Bulletin of the Earthquake
Research Institute
Vol. 47 (1969), pp. 1035-1048

49. *Regional Study on the Characteristic Seismicity of the World.*

Part I. Hindu Kush Region.

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(Read September 22, 1969.—Received September 30, 1969.)

Summary

Foci distribution of the earthquakes in and around Hindu Kush region (25°N∼45°N, 65°E∼85°E) during the period from January 1964 to April 1969 was studied with relation to the topography.

A remarkable localized and quite well-known upper mantle earthquake area beneath Hindu Kush was found to have an earthquake nest of approximately $(30\,km)^3$ in volume centering at 36.35°N, 70.75°E and 215 km, in which about 50 seismic events have originated during the whole period of 64 months. Other shallower foci in the upper mantle have gathered above the nest and formed V-shaped pockets along the profiles of N-S and/or NW-SE directions with the nest in their bottoms.

A suggestion was given for the existing of such V-shaped seismic pocket in the upper mantle in the restricted region.

A pronounced minimum seismic activity, on the other hand, was found around the depth of 160 km.

Seismic zones of shallow earthquakes with depths shallower than 50 km run parallel to several trends of mountain chains. The generation of upper mantle earthquakes beneath Hindu Kush appears to be connecting with the compressive force due to the interaction of Asian and Indian continental blocks.

1. Introduction

The mechanism of earthquake generation in the main seismic zones, Circum-Pacific zone and/or mid-oceanic one, for instance, have hitherto been deeply studied. In the main part of the Circum-Pacific zone which is accompanied by deep earthquakes, seismic activity as a function of depth forms a foci plane underthrusting into the continent. This foci plane has a good relation with the arrangement of trench—Island arc—a recent volcanic activity,[1] and the generation of earthquakes in this

1) A. SUGIMURA, "Complementary Distributions of Epicenters of Mantle Earthquakes and of Foci of Volcanoes in Island Arcs (in Japanese)", *Zisin* **19** (1966), 96-106.

foci plane is well elucidated by supposing an anomalous structure (lithosphere) underthrusting deeply into the upper mantle (Asthenosphere) due to the convection current.[2] A shallow earthquake zone running along the oceanic ridge, on the other hand, coincides excellently with the zone of high heat flow, and the stresses in the earthquake foci beneath the ridge always show extension perpendicular to the axis of the ridge.[3] These evidences suggest that the earthquakes along the oceanic ridge may be generated due to the upward and extensive flow of convection current below the ridge. These ideas are mutually well combined with each other and matched well to the attractive hypothesis of the sea-floor spreading which has recently been developing from geomagnetic surveys[4].

Even in the Circum-Pacific seismic belt, however, there are also some regions in which earthquakes occur in more or less specialized ways.[5] Further, there are many other seismic active areas which have special features on the distribution of foci different either from those in the island arc—trench system or in the oceanic ridge, for which the mechanism of the generation of earthquakes is still open to a solution.

In the present paper as well as following ones, endeavores will be made to find some specialized features on the seismicity of these special areas, if such exist, and to thereby offer evidences for taking steps to expand the study on earthquake generation in these special seismic areas too. Tentatively, the following seismic areas will be taken.

1) The seismic area with localized earthquakes in the upper mantle.
2) The seismic area which has conspicuous earthquake nests.
3) The seismic region in which deep seismic zones do not run parallel to shallower ones.
4) The seismic region which includes many local areas of earthquake swarms.
5) Distinct non-seismic area in quite active seismic area.

Special attention will be paid for the seismic area beneath which upper mantle earthquakes with the depth range from 100 km to 200 km have been taken place quite active. Because the upper mantle part in the depth range as above given corresponds to that through which rather soft layer—low-velocity layer—runs globally. The depth range above given,

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2) J. OLIVER and B. ISACKS, "Deep Earthquake Zones, Anomalous Structures in the Upper Mantle, and the Lithosphere," *J. Geophys. Res.*, **72**, (1967), 4259-4275.

3) B. ISACKS, J. OLIVER and L. R. SYKES, "Seismicity and New Global Techtonics," *J. Geophys. Res.*, **73** (1968), 5855-5899.

4) X. LE PICHON, "Sea-Floor Spreading and Continental Drift", *J. Geophys. Res.*, **73** (1968), 3661-3697.

5) T. SANTÔ, "Characteristics of Seismicity of South America," *Bull. Earthq. Res. Inst.*, **47** (1969), 635-672.

therefore, is considered to be inadequate, in general, for seismic events to take place.

The seismic area in and around Hindu Kush, from 25°N to 45°N longitude and 65°E to 85°E latitude, will be taken first in this paper. As is well known, the seismic area beneath Hindu Kush is one of the most interesting ones in which earthquakes have been generated in quite restricted location and depth in the upper mantle.

2. Distribution of observation stations

All of the earthquake data used in the present study were taken from the Earthquake Data Report or Preliminary Determination of Epicenters by U.S. Coast and Geodetic Survey (USCGS) during the period from January 1964 down to April 1969. As a check on the accuracy of the foci determinations, the distribution of the observational stations whose data were used by USCGS to determine the foci of the weaker

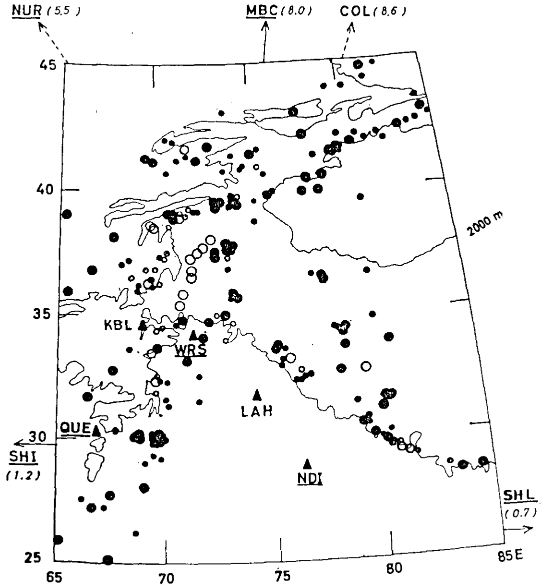


Fig. 1. Distributions of epicenters and observational stations the data of which were quite often available for determining the smaller ($m \leqq 4.5$) earthquakes. Filled circles: epicenters with the depth of shallower than 50 km. Open circles: epicenters with the depth range from 50 km to 100 km. Large circles: $m \geqq 5.0$. Small circles: $m < 5.0$ and m undetermined. Triangles: observational stations. Underlined stations: WWSSN (World-Wide Standardized Station Net). Numerals in parenthesis beside or below the station abbreviations: distance of stations in 1000 km. Brocken arrows: directions of the stations whose data were sometimes (more than once in two events) available.

events ($m \leqq 4.5$) was examined. In order to see further if there was a remarkable difference in the ability of detection by the observational net in the whole period, the examination was made for the two periods, the beginning of 1964 and the end of 1968 as representative ones.

Data at two stations WRS (Warsak, Pakistan), QUE (Quetta-WWSSN, Pakistan) were always available in both periods, and data at two other stations NDI (New Delhi-WWSSN, India) and KBL (Kaboul, Pakistan)* were found to be constantly used in the later period. The locations of these four stations are plotted in Fig. 1. In the earlier period, data at SHI (Shiraz-WWSSN, Iran) was also always available. In the later period, SHL (Shillong-WWSSN, India) took the place of SHI. The directions of these two stations are also shown in Fig. 1 by arrows. The numerals in parenthesis in the figure is the distance of these two stations from the starting point of the arrow. For farther stations, data at two stations MBC (Mould Bay, Canada) and COL (College-WWSSN, Alaska) were always available in both periods. Two other stations NUR (Nurmijarvis-WWSSN, Finland) and LAH (Lahore-WWSSN, Pakistan) sometimes (about once in two events) sent valuable data to USCGS in both periods and in the later period only respectively. Directions and distances for these distant stations against the center of the map are also shown in Fig. 1 by arrows and numerals in parenthesis respectively. Epicenters of the smaller earthquakes with $m \leqq 4.5$ were found to be

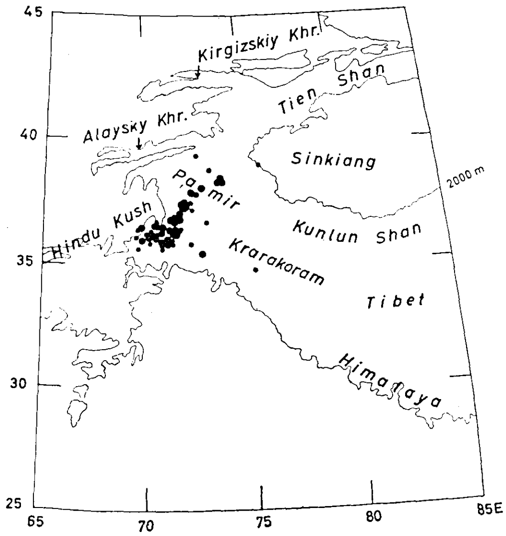


Fig. 2. Distribution of epicenters of the earthquakes with the depth range from 100 km to 200 km.

* The data at Kaboul were available after June 1968 only.

determined in both periods by 7~12 stations.**

Judging from the distribution of these stations around the active areas, the accuracy of the foci determinations can be supposed to be always fairly good during the whole period.

3. Epicentral distribution

Epicenters of the earthquakes with depths of less than 100 km are plotted in Fig. 1 together with a contour line of 2000 m. Shallow earthquakes look like spreading along several lines, each of which runs a little on the southern or eastern side of and parallel to the mountain chains, such as the Kirgizskiy (refer Fig. 2) and other mountain series which run in a NE-SW direction at the western tip of Tibet respectively. Another shallow earthquake runs along Himalaya.

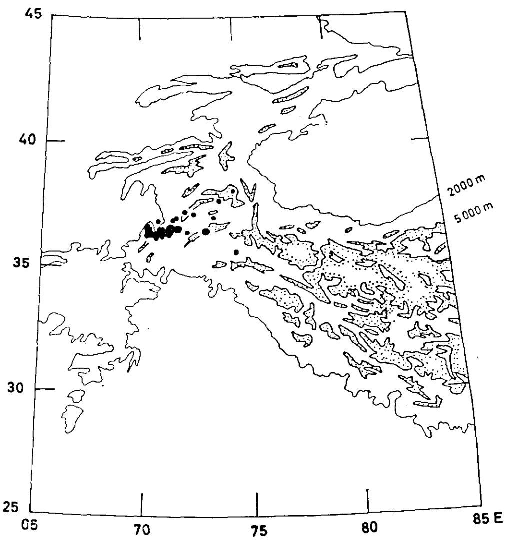
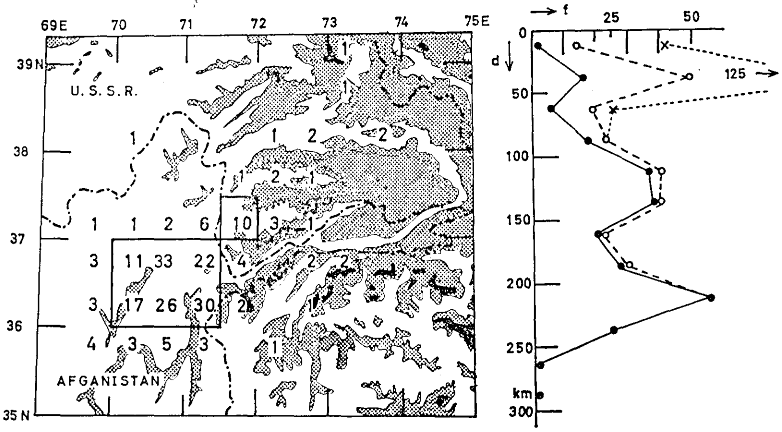


Fig. 3. Distribution of epicenters of the earthquakes deeper than 200 km.

** Epicenters and depths of earthquakes in the earlier period could be examined by the Bulletin of I.S.C., Edingburgh, in which many Russian data were included. It was found that the data at nearby stations of DSH (Dushanbe, Tadzhikistan) and TAS (Tashkent, Uzbekistan) were always and the data at a few other stations at moderate distances were sometimes available for determining the foci of the weaker events of $m \leqq 4.5$. Almost all the epicenters used in the present paper coincided well with those reported in I.S.C. within the difference of less than $\pm 0.2°$. Differences of the depths were comparatively larger, still most of them lie less than ± 20 km with small number of exceptional cases in Afganistan-USSR border, which have the differences of more than ± 50 km. The number of these exceptional cases, however, were found to be too small to give any important changes on the general conclusions in this paper.

(a)



(b)

Fig. 4-(a). Frequency distribution of upper mantle earthquakes (deeper than 100 km) in every 0.5°×0.5° mesh. Areas of higher than 2000 m and 5000 m is respectively shown by dotted and filled areas.

4-(b) Frequency distribution versus depth in the fringed area (filled circles), in the area of 35°N∼39.2°N, 69°E∼75°E (open circles) and whole area of 25°∼45°N, 65°E∼85°E (crosses).

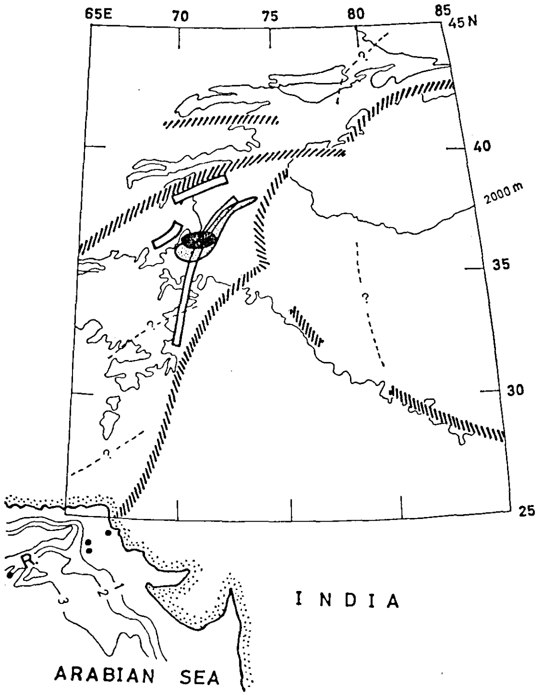


Fig. 5. Schematical pattern of the main trendings of seismic zones in different depth ranges. Hatched zone: $d<50$ km. Open band: 50 km∼100 km. Dotted area: 100 km∼200 km. Filled area: nest of upper mantle earthquakes deeper than 200 km. Numerals in the contour lines in Arabian Sea mean the sea depth in km. R.: Masira-Karachi Ridge.

One active line of the earthquake with the depth range from 50 km to 100 km also runs parallel to the mountain chain of NE-SW direction.

As has been well known[6] the epicenters of deeper events, on the other hand, gather into very small areas as are shown in Fig. 2 (depth range from 100 km) and Fig. 3 (deeper than 200 km) respectively. Epicenters with the depth range from 100 km to 200 km distribute almost in a NE-SW direction with the concentration around the spot of 36.3°N, 71.0°E. The concentration is more remarkable for the epicenters of earthquakes deeper than 200 km. Frequency of these shocks deeper than 100 km in every 0.5°×0.5° mesh is given in Fig. 4-(a). The most dense district fringed by a thick line is located in Afganistan, and the total number inside the fringed area is counted as 149 in 64 months, which corresponds to more than twice a month in average. In the diagram (b) of this figure, frequencies versus depth are presented in the fringed area (filled circles), in a somewhat wider area (35°N~39.2°N, 69°E~75°E) corresponding to Fig. 4-(a) (open circles) and much wider area (25°N~45°N, 65°E~85°E) corresponding to Fig. 1. Two peaks of frequency in the depth range

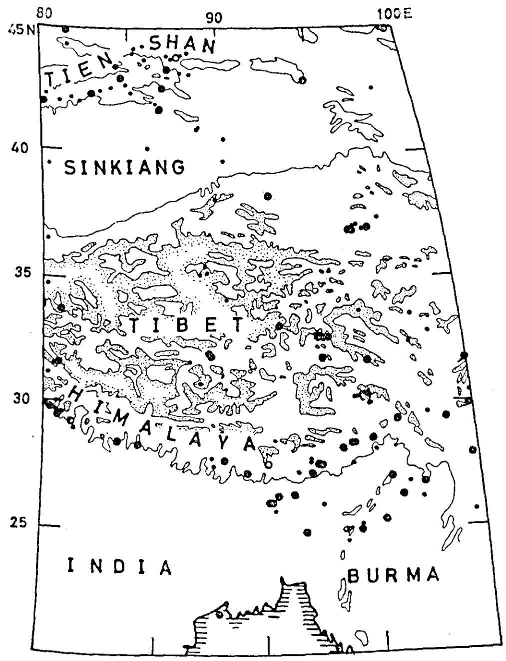


Fig. 6. Eastward extension of shallow earthquake zones along Tien Shan and Himalaya.

6) B. GUTENBERG and C. F. RICHTER, *Seismicity of the Earth and Associated Phenomena* (Princeton Univ. Press 1954), pp. 66-67.

between 100 km–150 km and 200 km–225 km are noticeable.

In Fig. 5, foci distribution around the Hindu Kush seismic region is schematically presented as being classified by different depth ranges. As was mentioned before, the main shallow seismic belts run along the southern or eastern side of the mountain chains. Among them, two seismic belts running eastward extend deeply along Tien Shan and Tibet respectively (Fig. 6). Another one which runs down and enters into the Arabian Sea seems, to some extent, to belong to the oceanic ridge system, because it can be combined with a shallow seismic zone along the Masira-Karachi Ridge. Several spots in the Arabian Sea indicate the locations of epicenters presented in the epicenter map given by M. Barazangi et al.[7] They lie just the extension of the shallow seismic zone which runs down from Hind Kush region.

Table 1. (a) Frequency of earthquakes versus magnitude in the whole area of 25°N～45°N, 65°E～85°E.
(b) Energy released from different regions and depths.

(a)

m \ depth	<100 km	>100 km	Total
<4.5	4	3	7
4.1～4.5	27	36	63
4.6～4.5	95	90	185
5.1～5.5	69	33	102
5.6～6.0	10	8	18
6.1～6.5	5	1	6
6.6<	0	1	1
Total	210	172	382

(b)

Region	Depth	Frequency	Energy
Whole region	d<100 km	207	6.3×10^{22}
	d>100 km	208	4.7× ,,
	all depth	515	12× ,,
Region A*	d>200 km	149	3.2× ,,

* Region A: The most active upper mantle earthquake area inside the fringe shown in Fig. 4-(a).

7) M. BARAZANGI and J. DORMAN, "World Seismicity Maps Compiled from ESSA, Coast and Geodetic Survey, Epicenter Data, 1961-1967," *Bull. Seism. Soc. Amer.*, **59** (1969), 369-380.

Frequency of the earthquakes in different depth ranges and energy released from different regions and depths are presented in (a) and (b) of Table 1 respectively. In the energy calculation, formula $\log E = 1.2m + 14.2$[8] was used. This formula was derived from the combination of $\log E = 11.8 + 1.5M$[9] and a revised formula of $M = (0.76 \pm 0.08)m + (1.58 \pm 0.45)$ which has been found to fit more the observational data for the earthquakes of $m \leqq 6.5$.[10]

5. Foci distribution

In order to make a comparative study on the generation of deep earthquakes with relation to tectonical features, foci distribution of these events must be compared with topography along suitable profiles. Figure 8 and 9 give the results along several different profiles as shown in Fig. 7.

Profiles (A) and (B) in Fig. 8-(a) were taken in N–S direction crossing the most dense region of deep events at the south-west edge of the

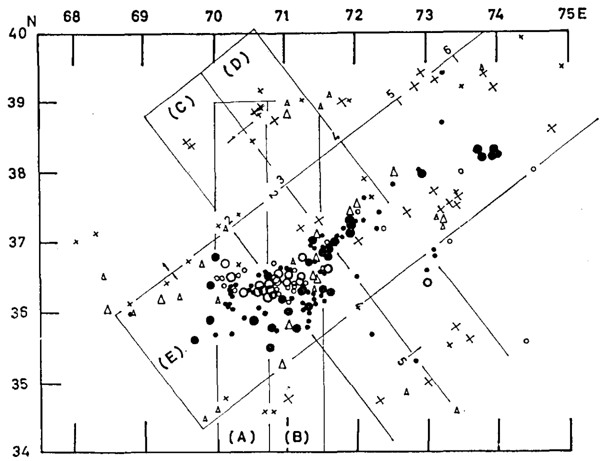


Fig. 7. Detailed epicentral distribution of the earthquakes in and around the nest of upper mantle earthquakes. Crosses: depth <50 km, Triangles: depth range from 50 km to 100 km. Filled circles: depth range from 100 km to 200 km. Open circles: deeper than 200 km. Large marks: $m \geqq 5.0$.

8) M. Ichikawa, "Relationship Between Local Earthquake Magnitudes Determined by Body and Surface Waves (in Japanese)", *Zisin* **19** (1966), 280-282.

9) B. Gutenberg and C. F. Richter, "Magnitude and Energy of Earthquakes", *Ann. di. Geof.*, **9** (1956), 1-15.

10) M. Ichikawa and P. M. Basham, "Effects of Location of Seismograph Stations on the Records Obtained," Minutes of Meeting of Seismic Project (AFORS) Advisory Committee (1963).

zone between 70°E and 71.5°E (refer to Fig. 7). The results in Fig. 8-(a) show quite characteristic features. Different from the foci distributions which are commonly obtained along the profiles perpendicular to the axis of trench and/or island arc, foci form V-shaped pockets with a nest at the position around 36.3°N, 70.4°E and the depth of around 225 km. The dips of these V shaped pockets are in both cases approximately 55°, and the volume of the nest is about 30 km × 30 km × 30 km existing beneath the northern slope of Hindu Kush. Foci appears to be concentrating more around the axis of the pocket along another profile (C) (Fig. 8-(b)) which is taken nearly parallel to the trend of Western Tibet.

A. R. Ritzema[11] studied the mechanism in the foci of 21 Hindu

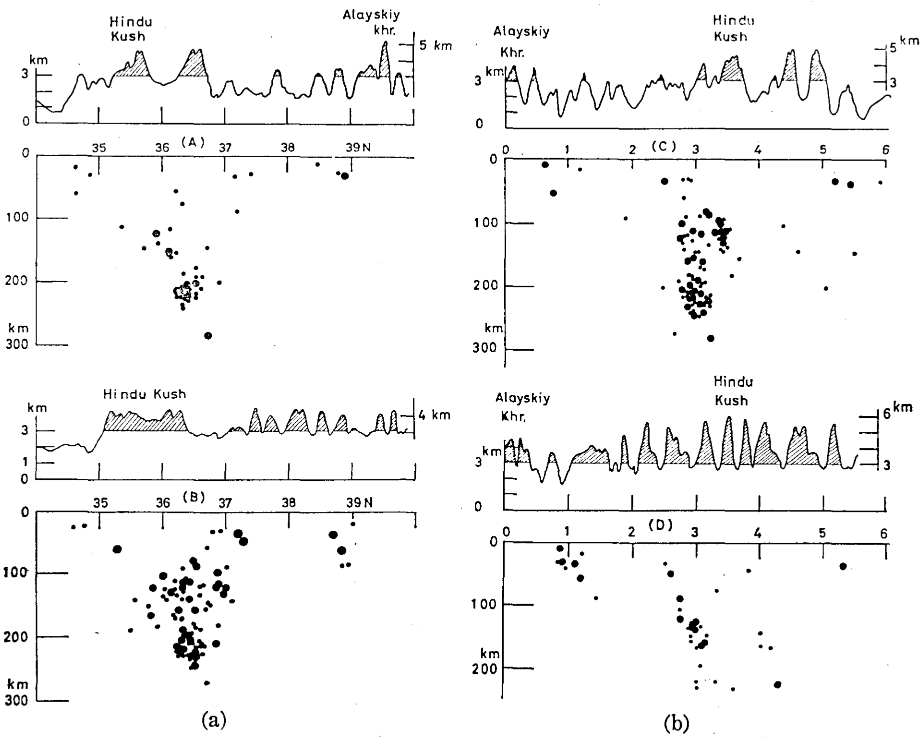


Fig. 8-(a). Depth distributions of the earthquakes along two profiles (A) and (B) which are shown in Fig. 7. Horizontal scales are both approximately the same with vertical ones. Topography along the center line of each profile is respectively shown above for comparison.

8-(b). Depth distributions of the earthquakes along two profiles (C) and (D) which are shown in Fig. 7. Topography along the center line of each profile is respectively shown above for comparison.

11) A. R. Ritzema, "The Fault Plane Technique and the Mechanism in the Focus of the Hindu Kush Earthquakes", *Ind. J. Met. Geophys.*, **6** (1955), 1-10.

Kush earthquakes in the period of 1917–1941 with the depths of around 220 km centering at 36.5°N, 70.5°E and obtained the stress condition of compressive force acting in the NW–SE azimuth with large horizontal compoment, e.g., almost perpendicular to the SW–NE trending Hindu Kush mountain system. From the seismograms of 11 earthquakes in another period of 1951–1957 originating at similar spots, E. I. Shirokova[12] also obtained similar results regarding the stresses effective in the foci of the Hindu Kush earthquakes.

Paleomagnetic work on the Decan plateau basalts, on the other hand, shows that India, referred to as the latitude of Bombay for easy comparison, drifted northward from 37°S to 13°S during the period of Lava extrusion, i.e., from the late Cretaceous to the Eocene[13]. The average rate covering that period has been about 7 cm/year.

Referring to the above evidences, our results of gathering the foci in a steep V-shaped pocket along N–S and/or NW–SE profiles may suggest that the V-shaped lithosphere exists in the upper mantle beneath the Hindu Kush as a result of the strong stress acting in these directions due to the interaction between two continental blocks caused by the northward drifting of the Indian continent. Margins of the two continents might have been projected into the sea around the area in question. Due to the northward drifting of the southern continent, India, two lithosphere layers might be underthrusted from both sides. This suggestion may be available for explaining the formation of the V-shaped seismic area in the upper mantle in such restricted region.

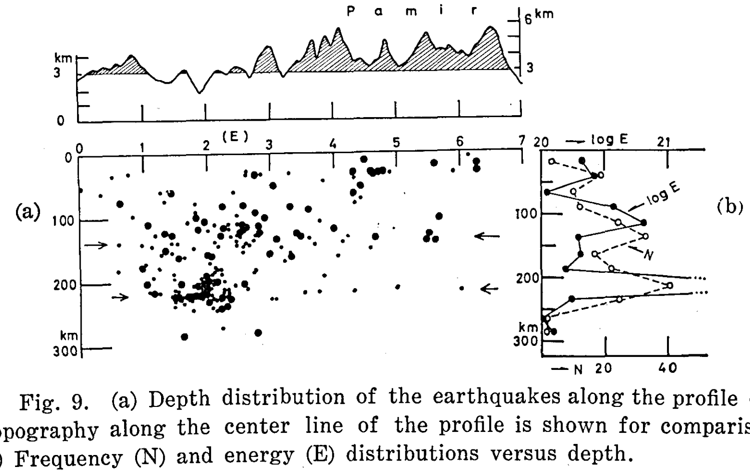


Fig. 9. (a) Depth distribution of the earthquakes along the profile (E). Topography along the center line of the profile is shown for comparison. (b) Frequency (N) and energy (E) distributions versus depth.

12) E. I. Shirokova, "Determination of the Stresses Effective in the Foci of the Hindu Kush Earthquakes," *Izv. Geophys. Ser.* (1959), 1224-1227.

13) A. Holmes, *Principles of Physical Geology.* (Thomas Nelson Ltd., London 1965), p. 1224.

Foci distributions along the profile (E) being taken perpendicular to the profiles (C) and (D) is shown in Fig. 9. Along the profile, the deepening of the foci have different slopes, steep in the SW side and loose in the NE side. The foci distribution in this figure reveals another interesting fact. That is, a lot of foci lie horizontally around the depths of 130 km and 210 km and foci are remarkably scantly around 160 km. As the profile (E) contains almost all the earthquakes originating in the upper mantle around Hindu Kush, frequency distribution of the earthquakes versus depth along the profile can provide one aspect of the representative feature of seismicity of upper mantle events. The result is shown in the diagram of Fig. 9. As expected, a sharp minimum of frequency is revealed. The same is of course suggested in each foci distribution along any other profile which were presented in the previous Fig. 8. The energy distribution as a function of depth also shows an extreme minimum around the same depth (see the solid line in Fig. 9). In this case, the amount of the energy in both sides around the depth 160 km at the depth ranges of 125 km$\sim$150 km and 175 km$\sim$200 km are also very low. The materials in the upper mantle between the depth of 125 km and 200 km, therefore, look like losing the capacity of storing a large amount of energy.

In the various tectonic regions, it has been found that deep seismic activity has its own depth range in which seismicity loses its activity remarkably. With regard to frequency, the minimum ranges appear between 150 km and 250 km in and around Japan,[14] between 200 km and 450 km in Tonga-Kermadec region[15] and between 340 km and 520 km in South America[16] for example. Concerning the energy distribution versus depth, example of the existence of a conspicuous minimum depth range are also found in the Philippine region between 200 km and 500 km, in the New Zealand region between 160 km and 520 km[17] and in South America between 160 km and 520 km[18] respectively. One suggestion can be made based upon such evidence and that is that the diminishing of seismic activity in such depth ranges as given above as well as the present one comes from the effect of the low-velocity layer in the upper mantle. If the above suggestion is correct, the observation of minimum seismic activity in the upper mantle can inform us the regional variation of the depth as well as the thickness of the low-velocity layer beneath the

14) *ibid.*, 1)

15) L. R. SYKES, Seismicity and Deep Structure of Island Arcs," *J. Geophys. Res.*, **71** (1966), 2981-3006.

16) *ibid*, 5)

17) M. MIZOUE, "Variation of Earthquake Energy Released with Depth. Part I," *Bull. Earthq. Res. Inst.*, **45** (1967), 679-700.

18) *ibid.*, 5)

tectonic regions.

6. Conclusion

Through the present study, the following may be concluded as the characteristic of seismicity in and around the Hindu Kush region. Among these, Nos. 2 and 4 are the most interesting for the present author.

1. There is a nest of upper mantle earthquakes centering at 36.35°N, 70.75°E with the depth of 215 ± 15 km. In this nest with the volume of $(30\,\text{km})^3$, about 50 events have been occurring over a period of 64 months in average.
2. Distribution of the foci above this nest forms a V-shaped pocket with dips of approximately 55° both in N-S and in NW-SE direction respectively with a nest in each bottom (Fig. 8.)
3. Directions of the dips of these V-shaped active volumes are approximately perpendicular to the NE-SW trending of mountain system at the western tip of Tibet and have good coincidence with the stresses which have been suggested from the study of earthquake mechanism to act.
4. Upper mantle earthquakes in the Hindu Kush region have two peaks in their activity around the depths of 130 km and 220 km respectively with a conspicuous trough between them. (Figs. 4(b) and 9).
5. Earthquakes shallower than 50 km run along several lines which lie on the southern or eastern slopes of the corresponding mountain series (Fig. 1).
6. One of the shallow seismic zones which enter into the Arabian Sea looks like belonging to the zone of oceanic-ridge system (Fig. 5).

Most of the facts suggest that the earthquakes in and around the Hindu Kush region generate due to the formation of V-shaped lithosphere space as a result of the interaction between two continental blocks by the northward drift of the Indian continent. Before these two continents were put into one, their margins might have been projected into the sea around the area beneath which V-shaped seismic space is now restrictedly exists. Conspicuous minimum seismic activity around the depth of 160 km may also be due to the existence of a low-velocity layer around that depth with depth range of nearly one hundred kilometers.

49. 世界の特殊な地震地域の活動について

(その一) Hindu Kush 周辺

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本研究のねらいは，世界中で特殊な地震活動をしている地域をさがして，その地震活動の特徴を調べ，地震を起こすしくみについての研究をさらにおしすすめるための資料を提供することにある．

まず，マントル上層部に局地的に昔から地震を起こしていることで有名な Hindu Kush 周辺の地震活動の様子を調べてみた．わかつたことは次のとおりである．

1. Afganistan 領内の，36.35°N, 70.75°E, 深さ 215 km を中心としたおよそ 30 km 立方の体積中に地震のかたまりがあり，付近の山脈にほぼ直角な切口でみると，その付近の地震は，この地震のかたまりを V 字形 (傾斜は約 55°) の谷底におしこんだふうにこの V 字形内に分布している (第 8 図).

   このかまたりの中で起こる地震の発震機構から想像される最大ストレスの方向が，上記の切口の方向と一致していることからみて，このV字形内部の地震は，印度大陸の北上に伴つて生じた二つの大陸塊間のストレスによるものと考えられる．また，この地震活動地域が Hindu Kush 周辺にられているのは，アジアと印度大陸が一つになる以前の形が，ちょうどこのあたりで互いに海洋側につき出た恰好になつていて，そのために印度大陸の北上で，そこの岩石圏が南北両側から V 字形にマントル中におしこまれたためだ，と考えたらどうであろうか．

2. 上部マントル地震の活動は，その頻度においても，またその放出エネルギー量からいつても，深さ 130 km と 220 km に大きな極大があり，それにはさまれた 165 km 前後の地震活動には著しい衰弱が見られる(第 9 図). このことは，上部マントル中の低速度層と関係があるのかも知れない．

3. 深さ 50 km 以下の浅い地震は，いくつかの褶曲山脈沿いに起こつている．これらの地震帯のうち，天山山脈とヒマラヤに沿う地震帯は，そのままかなり長く東に伸びている (第 6 図). また，南下してアラブ海に入る地震帯は，その延長が Masira Karachi 海嶺下の地震系列と合流している (第 5 図) ので，この地震帯の少くとも南の部分は，海嶺性地震帯が大陸内部に延長されたものであろう．