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SEISMIC EVIDENCE FOR THE TECTONICS OF CENTRAL AND WESTERN ASIA

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ABSTRACT

A statistical analysis of the null axes of the fault-plane solutions of earthquakes in any one area permits determination of the average tectonic motion direction of that area. In the present paper this method has been applied to areas in central and western Asia for which several hundred fault-plane solutions are readily available in the literature. The investigation yields the result that (seismically) calculated tectonic motion directions in a series of small areas that are part of a larger unit are consistent with each other and that there is in every case an excellent correlation with the tectonic motion of the area as postulated from geological studies. This appears to justify completely the seismic method.

The seismically determined tectonic motion in central Asia appears to be mainly in a north–south direction. The motion refers to the present time (since the earthquakes occur at the present time), but it is the same as that postulated in geology for an explanation of the folding of the central Asian mountain ranges. This demonstrates that the stress system which created the central Asian mountains is active at the present time.

INTRODUCTION

IT IS well known that, in a general way, the seismic activity of an area is somehow related to its present-day tectonic activity. Usually, the active seismic belts and the zones of recent mountain building run roughly parallel, and hence it may safely be assumed that the causes of orogenesis and of seismic activity have some relation to each other. Both mountain building and earthquakes are manifestations of the release of underground stresses. It stands to reason that the stress systems causing these two phenomena are the same and that it ought to be possible to verify this in some detail.

Attempts at a correlation of seismic with tectonic observations have been reported on several occasions. As mentioned above, there is the well-known correlation between seismicity and mountain ranges (particularly applicable in the circum-pacific and Alpine-Himalayan active belts; cf., for instance Gutenberg and Richter, 1954), which, however, does not allow one to correlate the actual stress systems beyond stating that the tectonic as well as the seismic stresses must be "large" in the same localities.

A more direct way to elucidate the pattern of stresses that cause earthquakes is implicit in the method of *fault-plane solutions*. In this method one assumes that an earthquake represents simple faulting. The fault plane and the plane orthogonal to the slip direction (the "auxiliary" plane) are then determined by an analysis of the first motion generated by the earthquake under consideration at many seismic observatories. The method, in general, yields two orthogonal planes, either of which could be the fault plane, the other then being interpreted as the auxiliary plane.

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It is natural to suspect that the earthquake faults thus determined by fault-plane solutions should correlate with the pattern of tectonic faulting in any one area. However, attempts at obtaining such a correlation have generally ended in failure. It turned out that the actual faults evident in earthquakes are oriented in a quite random fashion and that there is no obvious correlation with the tectonic structure of the area in which the seismic shocks occurred.

The writer has therefore proposed that fault-plane solutions should be regarded as having only a statistical significance (Scheidegger, 1958*a*). In any particular instance the orientation of the fracture (fault) surface is generally random. However, the orientation of the null axis (the axis of zero motion, which is identical with the intersection of the fault plane and the auxiliary plane) is on the whole such that it tends to be orthogonal to the mean tectonic motion which is prevalent within the area. Conversely, the direction of the tectonic motion in an area can be assumed to be that which is, on the average, orthogonal to the null axes of the earthquakes of that area.[1]

The idea indicated above has already been applied to the northwest Pacific Ocean, where rather consistent results were obtained (Scheidegger, 1958*b*). Unfortunately, the number of fault-plane solutions available in that area was rather limited, with the result that the analysis in question suffered somewhat from lack of data.

Looking for an area where the idea could be further tested, the writer noted that a good possibility exists in central Asia, where several hundred earthquakes have been investigated by various Russian groups. Many areas in central Asia are characterized by the occurrence of numerous small earthquakes, felt almost daily. In order to investigate these shocks, expeditions have been sent out to establish field stations for various lengths of time. The presence of these stations enabled the Russian investigators to obtain fault-plane solutions for many of the earthquakes which are now available in the literature. The chief aim of these researches was to show a correlation between the fault-plane solutions and the tectonics of the various areas, but only rarely was there an obvious relationship.

In the present paper we shall undertake to analyze the Russian fault-plane solutions with regard to the statistical significance of their null axes. It turns out that the tectonic motion directions thus obtained are, in every case, in agreement with the tectonic motion postulated from geological studies. This result appears to justify the seismic method completely.

Method of Analysis

The method for the analysis of the statistical significance of the null axes of the earthquakes in any one area has been described earlier in detail (Scheidegger, 1958*a*). However, for the convenience of the reader we recall here briefly the principal ideas.

The basic hypothesis is that the null axis in every earthquake tends to be orthogonal to the tectonic motion direction which is prevalent in the focal area. Thus, denoting the components of the tectonic motion direction by ξ, η, ζ (north, east, and down, respectively) and the components of the unit vector along the null axis

[1] The history of this method has also been outlined in the reference given (Scheidegger, 1958*a*).

of the i-th earthquake by n_{ix}, n_{iy}, n_{iz} (north, east, and down, respectively), the sum of the squares of the scalar product of the two vectors, taken over all earthquakes in the area, must be a minimum. This enables one to determine ξ, η, ζ for a given series of n_i's. Since the direction of the tectonic motion is only determined up to an arbitrary multiple, it can always be normalized so that ξ is equal to 1. The result then is

$$\eta = \frac{\Sigma n_{ix} n_{iy} \Sigma n_{iz}^2 - \Sigma n_{ix} n_{iz} \Sigma n_{iy} n_{iz}}{\Sigma n_{iy} n_{iz} \Sigma n_{iy} n_{iz} - \Sigma n_{iy}^2 \Sigma n_{iz}^2}$$

$$\zeta = \frac{\Sigma n_{ix} n_{iz} \Sigma n_{iy}^2 - \Sigma n_{ix} n_{iy} \Sigma n_{iy} n_{iz}}{\Sigma n_{iz} n_{iy} \Sigma n_{iy} n_{iz} - \Sigma n_{iy}^2 \Sigma n_{iz}^2}$$

The azimuth ϕ of the tectonic motion is then given by

$$\tan \phi = \eta$$

and the dip ψ by

$$\tan \psi = \sqrt{\frac{\zeta^2}{1 + \eta^2}}$$

The *sign* of the tectonic motion (tension or thrust) cannot be determined by the present analysis.

In order to analyze a series of earthquakes it is therefore necessary to know the direction cosines of the null axes. For the present analysis these direction cosines have been calculated by an electronic computer (the Datatron of the California Institute of Technology) from the fault-plane solutions which the writer had collected from the literature.

The earthquakes that were used for the present analysis were mostly small local shocks in central and west-central Asia (except for some large ones in the Hindu Kush area), the fault-plane solutions for which had been determined earlier by various Russian investigators. Part of the data had already been collected by the writer from various Russian publications and was tabulated in one of his catalogues of fault-plane solutions (Scheidegger, 1957). Most of the data, however, were taken from a publication by Gotsadze *et al.* (1957) in which much recent Russian work is summarized. A few solutions (in the Caucasus) were taken from a recent paper by Karapetyan (1958). In the last two publications the fault-plane solutions were represented on small charts from which the standard form of representation (dip and dip direction of fault and auxiliary planes) had to be extracted. Because of the great number of solutions these are not listed here in detail; the reader is referred to the original publications for an inspection of the individual fault-plane solutions.

The data were fed to the electronic computer which was programmed to do the rest of the work, i.e., to calculate the direction cosines of the null axes and to make the various least squares solutions.

The results obtained are shown in table 1. A detailed discussion of these results will be given in the next section.

TABLE 1
RESULTS OF ANALYSIS

Description	Area between		No of earth-quakes	η	ζ	Azimuth	Dip
	Lat N	Long. E					
Caucasus 1 . . .	40 5 -42.0	43 0 -45.0	16	0.537	0.038	N 28° E	02
Caucasus 2 . . .	40.0 -42 0	47 0 -49 0	12	0 041	0.060	N 02° E	01
Caucasus 3 . .	42 0 -44.0	45 5 -48 0	9	−1 166	0.407	N 49° W	15
Caucasus 4. . .	42 0 -43 0	44.0 -45 5	6	−0 504	0.961	N 27° W	41
Caucasus all. . .	40.0 -44 0	42.0 -50 0	46	0 172	−0.064	N 10° E	−01
Turkmenia 1 .	39 5 -40 5	53 5 -54.5	9	0 386	−0.062	N 21° E	−01
Turkmenia 2	38 5 -40.5	54 5 -55 5	9	0.021	0.157	N 02° E	09
Turkmenia 3 . .	37.5 -40 5	55 5 -58 0	4	0 547	0.093	N 29° E	05
Turkmenia all .			22	0.244	0.040	N 14° E	03
Tyan-Shan. . . .	42 5 -43 8	77.0 -79 0	23	0.100	−0.134	N 06° E	−08
Hindu Kush . . .	36 0 -38 0	69 0- 72 0	9	0.355	0.418	N 20° E	22
Pamir 1	38 95-39.45	70.05-70.45	11	−0.121	−0.304	N 07° W	−17
Pamir 2. . .	38.45-38 95	70 05-70 45	15	−0 254	−1 073	N 14° W	−46
Pamir 3 . . .	38.45-38 95	69.65-70 05	4	−0 357	−3.312	N 20° W	−72
Pamir 4	38.45-38.95	70.45-70.85	25	0.030	−0.013	N 02° E	00
Pamir 5 . . .	38.95-39.45	70.45-70.85	57	−0 070	−0.299	N 04° W	−17
Pamir 6	38 45-38.95	70 85-71.25	7	0 550	−0.331	N 29° E	−16
Pamir 7. .	38 95-39 45	70 85-71 25	37	−0 200	−0.151	N 11° W	−08

DISCUSSION OF RESULTS

The regions in which the earthquakes occurred that were analyzed in the present study lie in central and west-central Asia. The reason for choosing this area was, first, that a very large number of fault-plane solutions were readily available, and second, that this area represents a rather interesting section of the Alpine-Himalayan orogenetic cycle. With respect to the individual regions the results were as follows.

Caucasus.—The first area to be considered lies in the Caucasus between the Black and the Caspian seas. A total of 46 fault-plane solutions of earthquakes were available, of which 43 could be assigned to four rather small regions. A comparison of the results obtained with the tectonics of the area (the latter after the drawing in Gotsadze *et al.*, 1957) is shown in figure 1.

An inspection of this figure shows that the earthquakes south of the 42d parallel (areas "Caucasus 1" and "Caucasus 2") indicate a tectonic motion direction that strikes slightly east of north. This could be interpreted as a result of the thrust that caused the folding of the Caucasus mountains.

North of the 42d parallel (areas "Caucasus 3" and "Caucasus 4") the tectonic motion directions, as determined seismically, are almost turned round by 90° as compared with those south of that parallel. This would indicate that a different

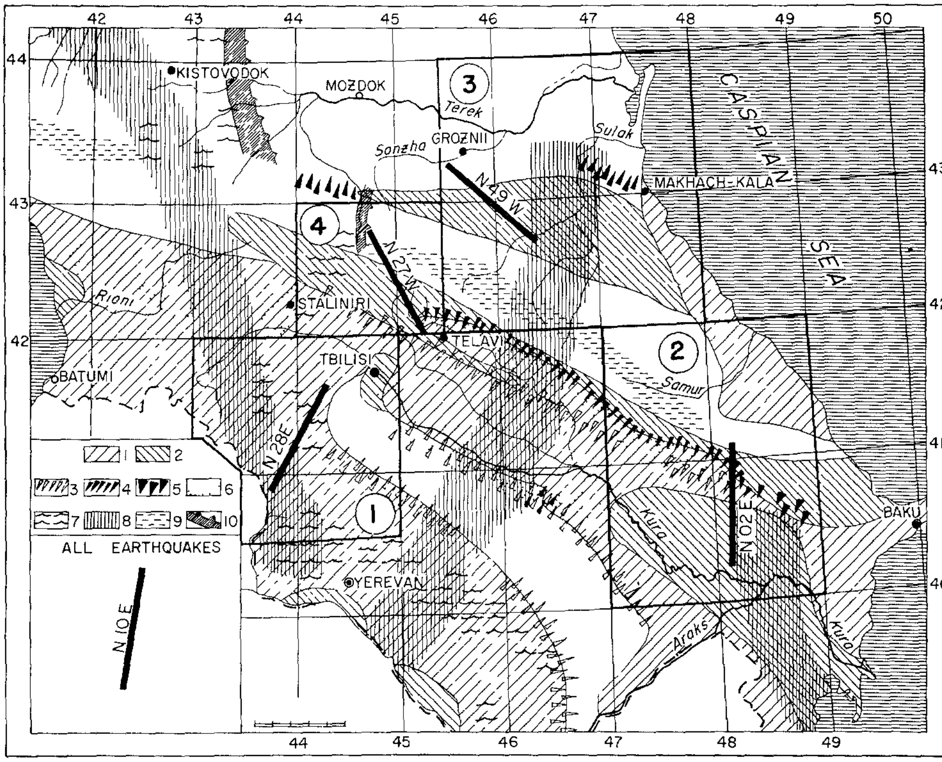

Fig. 1. Comparison of seismically defined tectonic motion directions with the tectonics in the Caucasus region (the latter as given by Gotsadze *et al.*, 1957). 1. Areas in which a repeated change of direction of the tectonic motion occurred in the course of the Alpine cycle. 2. Areas that have undergone a single change of the direction of the tectonic motions (from sinking to uplift) in the second half of the Alpine cycle. 3. Zones across which the ancient tectonic motions changed laterally. These motions were manifest at the beginning of the Alpine cycle and repeatedly in the course of every cycle. 4. Zones across which recent tectonic motions change laterally. 5. Zones across which the most recent tectonic motions, with a large gradient, change laterally. 6. Young depressions that lie at the edge of the Quaternary uplift 7. Zones of Pliocene or Quaternary volcanism. 8. Zones of transverse anticline folds in the contemporary tectonic structure. 9. Zones of the newest change-over of the relief. 10. Edge of submeridional flexures or of ancient structural joints.

tectonic stress system is operative north of the 42d parallel as compared with the stress system south of it. A confirmation of this interpretation of the seismic data is obtained if one compares the results with the tectonic structure of the area as it had been determined from geological studies (see fig. 1). The area 1 lies entirely south of a line across which the recent tectonic motion changes. Most of the earthquakes of area 2 also lie to the south of that line, whereas areas 3 and 4 lie entirely north of it (the line is indicated by black triangles in fig. 1). Therefore, the results from the statistical analysis of the fault-plane solutions and the geological studies are in complete agreement.

The average motion-direction for the whole Caucasus area has also been calculated. Some earthquakes were scattered outside the four small areas shown in figure 1 but still were within the confines of that figure; that is why the total number of earthquakes is greater than the sum of the earthquakes contained in the four small areas.

Turkmenia.—Many fault-plane solutions of earthquakes are also available in an area east of the Caspian Sea, in the plain north of the Kopet-Dagh fold system. As is evident from figure 2, the main tectonic motion direction as calculated from the fault-plane solutions is east of north. This can be interpreted as an expression of the thrust from the southwest which caused the folding of the Kopet-Dagh Mountains.

The basic tectonics of the area is also shown in figure 2, which has been taken from the recent tectonic map of the USSR. Accordingly, most of the earthquakes under discussion occurred just at the edge of the Kopet-Dagh frontal depression. It

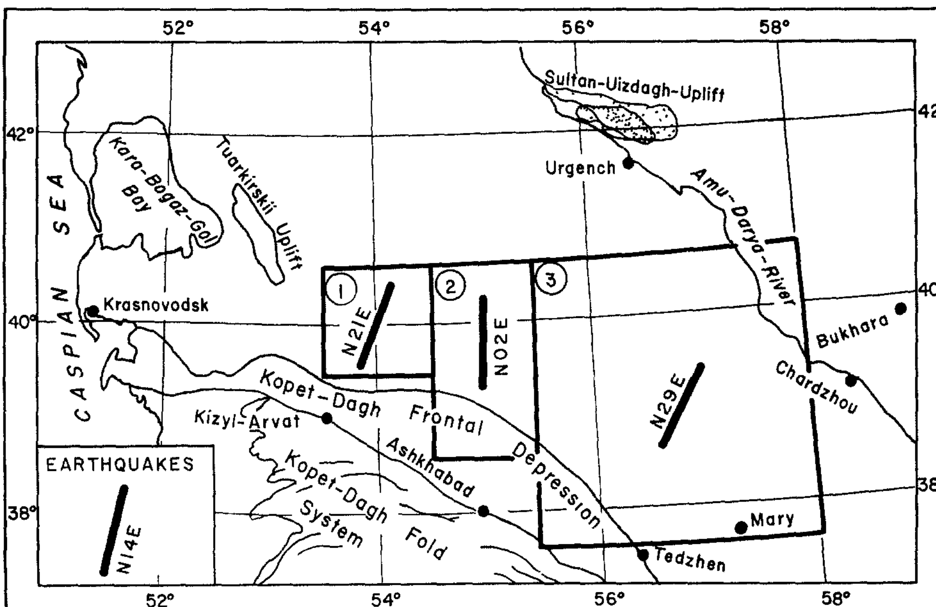

Fig. 2. Comparison of seismically defined tectonic motion directions with the tectonics in Turkmenia (the latter as taken from the recent tectonic map of the USSR).

stands to reason that a downward force must somehow be present to cause this depression. This might explain the dip toward the northeast of the motion direction (calculated from the earthquakes) that is present in the area.

Tyan-Shan.—Moving further east, the next area for which there is a sufficient number of fault-plane solutions for a statistical analysis of the null axes is just east of Alma-Ata in the Tyan-Shan Mountains. Unfortunately, this area cannot, like those discussed above, be split into smaller sections; the number of fault-plane solutions is not large enough. It can only be deduced that the mean tectonic motion, as calculated from seismic evidence, is acting almost exactly in a north–south direction. The correlation of this result with the local tectonics is shown in figure 3.

The seismically calculated tectonic motion direction fits well with that deduced from geological studies (cf. Mushketov, 1933). Accordingly, the Tyan-Shan Mountains, as well as the mountains to the south, were formed by an almost identical north–south compression, although they belong to different systems. The seismic investigations seem to indicate that the stresses are active to the present day.

Hindu Kush.—Another area for which it is not possible to calculate a detailed distribution of the tectonic motion from seismic evidence, but for which at least the general trend can be determined, exists in the Hindu Kush. The earthquakes used are mostly deep, large shocks. In an earlier paper (Scheidegger, 1959) the

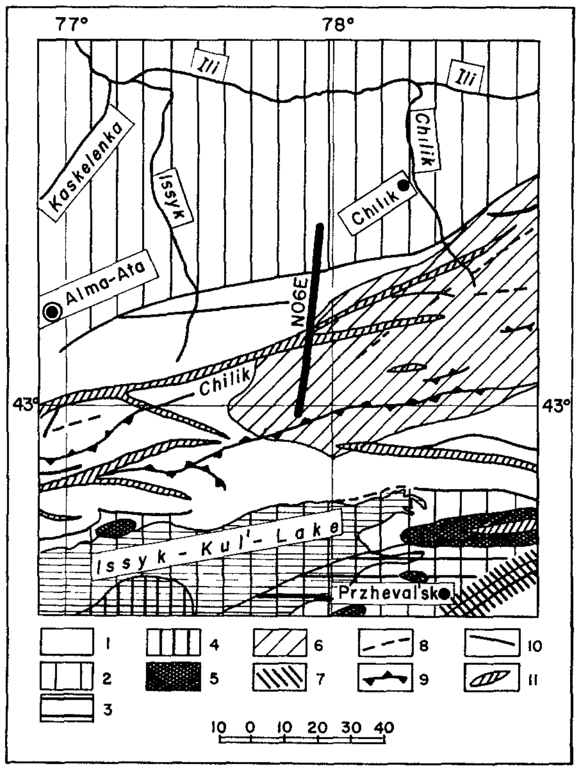

Fig. 3. Comparison of seismically defined tectonic motion with the tectonics of the Tyan-Shan area. The tectonics is as given by Gotsadze *et al.*, 1957. 1. Structural uplifts that were active from the upper Paleogene to the present time. 2. Structural depressions that were occasionally active in the lower Jurassic, and after that from the lower Paleogene to the present. 3. Areas in general structural depressions that have undergone sinking in the lower Jurassic, upper Paleogene, Neogene, and early Quaternary. 4. Areas within general structural depressions that have undergone a large amount of sinking in very recent time 5. Uplifts in general structural depressions that occurred in the upper Quaternary. 6. Areas in general structural rises and depressions that have undergone a motion of opposite sign at the end of the Pliocene 7. Areas with a high velocity gradient of recent motions. 8. Fractures. 9 Zones of intensive Quaternary motions along the fractures. 10. Fractures along which the motions during large earthquakes reached amplitudes up to 10 m. 11. Axes of basic uplifts.

writer has given reasons why it seems permissible to assume that the tectonic motion is the same at all depths; hence no depth differentiation of the earthquakes needs to be made for the present purpose.

It turns out that the tectonic motion, as calculated from seismic evidence, strikes east of north. The primary data are rather poor, and not too much significance can be assigned to this result. However, it may be possible to interpret this as a thrust from the south. The correlation of the postulated motion with the geology of the area is shown in figure 4.

Pamir Knot.—The most detailed analysis of any area that can be made to date is undoubtedly that for the Pamir district. Here, in the vicinity of the town of Garm, the Russians had several expeditions operating at various times, so that a total of some 150 fault-plane solutions of small earthquakes are now readily available in the literature. The great number of fault-plane solutions enables one to divide the area into sections as small as measuring only 30 by 40 kilometers. The correlation of the seismic results with the local tectonics is shown in figure 5.

The main result is that the seismically determined motion is almost exactly north–south, and this consistently in all areas except for some scattering in "Garm 3" and "Garm 6." In these areas, however, only 4 and 7 earthquakes, respectively, are available, which makes their analysis rather unreliable.

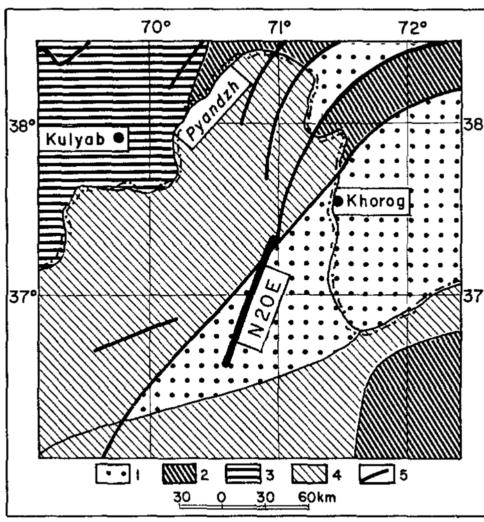

Fig. 4. Comparison of seismically defined tectonic motion with the geology of the Hindu Kush area. The geology is after Gotsadze *et al.*, 1957. 1. Paleozoic structural formation. 2. Mesozoic structural formation. 3. Frontal depressions. 4. Area of undifferentiated Alpine folding. 5 Systems of tectonic fractures.

The suggested interpretation of the foregoing results is that the tectonic motion is due to an overthrust from the south. The dip found (which is negative, i.e., toward the south) supports this view. Older (Mushketov, 1933) and very recent (Gzovskii *et al.*, 1958) tectonic investigations are in complete agreement with such an interpretation. The general consistency of the seismic results for all the small areas under consideration, and the good correlation with geological studies, supply an excellent justification of the seismic method.

Conclusion

Looking over the results presented in the present paper, we note that the statistical interpretation of the null vectors in terms of a tectonic motion direction of a given area correlates exceedingly well with the known tectonics of that area. Thus, the seismic method appears to be completely justified.

The tectonic motion in central and western Asia appears to be mainly in a north–south direction. This motion has been interpreted above as a thrust from the south, although the seismic method is of course unable to determine the sign of that motion.

One can speculate about the significance of this rather general north–south motion with respect to geotectonic hypotheses (for a review of the latter see, e.g., Scheidegger, 1958*c*). If the motion be interpreted as a thrust, as suggested above,

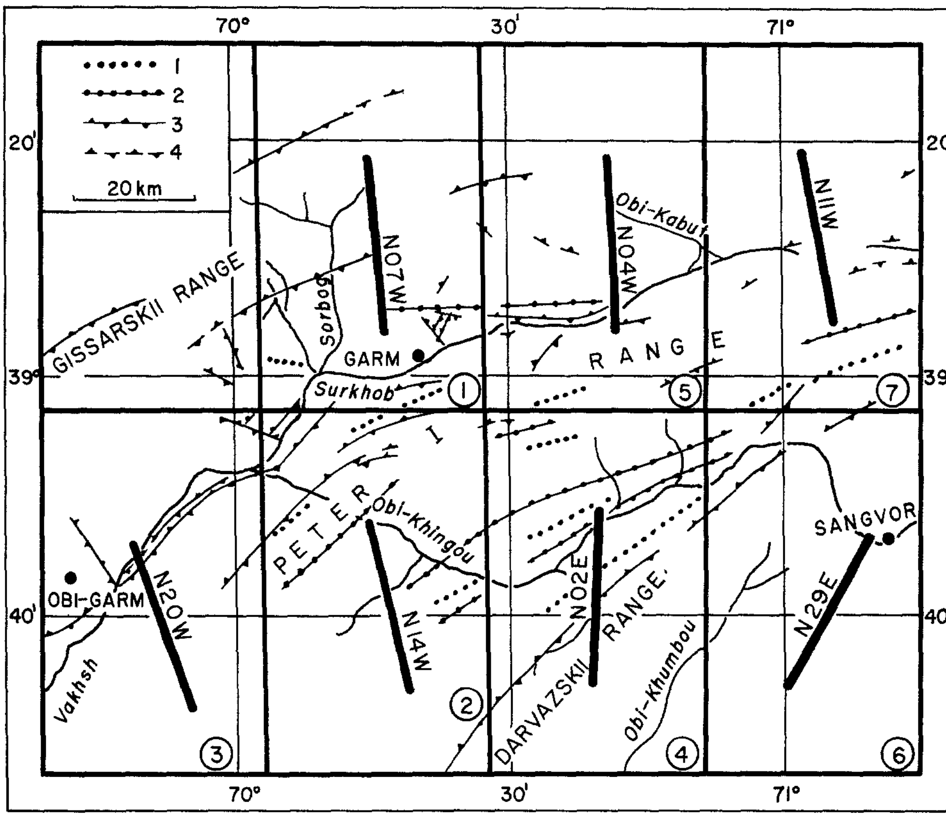

Fig. 5. Comparison of seismically defined tectonic motions with the tectonics of the Pamir Knot area. 1. Axes of synclines. 2. Axes of anticlines. 3. Lines of tectonic fractures. 4. Assumed lines of tectonic fractures. (After Gotsadze *et al.*)

then it is not inconsistent with the concept that India is moving northward by continental drift (see, e.g., Deutsch, 1958). This would be occurring at the present time since the tectonic motions as determined seismically refer to *present* motions. However, not too much weight should be assigned to such speculations, since the postulated thrusts might also be due to other causes. Nevertheless, the fact that the stress system which has been postulated to explain the folding up of the central Asian mountains evidently is still active today (as shown by the seismic analysis), is in itself of some interest.

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References

Deutsch, E. R.
1958. "Recent Paleomagnetic Evidence for the Northwest Movement of India," *Jour. Alberta Soc. Petrol. Geol.*, Vol. 6, No. 6.

Gotsadze, O. D., V. I. Keilis-Borok, I. V. Kirillova, S. D. Kogan, T. I. Kukhtikova, L. N. Malinovskaya, A. A. Sorskii
1957. "Issledovanie mekhanizma zemletryasenii," *Trudy Geofiz. In-ta, Akad. Nauk SSSR*, No. 40 (166). 148 pp.

Gutenberg, B., and C. F. Richter
1954. *Seismicity of the Earth*, 2d ed. (Princeton Univ. Press).

Gzovskii, M. V., V. N. Krestnikov, I. L. Nersesov, and G. I. Reiser
1958. "Sopostavlenie tektoniki s seismichnost'yu Garmskogo raiona Tadzhikskoi SSR I," *Izv. Akad. Nauk SSSR, Ser. Geofiz.*, No. 8, pp. 959–976.

Karapetyan, N. K.
1958. "Dinamicheskie parametry ochagov nekotorykh zemletryasenii Kavkaza," *Izv Akad. Nauk SSSR, Ser. Geofiz.*, No. 2, pp. 260–268.

Mushketov, D.
1933. "Modern Conceptions of the Tectonics of Central Asia," *Rep. XVI Sess., Int. Geol. Congr.*, pp. 885–894.

Scheidegger, A. E.
1957. "Table of Russian Fault-Plane Solutions, *Pub. Dom. Obs. Ottawa*, 19: 97–109.
1958*a*. "Tectonophysical Significance of Fault-Plane Solutions of Earthquakes," *Geofis. Pura Appl.*, 39: 19–25.
1958*b*. "Seismological Evidence for the Tectonics of the Northwest Pacific Ocean," *Bull. Seism. Soc. Am.*, 48: 369–375.
1958*c*. *Principles of Geodynamics* (Berlin: Springer Verlag).
1959. "Statistical Analysis of Recent Fault-Plane Solutions of Earthquakes," *Bull. Seism. Soc. Am.*, 49: 337–347.

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