.1974	12 h 56 min 00 sec	39.3	73.7		6.0	15

The area may be estimated by taking it as a rectangle, so that $S = LW$, whence we get a minimum value $M_0 = 1.2 \times 10^{24}$ dyn/cm (with $W = 5$ km and $\mu = 1.15 \times 10^{11}$ dyn/cm^2) and a maximum $M_0 = 2.6 \times 10^{24}$ dyn/cm (with $W = 7.5$ km and $\mu = 1.75 \times 10^{11}$ dyn/cm^2).

It is not possible to calculate the seismic movement directly from the seismological data, and therefore we used measurements on the coda waves, the scattered waves forming the tail of the seismogram [4, 19]. If one constructs the sequence of double amplitudes to A with predominant periods T_k as a time function measured from the instant at the focus $t - t_0$, we get envelope codas; beginning with a certain time $t_i - t_0$, these envelope codas from a given earthquake at different stations coincide, apart from constant coefficients defining the station features. This time is dependent on the hypocentral distance. Usually, $t_i - t_0 \simeq 3\ (t_S - t_0)$, where $t_S - t_0$ is the transverse-wave transit time [4, 19].

If the coda is of sufficiently long period (i.e., if the predominant periods are greater than the focus operating time or the related angular period in the focal radiation spectrum), the envelope level at a certain time $t_\varphi - t_0$ is proportional to the seismic moment at the focus [4, 19]. As the form of the envelopes is independent of the hypocentral distance starting at time $t_i - t_0$, and is also independent of the station and source orientation, as well as of the structural features on the path of the regular waves to the station, the seismic moment given by the coda is independent of these factors, i.e., the values are free from errors associated with the effects of the medium on the path of the regular waves from the source to the station and the directional pattern in the source radiation.

To transfer to the absolute values of the seismic moment, one needs only one or a few earthquakes whose moments have been measured both from the coda and independently from the regular body or surface waves. As such calibration events, we used several aftershocks from the 1970 Dagestan earthquake and the 1974 Markansu earthquake, for which basic data are given in Table 1. The seismic moments at the foci of the Markansu aftershocks have been determined by Molnar from recordings on the world network of long-period (40–60 sec) Rayleigh and G waves (p. 101 of [19]). Those for the Dagestan earthquake aftershocks were obtained from the transverse-wave spectra recorded in the epicentral zone by an S5S-ISO-P apparatus (p. 134 of [5]).

Petrova's measurements (personal communication) indicated that the medium-period apparatus in the Turkmenian seismic stations, located on thick sediments, records a strong low-frequency surface wave with a group velocity of ~1.4 km/sec and predominant periods of 7–8 sec from earthquakes in the Caspian depression. Therefore, the time for the start of the coda is greater than the mean: $t_i - t_0 \sim 5\ (t_S - t_0)$. We took this value in constructing individual envelopes in their general form. We used seismograms from

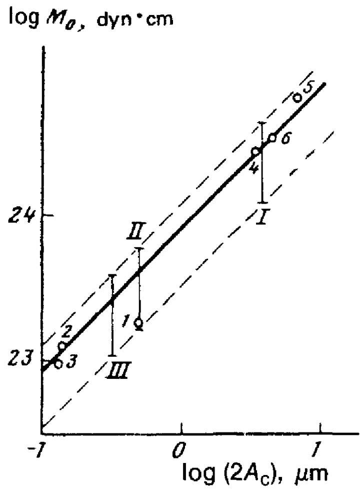


FIGURE 3. Correlation between aftershock seismic moments for the Dagestan [5] and Markansu [19] earthquakes and the level of the coda envelope $2A_c$ for $t - t_0 = 2000$ sec referred to the conditions at Ashkhabad seismic station: I) main Kum-Dag earthquake; II) foreshock of 14 March 1983; III) strongest aftershock of 18 April 1983. The Arabic numerals correspond to the numbers of the aftershocks in Table 1.

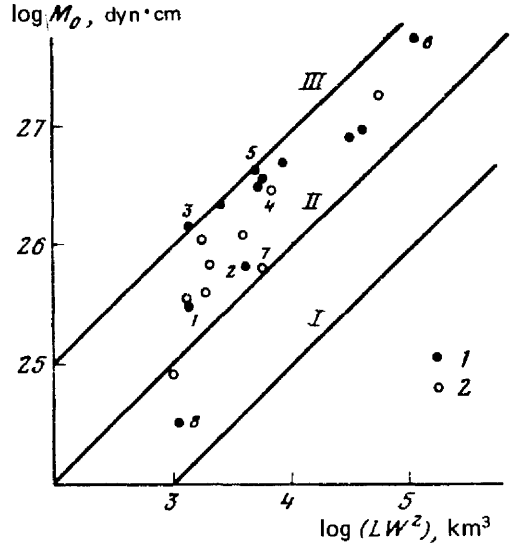


FIGURE 4. Dependence of seismic moment on focal volume: 1) shears; 2) fault-shears; I-III) lines of equal release stress $\Delta\sigma = M_0/LW^2$ in bar: I) 1; II) 10; III) 100; 1-8) earthquakes: 1) Parkfield, 28 July 1966 [21, 27], 2) Borrego, 9 April 1968 [21, 23], 3) Peak-Fairview, 16 December 1954 [21, 22], 4) Long Beach, 11 March 1933 [21], 5) Imperial, 19 May 1940 [21, 22, 27], 6) San Francisco, 18 April 1906 [22], 7) Dagestan, 14 May 1970 [5], 8) Kum-Dag, 14 March 1983.

shocks listed in the table and the largest earthquakes in the Kum-Dag focal zone. The measurements on the coda were made from the recordings by SVK instruments at stations at Ashkhabad and Kyzyl Arbat and by an SKD instrument at Nebit-Dag. The general form of the envelopes was obtained by combining individual ones with displacement parallel to the amplitude axis to give the best coincidence. The envelope level was measured from the doubled amplitude A_c of the coda corresponding to $t = t_0 = 2000$ sec. We applied our station corrections relative to Ashkhabad to the measurements at Kyzyl Arbat and Nebit-Dag.

Figure 3 gives the dependence of the seismic moments for the earthquakes listed in Table 1 on the level of the SVK coda envelopes referred to the conditions at Ashkhabad station. We show the values of $2A_c$ for the main Kum-Dag earthquake, the largest foreshock, and the largest aftershock, which enables one to estimate the seismic moments at the foci by comparison with the tremors represented in Table 1. The data for the calibration earthquakes fit closely to the straight line. The limits for the seismic moment of the main Kum-Dag earthquake given by this relationship are $M_0 = 1.3 \times 10^{24}$ and $M_0 = 4.7 \times 10^{24}$, mean $M_0 = 3.0 \times 10^{24}$ dyn·cm. This agrees well with estimates of M_0 made from the field measurements. The seismic moments for the largest foreshock and aftershock were $M_0 = 4 \times 10^{23}$ and $M_0 = 2.5 \times 10^{23}$ dyn·cm.

The predominant periods in the working parts of the SVK coda $t - t_0 \geqslant 5\,(t_S - t_0)$ were 8-11 sec, but we do not know whether they exceed the angular period in the focal spectrum for the main earthquake. If they do not, the value obtained for the seismic moment may be an underestimate. However, the M_0 from the field and instrumental data agree closely, so they are probably close to correct.

The magnitude and seismic moment for the Kum-Dag earthquake agree well with the experimental relationship [19] for crustal earthquakes:

$$\log M_0 = 1{,}20\, M_{LH} + 17{,}70. \qquad (2)$$

The released stress, i.e., the difference in the mean stresses in the focal zone directly before the earthquake and after it, is given by

$$\Delta\sigma = c\mu \frac{\overline{U}}{L},$$

where c is a dimensionless quantity dependent on the form of the rupture area at the focus and on the focal mechanism. The value of c has been determined for many particular cases [20, 25] and varies from 2.5 to 5.0 in those of greatest interest. We use these values with $\overline{U}$ = 10 cm and L = 20 km in the above formula to determine that the released stress is in the range from 2.2 to 4.4 bar with μ = 1.75 dyn/cm^2; if μ = 1.15 dyn/cm^2, then $\Delta\sigma$ varies from 1.3 to 2.6 bar.

In estimating $\Delta\sigma$ from the instrumental measurements, one also carefully allows for the shape of the rupture area and the focal mechanism [25]. In our case, this is hardly meaningful because of the errors in measuring the quantities appearing in such formulas. For example, for a buried horizontal rupture

$$\Delta\sigma = \frac{16}{3\pi} = \frac{LM_0}{S^2}.$$

If we take the rupture area as a rectangle ($S = LW$) with W = 7.5 km (i.e., the value giving the best agreement between the instrumental and field data for the seismic moment), the formula gives $\Delta\sigma$ = 4.4 bar, whereas $\Delta\sigma$ = 6.7 bar if the area is elliptical.

The likely $\Delta\sigma$ is 3-5 bar; this value is anomalously small even by comparison with minor earthquakes associated with the San Andreas fault (1966 Parkfield and 1968 Borrego Mountain). Figure 4 illustrates a feature of the Kum-Dag focus from the dependence of the seismic moments of medium-strength crustal earthquakes on the volume LW^2 of the focus. The curve has been constructed from the data of [5, 21-24, 26, 27] only for earthquakes caused by shearing and shear faulting. The graph shows both emergent and buried ruptures; there are no systematic differences. The nominal lines of equal $\Delta\sigma$ of 1, 10, and 100 bar have been calculated simply as $\Delta\sigma = M_0/LW^2$.

The mean stress σ is $(\sigma_1 + \sigma_2)/2$, half the sum of the mean stresses at the focus before and after the earthquake, which is directly related to $\Delta\sigma$ [7], so $\overline{\sigma}$ and the stress σ_1 producing the failure at the Kum-Dag focus may be taken as anomalously small.

The apparent stress $\eta\overline{\sigma}$ is defined by [28]

$$\eta\overline{\sigma} = \mu E/M_0, \qquad (3)$$

where E is the seismic energy and η is the seismic efficiency, namely the ratio of E to the total energy released at the focus. The Kum-Dag focus lay in relatively soft rocks with low elasticity and strength, so there is no reason to assume that η was higher than the mean, and one assumes that the apparent stress was anomalously low.

The seismic energy can be estimated from the known magnitude (M_{LH} = 5.7); the correlation

$$\log E, \mathrm{J} = 1{,}5\, M_{LH} + 5{,}0 \qquad (4)$$

for crustal earthquakes in Central Asia [19] gives $E \simeq 7 \times 10^{13}$ J (K = 13.8), but in fact E for the Kum-Dag earthquake was clearly less. The focal dimensions are large for the magnitude, which indicates that the focal radiation spectrum is relatively low in high-frequency components, and then (4) gives overestimates for E [19]. In fact, (3) indicates that the Kum-Dag focus had small values not only for $\eta\overline{\sigma}$ but also for E/M_0. As the magnitude and seismic moment satisfied the average relationship of (2) closely, it is possible to reduce E/M_0 only if E is less than that given by the average relationship of (4).

Structural Setting of the Earthquake Focus

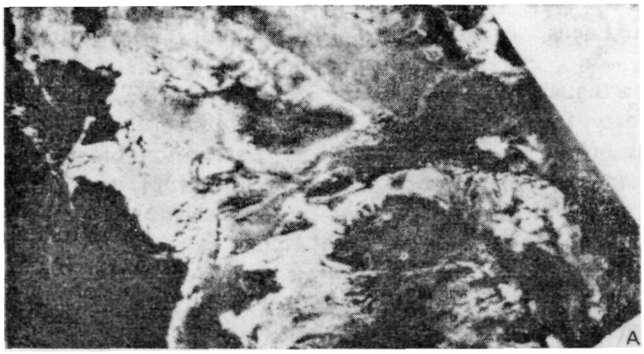
The fault trace in the Kum-Dag earthquake of 1983 coincides with a Quaternary fault clearly visible on aerial photographs of 1949 in places where the Pleistocene sandstones are exposed. Drilling in the surface of a takyr 2.15 km southeast of the village of Kum-Dag showed Late Quaternary beds at a depth of 0.5–1 m directly at the fault trace, which did not have a vertical component in the displacement at the surface: to the southwest of the line lie sands, while to the northeast there are sands containing grit and rubble rock, which vanish rapidly from the section further to the northwest. This indicates Late Quaternary movements on the fault before 1983.

Aerial photographs indicate that the Quaternary fault continues not only to the northwest but also to the southeast of the zone of movement in 1983. To the northwest, directly beyond the end of the movement zone of 1983, it joins up with a minor northeast-striking fault. In the southeast, the zone of the Quaternary fault runs on a 120–125° trend along the southeast flank of the Syrtlanli mountain massif. The zone consists of a regular en echelon of faults of northwest (305°) strike dipping very steeply to the southwest. A series of very fresh displacements along the northwest fault is marked by small hummocks 1–1.5 to 4 m high formed before 1983. The southwest flank is uplifted, but the vertical component of the displacement is less than a quarter of the shear component. Clearly, there have been at least two episodes of recent movement. The older Late Quaternary right-lateral displacements may have occurred along the southeast fault.

Vinogradov and Miroshnichenko [3] have observed a continuation of this Quaternary fault farther to the southeast: in Mount Tuzluchay, a western spur of Kyurendag. Here, on the surface of a clay plain black saxaul bushes are associated with the fault, with the bushes surrounded by hummocks of windblown sands, which enable one to recognize the fault line on aerial photographs. The black saxaul has grown because of recent movements on the fault, which have produced cracks and thus raised ground water levels in the soil. The state of the saxaul and the adjacent hummocks enabled those workers to date the last activation of the fault to the end of the 19th century, with a suggested relationship to the catastrophic Krasnovodsk earthquake of 1895.

This fault is a link in the Isak-Cheleken right-lateral shear zone [15], which spatially coincides with the Balkhan fold zone in the sedimentary cover and is probably genetically associated with it [12]. On 8 February 1984, the strong Burun earthquake occurred 55 km northwest of Kum-Dag in this same zone, at epicentral coordinates: φ = 39.25°N, λ = 54.03°E. The magnitude was ~6, while the tremor intensity in the epicentral region was 7–8 points. Compared to the Kum-Dag earthquake, the Burun earthquake had an anomalously small number of aftershocks, of which only one had energy class K = 9.6 according to Golinskiy's data.

The Burun earthquake also gave rise to a seismogenic rupture, which began 3 km west of the edge of the village 26 Baku Commissars and could be traced to the west for 10 km (Fig. 5). The trace had an approximate trend of 280°, but a difference from the Kum-Dag one was that it repeatedly varied from 250 to 315°. Often, it consisted of an en echelon series of downfaulting cracks of northwest strike. Along it, there were right-lateral displacements of vehicle tracks and surface microforms of up to 8 cm (Fig. 1F), with the southern flank raised by the same amount or somewhat less. Along with the main rupture, there were many secondary cracks of various orientations and of lengths of meters or tens of meters in a band 1–1.5 km wide. There were also eruptions from small mud volcanoes, some of them lying directly along the main rupture. The structural features of the Burun earthquake show the following differences from the Kum-Dag quake: smaller extent of the line on the surface and smaller displacement amplitudes in spite of the greater magnitude, as well as considerable curvature in the trace and abundance of secondary faults, which indicates considerable depth



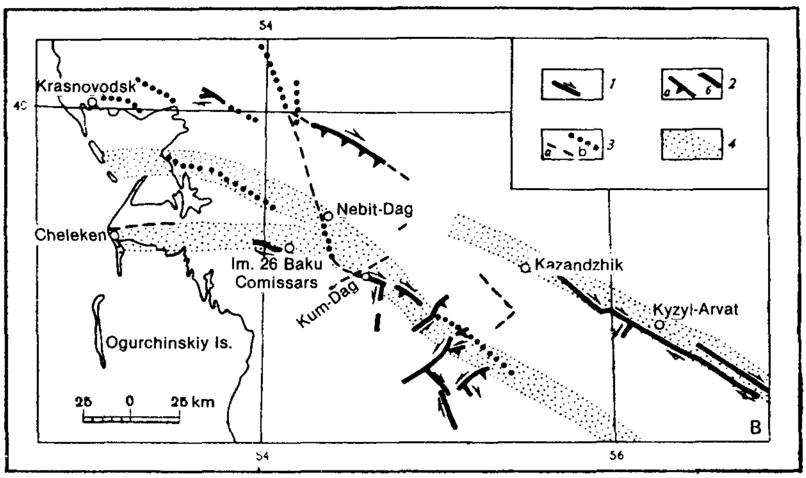
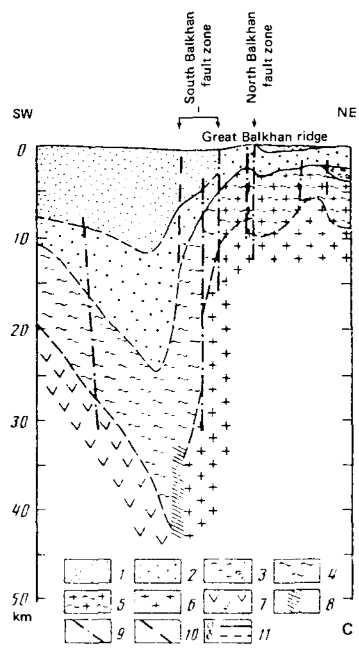


FIGURE 5. Focal position of the Kum-Dag earthquake in the regional structure: A) space photograph of the western part of the South Turkmenian suture system, *Salyut-4* spacecraft, KATE-140 camera; B) active fault zones in the western part of the South Turkmenian suture system: 1-3) faults with signs of Late Quaternary activation at the surface: 1) active shear faults, 2a) active upfaults and overthrusts, 2b) active tear faults with undetermined displacement directions, 3a) active faults suggested from interpreting space photographs and ground observations, 3b) active faults suggested from interpreting space photographs, 4) regional zones of major deep faults [1]; C) geological and geophysical section of the region of the Great Balkhan drawn by V. A. Kharikov from a regional profile from Ogurchinskiy Island to the Sarykamysh depression [1]: 1-5) beds: 1) Cenozoic, 2) Mesozoic, 3) Permian-Triassic, 4) consolidated Paleozoic sediments, 5) high-grade Paleozoic metasediments, including those cut by intrusions, 6) lower part of the granite layer, 7) basalt layer, 8) deep-fault zone, 9) deep faults in the crystalline layer of the crust, 10) fault lines in sediment cover, 11) boundaries of different layers in the crust: a) confirmed, b) hypothetical.



for the focus. In fact, seismological data (private communication from N. V. Shebalin and G. L. Golinskiy) give an estimate of ~20 km.

The epicenter of the catastrophic Krasnovodsk earthquake of 9 July 1985 lies directly to the north of the western segment of the Isak-Cheleken zone on the coast of the Caspian, to judge from macroseismic data [11, 13]; magnitude 8.2 ± 0.3 and focal depth 60 km (0–100 km). The current activity in the western segment is evident also from mud volcanism and hydrothermal activity.

The Isak-Cheleken zone is a surface expression of the southern branch of the South Balkhan deep-fault zone in the wide sense (Fig. 5). The grade of metamorphism in the Paleozoic rocks decreases sharply from north to south, and the foot of the Mesozoic-Cenozoic complex descends to 24 km, while rocks corresponding in velocity characteristics to the granite-metamorphic layer vanish [1]. The branches of the deep zone merge to the southeast and continue into western Kopet Dag, where they die out in the vicinity of the village of Kara-Kala. The Late Quaternary activity is seen as numerous young ruptures and folds at the western edge of Kopet Dag [6], which die away to the southeast.

The South Balkhan zone is part of the South Turkmenian suture system [15], as are the North Balkhan deep-fault zone and the zone of the principal Kopet Dag fault. The principal Kopet Dag fault bounds the Kopet Dag orogenic structure on the northeast and extends through all seismic layers of the crust to the Moho, with the surface of the crystalline basement depressed on the northeast flank by several kilometers [10]. The structural features define the fault as right-lateral normal [8, 14, 15]. In the region of Kyzyl Arbat, the deep fault branches. The southern branch can be traced to the northwest as far as the northeast end of the Oboy-Kyurendag zone of latest folding, and possibly the northeast closure of the Little Balkhan. The northern branch is continued by the North Balkhan deep fault zone, which reaches the Caspian at Krasnovodsk. As in the case of the main Kopet Dag fault, the northern block is depressed, but the displacement amplitude (at the surface of the crystalline basement) does not exceed 2 km (Fig. 5). Along the main Kopet Dag fault, there are Late Quaternary right-lateral normal displacements at the surface [17], which form two branches fitting one into the other. On the continuation of these, there is the young normal-lateral displacement in the northeastern flank of the Great Balkhan. Similar but less pronounced signs of young tectonic activity can be observed even farther west, in the region of the village of Belek, beyond which they gradually die away.

Therefore, young tectonic activity is evident at the surface in the region of the main Kopet Dag fault and its continuation in the North Balkhan fault zone, which probably die away gradually to the west in deep horizons in the crust, and the same applies to the southeast in the South Balkhan zone in the broad sense. The two zones thus fit together and jointly provide right-lateral displacement along the South Turkmenian suture system. In the region of junction, i.e., at the transition of the most vigorous young movements from one zone to the other, Amurskiy et al. [1] have identified several northeast-striking deep faults. In the sediment cover, these correspond to the Oboy-Kyurendag and Little Balkhan latest anticline zones [15]. This structural pattern in the junction region is similar to the faults arising in the junctions between individual shear segments in the seismogenic rupture from the Kum-Dag earthquake. The Holocene-Late Pleistocene tectonics can be seen from the left lateral normal faults extending along the northwestern foothills of Kyurendag. In Kyurendag itself and to the south, there is a complicated combination of young ruptures and folded forms with various directions and varying morphology [6]. On the northeastern continuation of the Little Balkhan, there is a Holocene anticline. Young ruptures and fissures extend along the northwest foothills of the Little Balkhan.

Therefore, the seismogenic rupture of the Kum-Dag earthquake of 1983 is a manifestation of a Quaternary fault occupying a definite position in the system of young tectonic faults in western Turkmenia. The rupture at depth corresponds to a fault involving displacement of the crystalline basement, but the earthquake focus lies higher, as indicated by seismological data: at the boundary between the consolidated Paleozoic rocks with the Mesozoic–Cenozoic cover and in the cover itself.

Conclusions

The Kum-Dag earthquake of 1983 involved movement on one of the active faults in the South Balkhan deep-fault zone. The movement was right-lateral, which completely agrees with the general kinematics of the active faults in southern Turkmenia. The earthquake was thus a normal episode in the current tectonic development of the region.

The right-lateral displacement on the 20-km Kum-Dag tear increases gradually from the ends, but it is not symmetrical: the maximum displacement (up to 40-50 cm) is much nearer the western than the eastern end, which is mainly due to the screening role of a minor fault of northeast strike bounding the focus, although it may have been determined also by the presence of the oil pools in the Kum-Dag deposit near the western end of the break.

The released stresses were only 3-5 bar, and the stresses acting in the focus were low, which is due to the focus being localized in the sediment cover rocks, which have low strength and elasticity. The energy released appears also to be less than that usual for earthquakes of this magnitude (M_{LH} = 5.7) in Central Asia. The dimensions of the focus are relatively large for such a magnitude, which indicates that the seismic radiation spectrum was rich in low-frequency components. These features distinguish the Kum-Dag earthquake of 1983 from most seismic events in Central Asia of a similar energy class, and in a certain sense they enable us to consider it as markedly accelerated creep. In other words, the Kum-Dag earthquake combines features of brittle failure and slip on a surface where there is loss of continuity in a region of quasiplastic flow. If this is so, then such shearing occurs in this zone not only in earthquakes, and this may possibly be indicated by the discrepancies in the estimates for the displacements measured directly after the earthquake and after a lapse of four months.

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