SEISMIC INVESTIGATIONS IN THE VAKHSH AREA OF TADZHIK REPUBLIC RELATING TO LARG DAM CONSTRUCTION PROJECTS

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The construction of several large dams is going to be undertaken on the Vakhsh river in the Tadzhik republic. Seismic forces affecting the dam are computed in terms of the K_c coefficient which is obtained on the basis of the seismic zoning map. The paper discusses the main principles in developing the seismic zoning map of the Vakhsh area and the results obtained in studying the seismic conditions by proceeding from data on the recurrence of earthquakes belonging to different energy classes.

K is the energy class of the earthquake ($K = \lg E_j$)

$\bar{N}_k$ is the average number of earthquakes of class K in a year according to long-term observations.

A is the seismic activity ($A_{10} = \frac{\bar{N}_{10}}{S} \cdot 10^3$; S km^2)

γ is the slope of the recurrence curve.

In the USSR when it is necessary to select the K_c coefficient for computing seismic forces affecting the dam, the seismic zoning map is consulted /1/. If the expected maximum of earthquake intensity is 7 degree, K_c is assumed to be 0.025; for 8 and 9 degree intensities, K_c is 0.05 and 0,1 correspondingly. The seismic zonal map for the USSR is drawn to 1:5 000 000 scale. Earth-quake regions where larg dams are going to be erected have been the objects of special seismological and

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geological activities with a view to obtain more precise seismic zoning maps [2,3]. The present paper presents the results of seismological investigations in the Vakhsh area in the Tadzhik SSR. Important seismological data have been collected by the expedition sponsored by the Institute of Physics of the Earth, the USSR Academy of Science, and the Institute of Earthquake-proof Construction and Seismology, Academy of Sciences of the Tadzhik SSR. The investigation results obtained have contributed to the design of the 300-m high dam for the Nurek hydroelectric power station on the Vakhsh.

1. Studying the Relationship Between the Sources of Earthquakes and the Features of Geological Structure and Developing the Map of Expected Maximum Earthquakes Intensity

Fig. 1 shows the epicentral zones of strong earthquakes with $K \geqslant 12$ and the main faults in the Vakhsh area. Even from the figure it can be seen that the sources of the earthquakes mainly coincide with the zones of large faults. The earthquakes grow in number where the faults branch out and intersect. However, the analysis of materials presented in fig. 1 fails to clarify a number of important points. Thus, we know very little about the focuses of deep earthquakes and do not know at all how the focuses are related to the structure and faults at depths over 10 - 15 km. These faults might possibly have been omitted by the compilers of geological maps and their importance from the viewpoint of seismic danger is almost unknown.

In order to obtain the necessary information a dense network of highly sensitive seismic stations was set up. Owing to the concentration of seismic stations around the epicentral zones it possible to reduce the errors in determining the coordinates of earthquake focuses to ± 5 km. For five years the coordinates of about 2000 focuses of weak earthquakes were determined, and these testified to a definite relation existing between the focuses and the faults. Fig. 2 shows the epicentres of earthquakes with $K \geqslant 9$ for that period.

The data on the location of epicentres with reference to the existing faults have been treated by the methods of mathematical statistics [4,5]. Thereby the conclusion that the earthquake focuses coincide with the zones of faults has been confirmed. The validity of this conclusion has likewise been corroborated by the investigation of the mechanisms of a great many earthquakes [6]. Proceeding from seismological data it has been possible to show that the faults bounding the Gissar valley on the North and South (Fig. 1) have steep incidence planes and extand to depths up to 40 km , i.e. they cut through the whole earth crust.

Apart from the study of genetic links, the correlation between the earthquake focuses and the features of geological structure has been examined for evaluating the maximum intensity of earthquakes. The maximum energy of the earthquake is largely dependent on the size of the geological structure within which the stresses are concentrated. For the Vakhsh region it was found convenient to examine the maximum earthquake force by drawing comparisons between the size of the geological structures and the maximum force of those earthquakes which had already been recorded in those structures[3].

Most essential for seismic zoning is the identification of Ist-category faults, viz. those of the Surkhob-Khanakin displacement zone or the Vakhsh boundary fault. The Ist-category fault extends over nearly 1000 km and divides large geological structures. In developing a seismic zoning map it was assumed that at any point within this zone (arbitrarily ± 10 km north or south from the projection of the fault on the earth surface) a 10-9 intesity earthquake of the Khait or Karatag type is possible. To draw isolines separating zones of different intensity, should the earthquake source occur in the vicinity of the Vakhsh fault, the isoseismals of the Khait earthquake were used as a basis[7].

IInd-category faults extend over 100-300 km and bound particular geological structures. With respect to the IInd-category faults it was assumed that at any point of such a fault an 8-intesity earthquake of the Nurek type, on November 22, 1956, may occur. These data were used to map of maximum possible earthquakes on rocky ground (Fig. 3).

2. Evaluating the Recurrence of Strong Earthquakes in the Vakhsh Region

The recurrence of earthquakes cannot be evaluated, unless the main parameters of the seismic regime, viz. A and γ, have been determined[8]. Equally important is to know the accuracy of these parameters, to determine the stability of seismic conditions and to study the variation of the main parameters with time. Let us consider the earthquake recurrence curve (Fig. 4).

Seismic parameters A and γ can be computed from observations conducted during a certain period of time on the earthquakes of three and more energy classes on the assumption that the seismic regime is stable. The hypothesis about the stability of seismic regime suggests that the parameters A and γ do not vary with time and γ = const. for a wide range of energy (K = 7-17). If this problem is to be considered more rigorously to take account of possible errors, the stability of the seismic regime for a given region implies that A and γ observed at different time intervals should coincide up to a certain value ε, and $\varepsilon_\gamma < \sigma_\gamma$, where σ_γ is the mean-root-square error in computing γ by the least-squares method according to long-term observations. For the Vakhsh region according to the data on the earthquakes with K=8-12 for 1930-1959 $A_{10} = 0.26 \pm 0.04$ and $\gamma = 0.51 \pm 0.02$. Corresponding to these constants are the following recurrences of earthquakes: once in five years for K = 13, once in fifteen years for K = 14 and once in fifty years for K = 15. In fact, during 30 years there were six earthquakes with K = 13, one earthquake with K = 14 and one earthquake with K = 15. The period of observations for K = 15 earthquakes can be extended to 50 years, because since 1911 every strong earthquake in this region has been recorded by the tele-seismic stations in Pulkovo, Tbilisi and Sverdlovsk and could not have passed unnoticed. Thus, it can be assumed that in the Vakhsh region there was not more than one K = 15 earthquake for the past 50 years. The above data indicate that in the Vakhsh region the observations conducted on weak earthquakes (K = 8 - 12) have been used to evaluate the recurrence of strong earthquakes (K=13-15), which proved to be pretty close to the observed values.

The earthquake recurrence $\bar{N}_k$ statistically computed from the material of a given sample is an approximate quantity. It will not aquire a definite meaning, unless the range in which lies with a certain probability (reliability coefficient) the virtual (constant) value of $\bar{N}_k$ is indicated. The interval within which lie with the indicated probability the possible values of $\bar{N}_k$ is referred to as fiducial interval. Fiducial probability (reliability coefficient) is chosen to conform to a given significance level. The combined data from five-year observations of weak K = 7 - 10 earthquakes made in expeditions, and thirty-year observations of K = 11 -13 earthquakes give a satisfactory answer for 5% significance level, viz. one K = 15 earthquake, on the average, for 25 - 60 years.

3. Fluctuations of A and γ Parameters in the Vakhsh Area

If A and γ are computed from observations made over two different intervals of time, two cases are possible. If $\gamma_1 - \gamma_2 < \sigma_{\gamma_1}$, it may be assumed that the difference in values is within the mean-root-square error in computing γ_1 or γ_2 and, apparently, we may consider that $\gamma_1 \approx \gamma_2$. If, one the other hand, $\gamma_1 - \gamma_2 > \sigma_\gamma$, the question arises as to how much the A and γ quantities may fluctuate, and whether there is a law in their variation.

The study of the variation of seismic-regime parameters with time usually turns out to be a rather complicated matter, because the amount of available material is quite inadequate.

This is also true for the Vakhsh region. In the foregoing paragraph the main parameters A and γ were computed from the data on the earthquake recurrence $\bar{N}_{8-12}$ on the assumption that the seismic process is stable. To identify fluctuations and variations of A and γ parameters during 30 years of observations, this range of energy is useless, because during that period only K $\geqslant$ 11 earthquakes were probably recorded without omission[9]. The number of such earthquakes is insignificant and only for the ten-year period it is possible to compute A_{12} and γ parameters from the data on the recurrence of K=11-13 earthquakes. Fig. 5 shows a curve illustrating the variation of A_{10} and γ for three different decades. In all cases A_{10} were computed from A_{12} with γ =0.51. In fig. 5 these values of A_{10} are represented as a broken line consisting of three segments. Plotted on the same diagram are the values of A_{10} for ten years, obtained by the moving-average method with one-year steps, a smooth curve being drawn through these points.

As can be seen from fig. 5, the values of A_{10} vary with time. The values of A_{10} and γ for thirty years are computed with the mean-root-square error σ (3). Plotted in fig.5 are these values and the respective zones of possible errors within $\pm 3\sigma$. Departures of A_{10} beyond $0.24 \pm 3\sigma_A$ and γ values correspondingly in excess of $0.50 \pm 3\sigma_\gamma$ testify to substantial disturbances in the normal seismic process. Less pronounced deviations can be regarded as accidental fluctuations. From fig.5 it is seen that the deep minimum at A_{10} plot, protruding beyond the limit of allowable fluctuations, corresponds to the period which saw the strongest earthquake for the past thirty years in the Vakhsh region, viz. the Faizabad earthquake, January 11, 1943 (K=15), and in the neighbouring Garm region the strongest earthquake for the past thirty years for the entire South-Tianshan area (Khait earthquake, July 10, 1949, K = 17). Minimum values of γ were recorded for the same period (see fig. 5). Observations show that variations of A and γ are both cyclic but differ in period.

4. Evaluating the Recurrence of Strong Earthquakes on the basis of Maps of Seismic Activity

The curve of earthquake recurrence compiled for the entire region fails to give an adequate description of the relative seismic danger of the various districts in the Vakhsh area, because the sources of strong earthquakes are not scattared throughout the territory, but mostly coincide with the places where the existing faults branch off and intersect. Different districts may be compared in respect of relative seismic danger by consulting either recurrence curves compiled for them or the maps of seismic activity[8]. As can be seen from fig. 6, the available materials make it possible to develop maps of seismic activity with comparative stable boundaries. A high-activity region, $A_{10} > 1.0$, located along the Vakhsh north-east of Nurek stands out in fig. 6. The rest of the area is characterized by lower activity, $0.2 < A_{10} < 1.0$; the sections of still lower activity can be seen in south-west and north-west, $A_{10} < 0.2$. Zonal outlines of different seismic activity in fig. 6 correspond, on the whole, to the distribution of strong earthquake focuses in fig. 1. The zones differing in activity about five times are found to differ in the relative frequency of strong earthquakes ($K \geqslant 12$) two or three times, on the average. This relationship was obtained from observations on strong earthquakes during twenty five years before starting observations on weak earthquakes which were used for compiling seismic activity maps, and during the following five years[9].

The analysis has shown that the relative frequency of strong earthquakes for the past twenty-thirty years is the highest within the zone identified from observations on weak earthquakes (K=7-10) for any two years during the five-year period 1955-1959. At the same time the two strongest earthquakes (1907 and 1943) for the past 80-100 years occurred in a less active zone, $0.2 < A_{10} < 1.0$. The explanation probably lies in the fact that the strongest earthquakes in the Vakhsh region are related to the largest geological structures and Ist-category faults. There is no regularity in the appearance of the sources of strongest earthquakes within such structures, and for developing a seismic zonal map it is not enough to confine observations to the seismic activity of weak earthquakes for a short period of time. For this reason the map in fig. 6 was found inadequate to be used as a basis for developing the seismic zonal map in fig. 3.

C O N C L U S I O N S

The main conclusions derived from five-year observations by using a dence network of highly sensitive seismic stations in the Vakhsh region are as follows:

1. Owing to the high sensitivity of seismic instruments

(10-15 thousand magnification) and the relatively dense network of seismic stations (10 to 18 stations located 30 to 60 km from one another were in simultaneous operation) there was a sharp rise in the number of earthquake epicentres whose coardinates were computed with great accuracy (length ± 5 km, on an average) In the period of five years (1955 - 1959) were determined about 2000 epicentres, i.e. approximately ten times as many as in the previous twenty five years (1930-1954). A sharp increase in the amount of information and its improved quality enabled the relation existing between the earthquake sources and the specific geological structures and faults to be established in a more precise way. This was made possible by taking into account the data on space distribution of earthquake sources and their mechanisms. Some outcropping geological faults were traced after the sources of weak earthquakes down to 30 km depth. The abyssal nature of those faults was thus corroborated. By using instrument data on the depth of a great many earthquakes, the main features in the distribution of earthquake sources throughout the earth crust were identified. The majority of the sources are at 5 to 20 km depth. No sources were found to occur below the earth crust (below 40 km depth) and very few at the boundary between the crust and the mantle. The data on the concentration of earthquake sources in the vicinity to large faults within the earth crust stressed the importance of using geological materials in seismic zoning. As a result, those zones where the occurence of earthquake sources is potentially possible have been defined with greater precision and reliability.

2. Preliminary conclusions as to the probability of re-

currence of strongest earthquakes within the boundaries of the Vakhsh region can be made from observation materials obtained through the general system of seismic stations.

The relatively large scope of information about weak earthquakes, obtained by detailed seismic investigations,provided additional support for the above conclusions. Detailed seismological investigations also made it possible to collect the necessary material for plotting earthquake recurrence curves for separate zones and regions of this area. Precisely such differentiation with reference to seismic danger contributes to a proper choice of sites for dam construction, In this case the general notions of the seismic features relating to a comparatively large area prove insufficient.

3. The materials furnished by detailed seismological investigations, coupled with the technique of seismic mapping, made it possible to identify within the given region several zones with a rather different level of seismic activity and to show that observations on strong earthquakes for the period of thirty years corroborate the validity of the evaluation of seismic activity from short-term (two to five years) observations on weak earthquakes.

It is worth remembering that seismic activity in a comparatively small region ($S = 30.10^3$ sq.km) may display perceptable fluctuations over a period of several years, Accordingly, the results of short-term expedition observations must be considered against the background of the seismic history of the given region during a long period of time. Moreover,it is necessary to take into account the main features of the seismic process in a sufficiently large region (for example in our case the data for the entire South-Tianshan zone must be considered). Nevertheless, it is quite apparent that from observations obtained through a dense network of highly sensitive stations over a period of two or three years sufficiently accurate maps of weak earthquake epicentres can be developed, and by using the maps of seismic activity the principal seismic zones can be identified. This conclusion is of paramount interest, because in many cases one has to evaluate seismic activity in regions, for which macroseismic data are unavailable, whereas the instrument observations available from the general network of seismic stations are inadequate. In these conditions detailed seismological studies coupled with geological and tectonic work will yield a sufficiently well-founded result.

Thus, detailed seismological investigations contributed to our knowledge of the places where strong earthquakes are most likely to occur and of the expected depth of their focuses and recurrence.

R E F E R E N C E S

1. Building Codes and Regulations, Part II, Section A, Chapter 12. Construction in Seismic Areas. Design Standards. CH and ПП-A, 12-62, M.1963.

2. Nersesov I.L., Grin V.P., Dzhanuzakov K. On eseismic zoning of the Naryn basin. Frunze, Kirghiz SSR Academy of Sciences Press, 1960.

3. Geological and seismic features of the Nurek hydroelectric power station area. Tadzh, SSR Academy of Sciences Press, Dushanbe, 1962.

4. Bune V.I. and Reiman V.M. On seismic and tectonic characteristics of the central part of Tadzhik depression. Proceedings of the Institute of the earthquake-proof construction and seismology, Tadzhik SSR Academy of Sciences,v.VII, Stalinabad, 1960.

5. Bune V.I. Some results of detailed studies of seismic conditions in Dushanbe region for 1955-1959. Izvestia Ak. Nauk SSSR, geophysical series, No. 3, 1961.

6. Kukhtikova T.I. The mechanism of earthquakes in Tadzhik depression. TISS Proceedings, vol. X, Dushanbe, 1962.

7. Leonov N.N. The Khait earthquake of 1949 and the geological conditions of its ocurrence, Izv.Ak.Nauk SSSR, geophysical series, No. 3, 1960.

8. Riznichenko I.V., Bune V.I., Gzovsky I.V. et al. Detailed seismic investigation techniques. Proceedings of the Institute of Physics of the Earth, USSR Academy of Sciences, No. 9, (176), M., 1960.

9. Bune V.I. An attempt of forecasting the recurrence of stronge earthquakes in the Vakhsh area in Tadzhikistan, Proceedings of the Institute of Physics of the Earth, No.33 (200), 1964.

CAPTIONS TO FIGURES

Fig. 1 The map showing pleistoseistic zones and epicentres of strong earthquakes in the Vakhsh region for 1907–1962 1,2 – Isoseismals of strong earthquakes (Roman numbers indicate intensity degree); 3 – Classification of earthquakes according to energy – K= lg E_j=12–14. Classification of earthquakes according to the accuracy of computing the focuse coordinates. 4 – class A ± 2.5 km; 5 – class B ± 50 km; 6 – unclassified (the error may be in excess of 50 km). Classification of earthquakes according to the depth of the focuse with the epicentres computed within ± 5 km; 7 – H= 5^{-10} km. 8 – H = 15^{-30} km; 99, 10 – Geological faults of the first[9] and second [10] categories; 11 – seismic stations.

Fig. 2. The map showing epicentres of earthquakes in the Vakhsh region for 1955–1959.
Classification of earthquakes according to the accuracy in computing the focuse coordinates: 1 – class A ± 2.5 km ; 2 – class B ± 5 km; 3 – class C ± 10 km; 4 – unclassified (the error being 15 km and more). Classification of earthquakes in depth: 5 – H=5 km; 6 – H= 10 km; 7 – H = 15 km; 8 – H=20 km; 9 – H=30–40 km; 10 – Vakhsh boundary fault of the first category. 11, 12 – main faults on the geological map; 13– Seismic stations; 14, 15 – Isoseismals of strong earthquakes; 16 – Classification of earthquakes in energy K = lg E_j = 9–13.

Fig. 3 Seismic zoning map of the Vakhsh area.

1 - lst-category faults [3]; 2 - IInd category faults. 3 - Boundaries between the zones of different intensity. 4 - Intensity of rocky grounds.

Fig. 4 The earthquake recurrence curve for the Vakhsh area.

Fig. 5 Variation of A_{10} and γ in the Vakhsh area with time.

Fig. 6 Comparison of A_{10} isolines on maps of seismic activity for the Vakhsh region, plotted from observations over different periods of time: 1955-1956 [1], 1957-- 1958[2] , 1958-1959 [3]. With reference to earthquakes with K= 7 - 10.

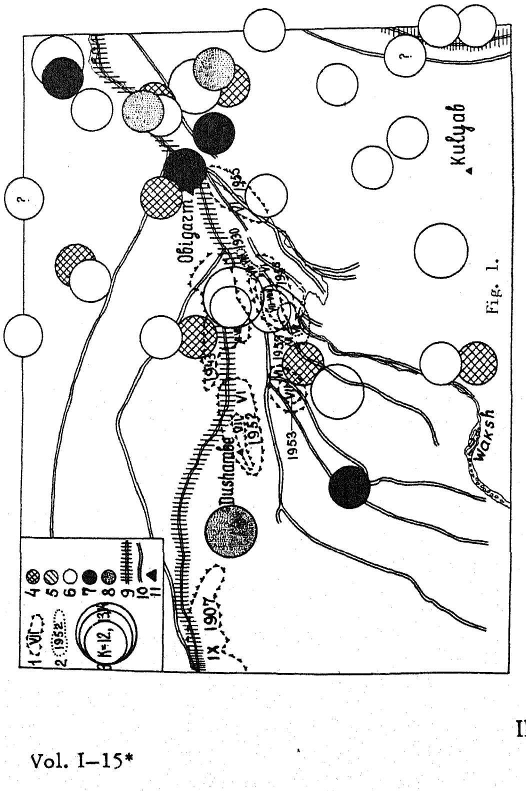


Fig. 1.

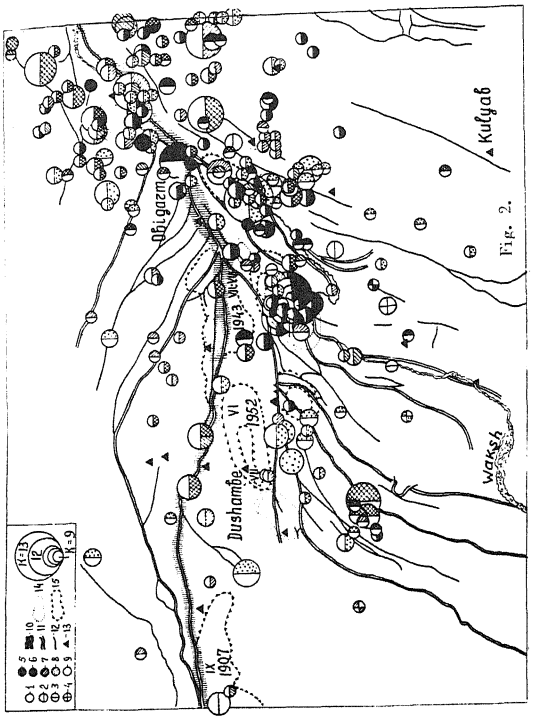


Fig. 2.

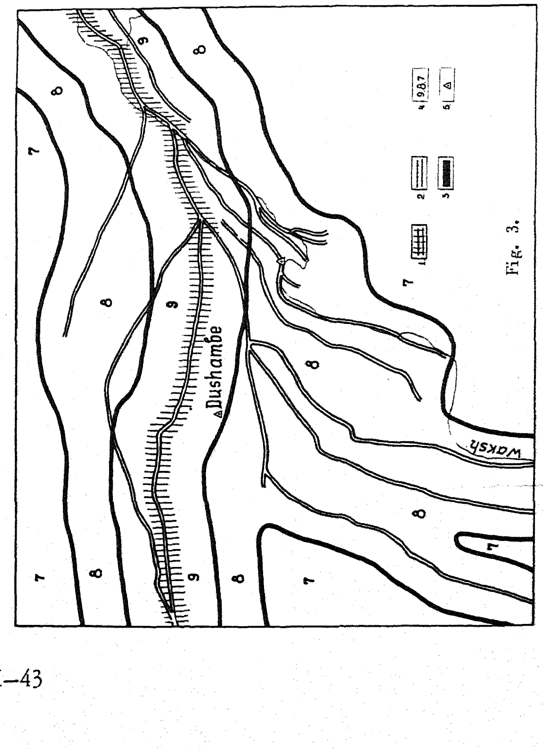


Fig. 3.

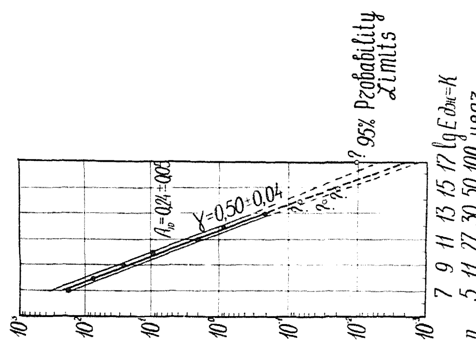
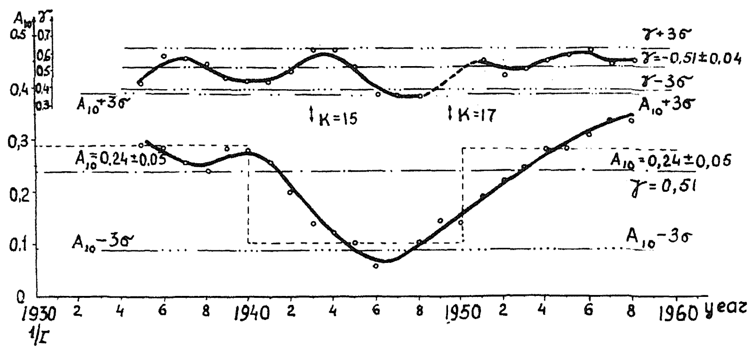
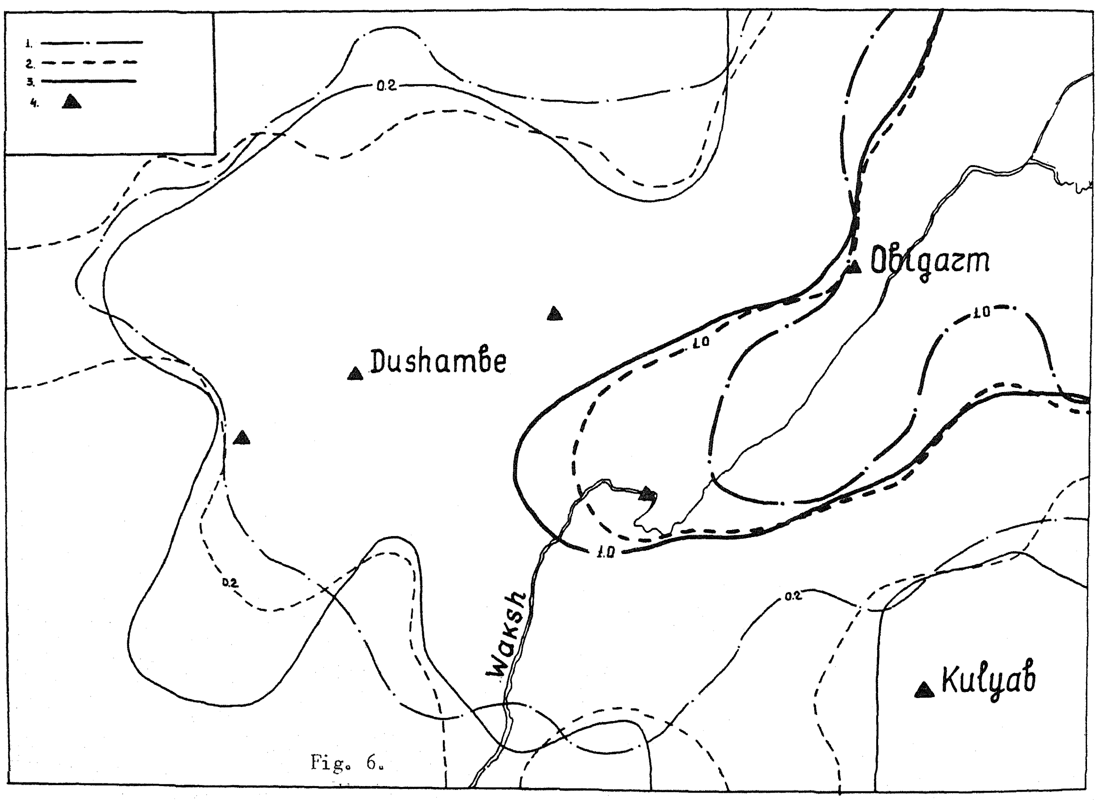


Fig. 4.



A_{10} γ
$\gamma+3\sigma$
$\gamma=0.51\pm0.04$
$\gamma-3\sigma$
$A_{10}+3\sigma$
K=15
K=17
$A_{10}+3\sigma$
$A_{10}=0.24\pm0.05$
$A_{10}=0.24\pm0.05$
$\gamma=0.51$
$A_{10}-3\sigma$
$A_{10}-3\sigma$
1930 2 4 6 8 1940 2 4 6 8 1950 2 4 6 8 1960 year
1/r

Fig. 5.



1.
2.
3.
4.
0.2
Obigarm
Dushambe
1.0
Waksh
Kulyab

Fig. 6.