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THE SPECTRAL CONTENT OF PAMIR-HINDU KUSH INTERMEDIATE DEPTH EARTHQUAKES: EVIDENCE FOR A HIGH-Q ZONE IN THE UPPER MANTLE

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Abstract. Very high frequencies (5-10 Hz) are recorded at Garm, Tadzhikistan ($\Delta \sim 200$ km), near Toktogul, Kirgizia ($\Delta \sim 600$ km) and at other close stations from intermediate depth earthquakes in the Pamir-Hindu Kush region. The seismic phase, S_n, is recorded with large amplitudes and high frequencies at stations in Pakistan and India from intermediate depth earthquakes. Such high frequencies require either extremely high average values of Q (several thousand) or very high stress drops of earthquakes (kilobars) or possibly both. Regardless of the stress drops, we infer that $Q \gtrsim 1000$ along paths through a portion of the mantle where Q is usually low. Thus these data indicate a discontinuity, or marked thinning, of the asthenosphere. Even if Q were infinite, the spectral content of the signals at Garm, in addition, could also be interpreted as evidence for relatively high stress drops for the intermediate depth earthquakes. If Q is equal to 3000, the highest calculated stress drops are for events with depths between about 50 and 180 km and range from several tens to several hundred bars.

Introduction

Intermediate and deep focus earthquakes ($h \gtrsim 70$ km) at island arcs are usually associated with descending slabs of oceanic lithosphere. The planar inclined zones of earthquakes are often used to map the cold part of the lithosphere that has penetrated into the asthenosphere within the last 10 to 20 m.y. [Isacks et al., 1968; McKenzie, 1969]. These narrow zones of earthquakes are usually associated with regions of high seismic wave velocities and low attenuation. Because of the buoyancy of continental crust, however, continental lithosphere is usually presumed to be too light to descend very deeply into the upper mantle. If this presumption is correct, the intermediate depth earthquakes within continental regions indicate the subduction of oceanic lithosphere within the last 10 to 20 m.y.

Among the four intracontinental regions where intermediate depth earthquakes occur (Burma, Pamir-Hindu Kush, Romania, and Spain) the Pamir-Hindu Kush region is probably both the most active and the most thoroughly instrumented (Figure 1). Intermediate depth seismicity occurs along a nearly vertical zone 700 km long, and beneath the Hindu Kush, abundant activity occurs at depths between 200 and 300 km (Figures 1 and 2) [Lukk and Nersesov, 1970; Nowroozi, 1971]. On June 10, 1971, an earthquake occurred approximately 380 km beneath the Hindu Kush. This event is the deepest known to us in this region. The seismic zone appears to be associated with a region of high seismic velocities [Vinnik and Lukk, 1973, 1974], and attenuation of seismic waves in the upper mantle of the Pamir-Hindu Kush region appears to vary laterally [Barazangi et al., 1975; Lukk, 1971]. Moreover, relatively high intensities are often felt far from the epicenters of intermediate depth earthquakes [Soboleva, 1968b]. Thus the seismicity and wave propagation suggest an upper mantle structure similar to that at island arcs.

The spectral content of seismic body waves is controlled primarily by two causes: parameters describing the source (seismic moment, source dimension, stress drop, etc.) and attenuation. Normally, one cause is assumed, and the other is deduced from the observations. In the present study we examine the spectral content of the intermediate depth earthquakes and show that a high-Q (low attenuation) zone is probably associated with the deep earthquake zone regardless of the source parameters of the earthquakes. We then interpret the spectral content of the seismic waves as possible evidence for relatively high stress drops for the intermediate depth earthquakes regardless of Q. Finally, we try to place more realistic bounds on Q and on the stress drops by making more reasonable assumptions about each and by examining its effect on determinations of the other.

Spectral Content of Seismic Waves From The Pamir-Hindu Kush Region

Frequencies as high as 10 Hz are commonly recorded with large amplitudes for both P and S waves at stations in the Garm region from earthquakes in the Pamir-Hindu Kush region (Figures 1, 3 and 4) with depths from 50 to 300 km (Figures 3 and 4). In fact, the largest events are often heard at Garm. Thus frequencies

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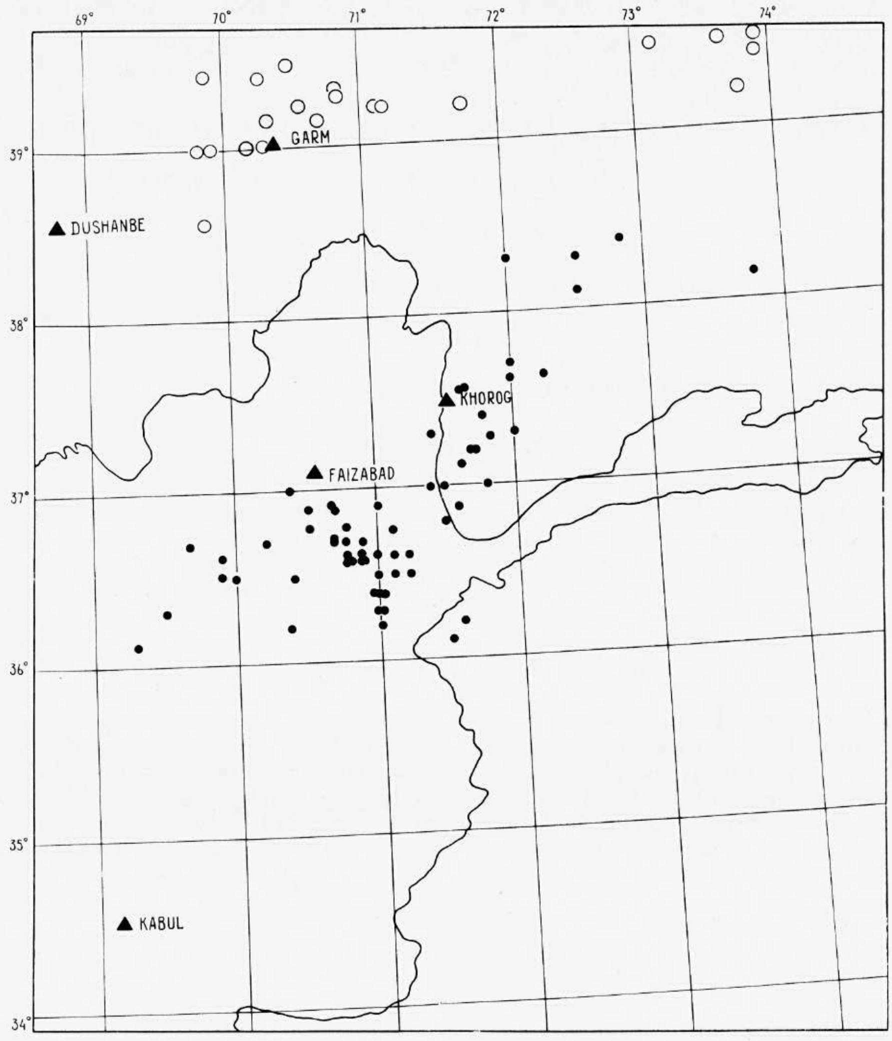

Fig. 1. Map of region. Triangles are seismograph stations. Circles mark epicenters of earthquakes analyzed in this study. Open circles represent shallow events (h < 50 km) and closed circles, deeper events.

in the audible range ($\gtrsim$30 Hz) are radiated and transmitted with large amplitudes. Epicentral distances are typically 200 to 300 km. Thus for the deepest earthquakes the paths to Garm make angles of about 45° with both the surface of the earth and the planar seismic zone. In general, S waves that traverse this depth range of the mantle are rarely recorded by short-period seismographs, and even when they are recorded, they usually have frequencies of less than 1 Hz. Only at island arc structures such as those in Japan [Katsumata, 1960; Tsujiura, 1972; Utsu, 1966, 1971], Tonga [Barazangi et al., 1972; Oliver and Isacks, 1967], New Zealand [Mooney, 1970], and other locations are frequencies as high as 3 to 4 Hz commonly recorded. To the best of our knowledge, only in Japan have predominant frequencies as high as 10 Hz been recorded [Tsujiura, 1972], but this probably results from the limited band-widths of the instruments at other arcs. In all of these regions, such high frequencies are considered strong evidence for a high-Q zone penetrating the asthenosphere, and this interpretation seems applicable to the Pamir-Hindu Kush region also.

From the spectral content of the recorded signals we can place a lower bound on the average value of Q for the paths to the north. Figure 4 shows ChISS spectra (see Appendix) for several intermediate depth earthquakes in the Pamir-Hindu Kush region recorded at Garm. For an impulse of ground displacement the ChISS spectrum increases linearly with frequency with a slope equal to 2. In such a case, attenuation or finite source dimensions will cause a peak in the spectrum. Thus in the extreme cases, where the earthquake radiated an impulse, attenuation alone would shape the spectrum. If we assume that attenuation will be described by a factor, $\exp[-(\pi ft/Q)]$, where f is frequency and t is travel time, the shape of the ChISS spectrum would be proportional to $S(f) = f^2 \exp[-(\pi ft/Q)]$. A maximum occurs when $d[dS(f)/df] = 0$ or approximately where $\pi ft/Q \approx 2$. The peak in the ChISS spectrum of S waves from events is often 10 Hz. As the travel time is about 70 s, $Q \geq 1000$.

As the earthquakes surely do not radiate delta functions, these are extreme lower bounds for Q. Figure 5 shows examples of spectra corrected for different high values of Q. In many cases, Q

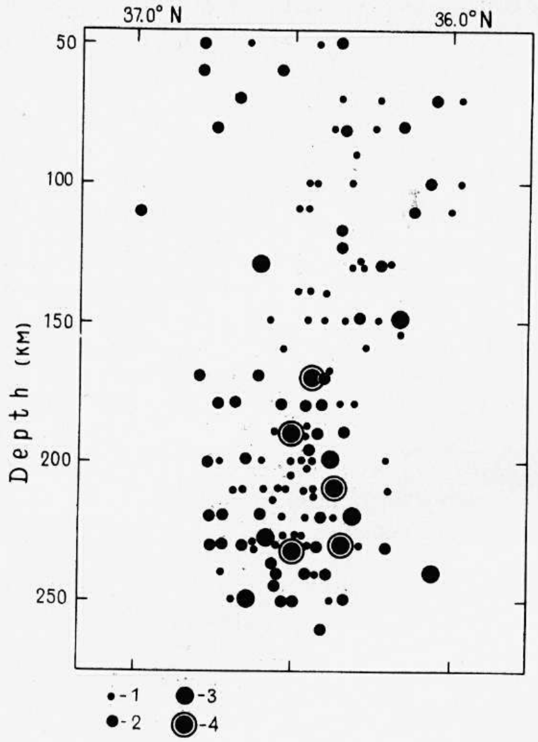

Fig. 2. Cross section of seismicity through the Hindu Kush. Events located by Lukk and Nersesov [1970] for 1966 between 36°N and 37°N and between 70°E and 71°E are plotted on a north-south profile. Size of symbols indicates energy class: K = log energy (in joules), with smallest (1) for K = 10 and largest (4) for K ≥ 14.

values of 1000 or 2000 lead to very high peak frequencies in ChISS spectra, corresponding to high corner frequencies of Fourier spectra and therefore to stress drops of earthquakes larger than 1 kbar (see below). As such high stress drops, when based on spectral content, are larger than those observed elsewhere for intermediate depth events [e.g., Wyss and Molnar, 1972], we infer that Q is probably even higher than 2000. Since values of Q in the asthenosphere are typically a few hundred or less [e.g., Barazangi and Isacks, 1971], the low-Q asthenosphere is apparently interrupted or thinned in the Pamir-Hindu Kush region.

High predominant frequencies (~5 Hz) are also recorded in the epicentral zone of the deep earthquakes at stations in Khorog, Faizābād, and other locations (Figure 1) [Lukk and Nersesov, 1970; Lukk, 1971]. Unfortunately, from these seismograms it is difficult to measure higher frequencies. Nevertheless, for either P or S, when paths traverse the upper 250 km of the mantle, 5 Hz is an unusually high frequency. Thus a high-Q zone is required for such paths also.

At the station no. 1/4 near Toktogul, Kirgizia (41.7°N, 73.2°E), some 600 km north of the intermediate depth earthquakes the frequency content of P and S waves from these earthquakes is almost the same as that at Garm (Figures 6 and 7). For these paths the average value of Q must also be at least 1000 and probably is greater. P and S waves to Toktogul probably enter the horizontal lithosphere of the Eurasian plate near the intermediate depth events and travel through the lithosphere as S_n. Thus these data imply a continuity of the lithosphere northward from the seismic zone.

Recordings of intermediate depth events by temporary stations in Kirgizia, 700 to 800 km northeast of the intermediate depth Pamir-Hindu Kush earthquakes, also show high predominant frequencies (~5 Hz) [Nersesov et al., 1968]. These observations imply continuity of the lithosphere in this direction. In contrast, signals recorded by ChISS systems 900 to 1000 km northeast of the seismic zone in Talgar (43.2°N, 77.2°E) and in Novosibirsk (54.9°N, 82.9°E, where $\Delta \approx 2000$ km) show considerably smaller amplitudes and lower frequencies than those recorded at Garm or at the temporary stations in Kirgizia. S waves are clear only on channels centered at frequencies less than 0.5 Hz, and ChISS spectra for P waves are peaked near 1 Hz. If the source is assumed to radiate an impulse, this peak corresponds to $Q \approx 200$. Alternatively, assuming an infinite value of Q for paths to Garm from a comparison of spectra at Talgar and Garm, we estimate an upper limit for the average Q for paths to Talgar of 390.

To the south, S_n is transmitted with high frequencies and large amplitudes by paths from intermediate depth Pamir-Hindu Kush earthquakes to stations in India and Pakistan (Figure 8) [Molnar and Oliver, 1969]. Unfortunately, the frequency response of the short-period instruments of the Worldwide Standardized Seismograph Network is peaked at approximately 1.7 Hz, and frequencies higher than about 1.5 Hz are difficult to recognize on the seismograms. In any case, it appears that the high-Q lithosphere beneath Afghanistan and Pakistan is essentially continuous with the earthquake zone.

The shape of the high-Q zone that penetrates the asthenosphere is difficult to map, and we defer discussion of it until after discussing the source parameters of the earthquake.

The Spectral Content of Seismic Waves Radiated By Pamir-Hindu Kush Earthquakes

Above we estimated a lower bound for Q, under the assumption that the sources radiated impulses. If, instead, we make an assumption about the value of Q, then from the shape and amplitude of the spectrum we may estimate parameters describing the source, such as the seismic moment, the source dimensions, the average displacement on the fault, and the stress drop. The low-frequency portion of the spectrum determines the seismic moment, $M_o = \mu A u$, where μ is the shear modulus, A is the fault area, and u is the average displacement [Aki, 1966, 1967].

Following Brune [1970], we assume that the average source dimension of the fault, r, or the radius of the equivalent circular fault, is inversely proportional to a characteristic frequency f_o which separates the low-frequency portion from the high-frequency portion of the spectrum. Brune [1970] considered the Fourier spectrum of displacement and defined f_o as the corner frequency where an extrapolation of flat

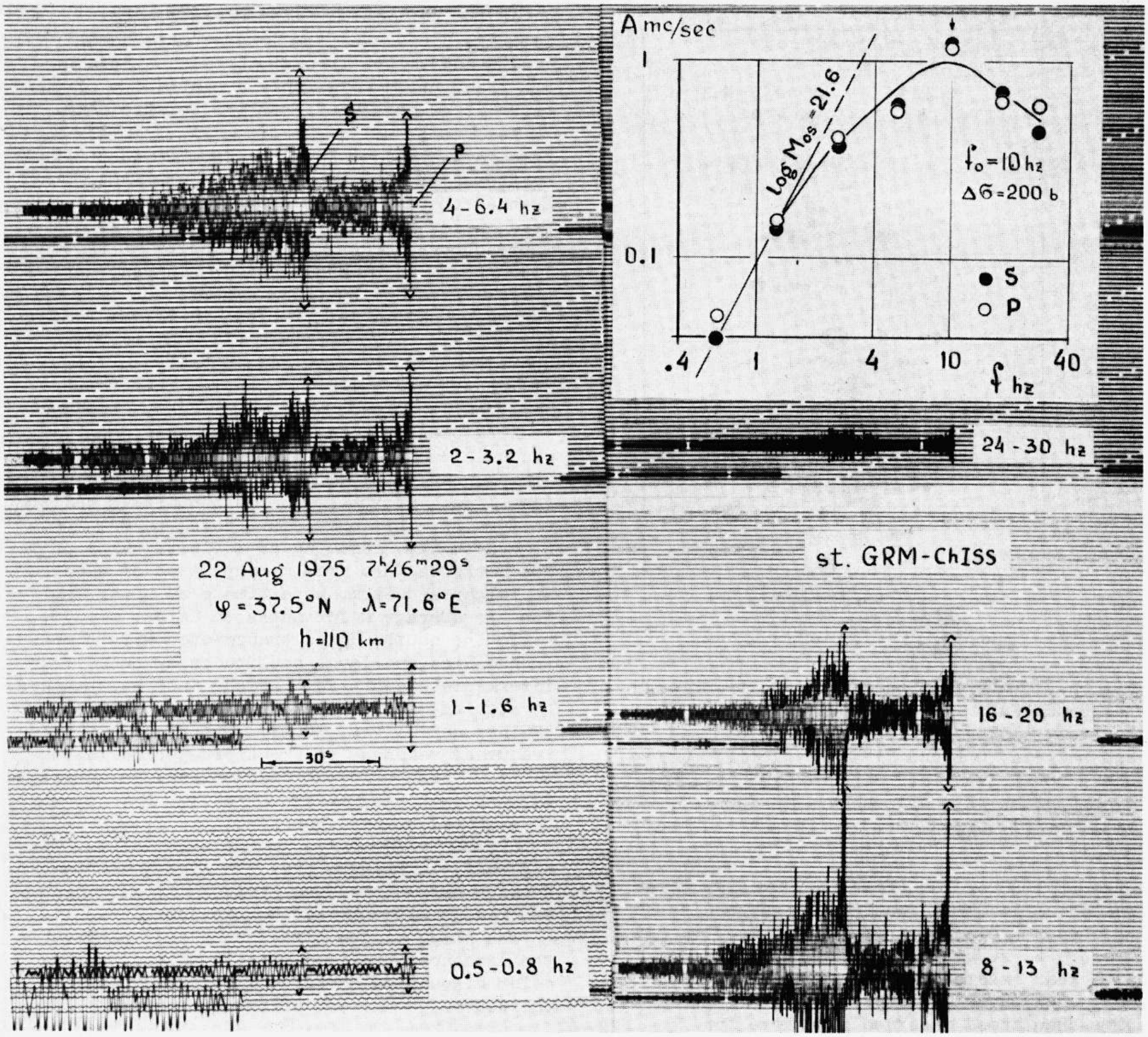

Fig. 3a. Seismograms recorded by ChISS at Garm for an intermediate depth event in the Pamir-Hindu Kush region. Band-widths of individual channels are shown. Calibration signals shown for some traces in lower figure.

low-frequency and decreasing high-frequency portions of the spectrum intersect. For ChISS spectra it is easier to define a peak frequency, which we assume is approximately the corner frequency for the corresponding Fourier spectrum. Following Brune [1970] and Wyss et al. [1971], we assume that $r = 2.34v/2\pi f_o$, where v is the wave velocity in the source region. However, if we recognize that our estimates of f_o from ChISS spectra may systematically differ from Brune's original concept and that the stress drop $\Delta\sigma = (7/16)/(M_o/r^3)$, [Keilis-Borok, 1959] depends on the cube of f_o, there exists the possibility of a systematic difference between our estimates of $\Delta\tau$ relative to those studies using Fourier spectra.

If we assume that Q is infinite, then the shape of the observed spectrum can be used to estimate the seismic moment, the peak frequency f_o, and therefore the stress drop (Tables 1 to 3 on microfiche).[1] As attenuation affects the high frequencies more than the low frequencies (Figure 5), corrections for attenuation will probably not alter estimates of the moment but will increase the peak frequency and therefore the stress drop.

When Q is assumed to be infinitely large ($Q > 10^4$), at depths greater than 50 km, there is no obvious variation with depth for the calculated stress drops (Figure 9). A more

[1]Tables 1 to 3 are available with entire article on microfiche. Order from American Geophysical Union, 1909 K Street, N. W., Washington, D. C. 20006. Document J77-001; $1.00. Payment must accompany order.

obvious difference can be seen for events deeper and shallower than about 50 km. For such a comparison we analyzed spectra of both Pg and Sg from several earthquakes with the same hypocentral distances as the deeper events and spectra of P and S waves from several earthquakes in the Garm region with approximately the same magnitude range as the deeper events. For the more distant shallow events, stress drops were determined by assuming that Pg and Sg travel as body waves. Although there is a large scatter in both populations (Figure 9) the intermediate depth earthquakes (h > 50 km) appear to have higher stress drops than the shallow events. The difference in the stress drops between the local events and the deeper ones, however, is less apparent than that between the distant shallow events and the deeper ones. Hence with the assumption of infinite Q, there is a suggestion of higher stress drops for intermediate depth events than for shallow ones, but the large scatter in the estimates makes such an inference only tentative.

For more reasonable values of Q this difference becomes more apparent. First, we note that a correction for attenuation will increase estimates of stress drops for the distant events more than for the local shallow ones and thus render the difference between shallow and intermediate depth events more apparent than is shown in Figure 9. In addition, there is an apparent increase of stress drop with seismic moment. Because smaller earthquakes have higher peak frequencies, attenuation might affect estimates of stress drops more for them than for the larger earthquakes. If we compare the stress drops of the larger deep earthquakes with those of the local events and the larger

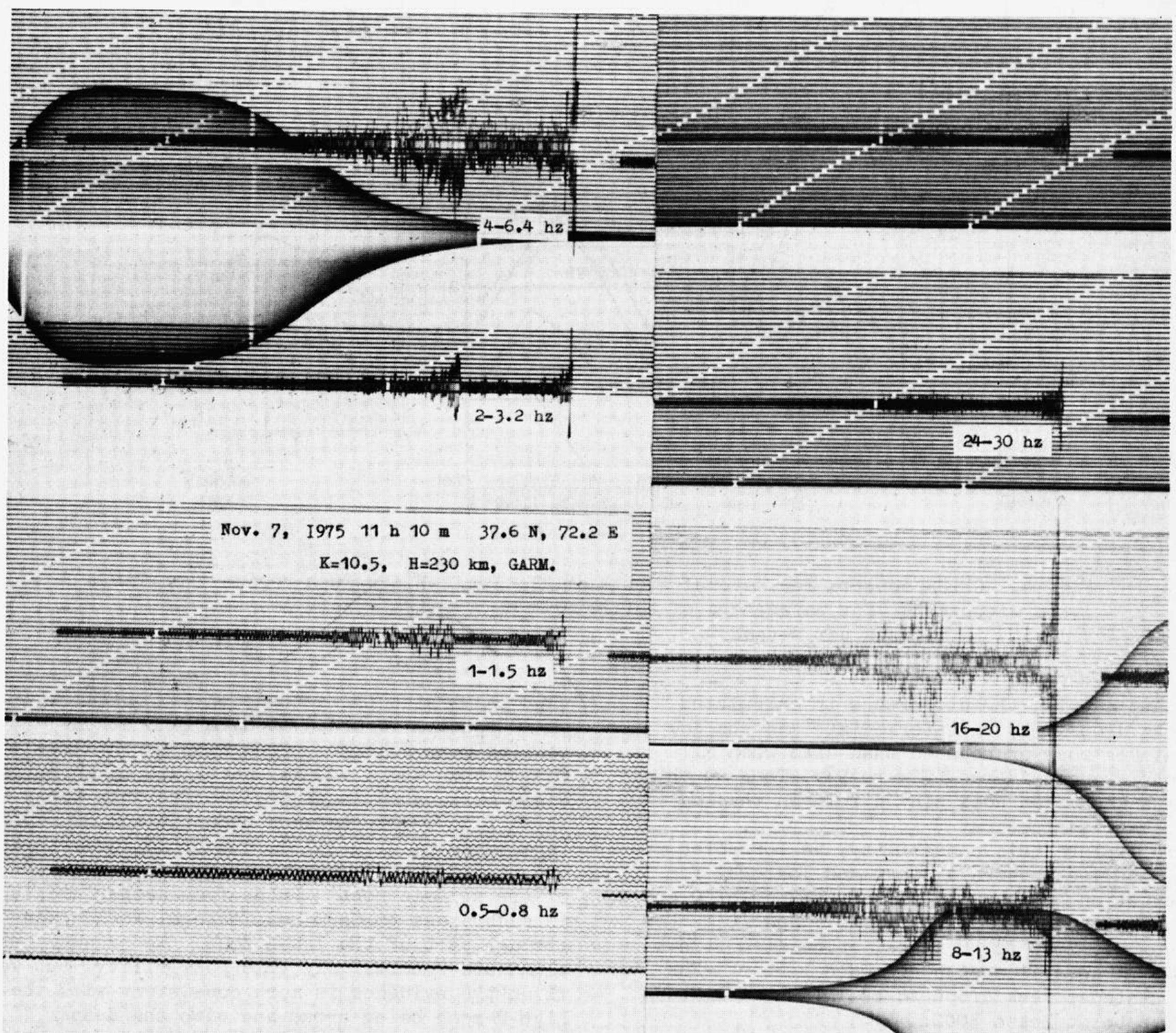

Fig. 3b. Seismograms recorded by ChISS at Garm for an intermediate depth event in the Pamir-Hindu Kush region. Band-widths of individual events are shown. Calibration signals are shown for some traces.

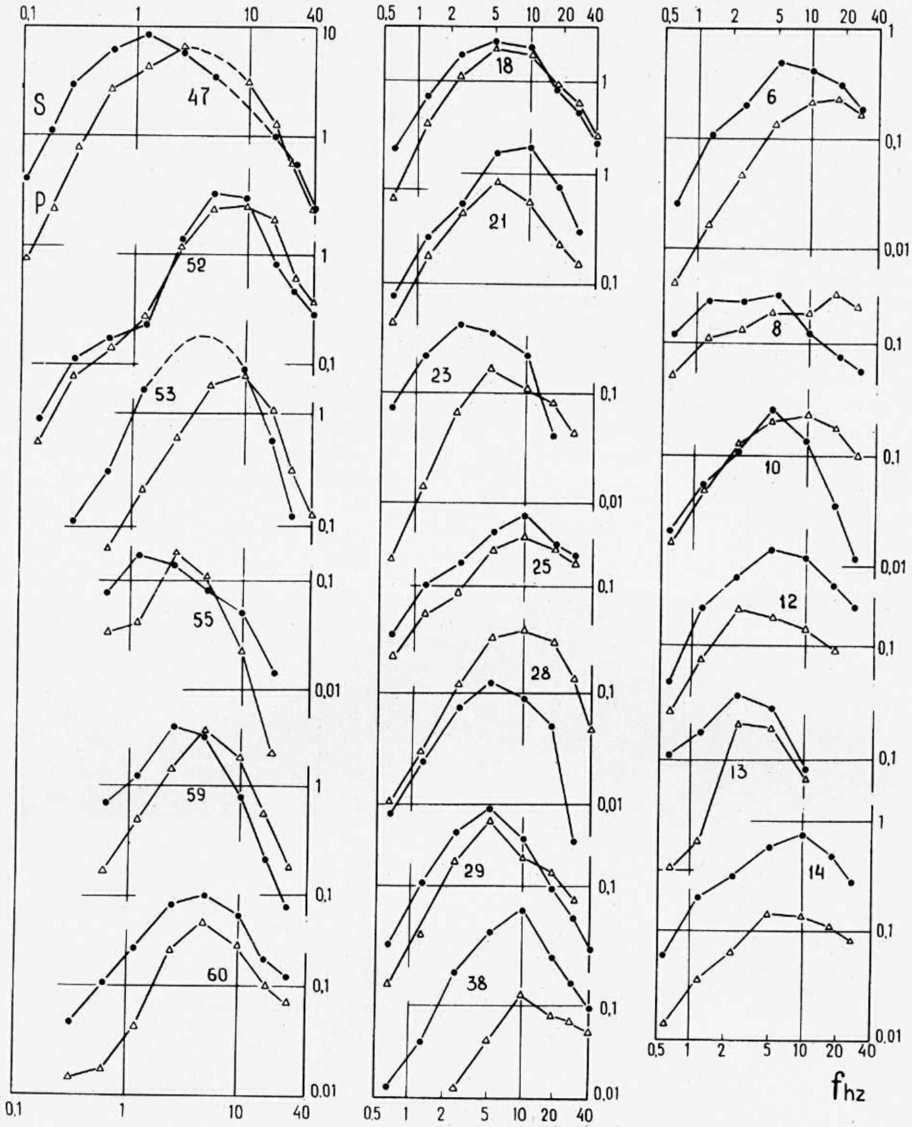

Fig. 4. ChISS spectra for several events in the Pamir-Hindu Kush region (see Table 1, on microfiche, for parameters of earthquakes). Vertical scale is particle velocity in microns per second.

distant events, the difference in calculated stress drops between intermediate and shallow events is more pronounced than that when all events are considered (Figure 9). Thus we think that attenuation does play a role in shaping the observed spectra.

To explore this possibility, we corrected the observed spectra at Garm and Toktogul for attenuation by assuming various values of Q and estimated stress drops (Figures 7 and 10). For Q equal to 2000 for S waves, calculated stress drops of several events exceeded 1 kbar. For calculated stress drops to be less than 1 kbar, Q must be at least 3000.

Shape of High-Q Zone

We do not have unambiguous evidence that tightly constrains the shape of the high-Q zone that penetrates the asthenosphere. Because ChISS spectra recorded at Garm (and at the station near Toktogul) from many earthquakes deeper than about 180 km, particularly from the Hindu Kush, show lower frequencies than those shown from events between about 50 and 180 km [Khalturin et al., 1975], one could infer that the high-Q zone is narrow near some portions of the seismic zone. Paths from deeper events in such areas to Garm and Toktogul would pass through part of the low-Q zone. We cannot eliminate conclusively this possibility, but we think the evidence is more consistent with the high-Q zone being broad and with the deeper events radiating lower frequencies than events between 50 and 180 km.

In general, the deeper events are recorded with somewhat lower frequencies also at Faizabad, Khorog, and other stations nearly directly above the deep seismic zone, where Q is presumably highest [Lukk and Nersesov, 1970]. This observation concurs with the suggestion that the deeper events radiate lower frequencies and therefore are associated with lower stress drops. We note that in other regions, earthquakes in the depth range 70 to 200 km appear to radiate the highest frequencies [Wyss, 1970; Wyss and Molnar, 1972].

The large S_n phases recorded in Pakistan and in India from the deeper earthquakes and the high frequencies recorded at Toktogul are most easily understood if the high-Q zone surrounding the earthquakes is broad. If the high-Q zone were narrow, waves carrying high frequencies would ascend vertically through the high-Q zone before turning sharply so as to travel horizontally through the high-Q lithosphere. Such paths do exist in other regions [Barazangi et al., 1972; Isacks and Barazangi, 1973], but in these regions the signals are quite small and do not dominate the seismograms as they do in Figure 8. Similarly, high intensities are often observed at large distances from the deeper events [Lukk and Nersesov, 1970; Soboleva, 1968b]. The isoseismal of highest intensity for the November 14, 1937, earthquake (L ∿ 200 km) included Lahore, Pakistan, 600 km southeast of the earthquake [Kinyapina, 1964]. Although

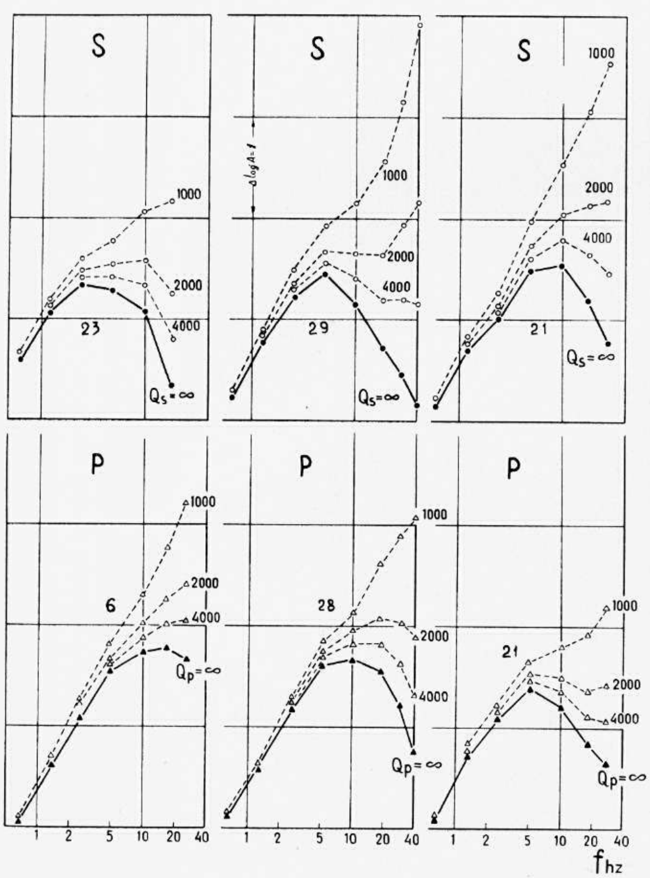

Fig. 5. The effect of attenuation on the ChISS spectra. For different assumed values of Q the calculated shape of the radiated spectrum changes. Note that Q cannot be less than 1000.

Soboleva [1968b] interpreted anomalies in the intensity distributions to be a result of the radiation patterns of the earthquakes, following Utsu [1966] we think they imply the existence of unusually high Q paths for seismic waves. The intensity distributions and the amplitude versus distance curves constructed from intermediate depth Pamir-Hindu Kush earthquakes [Lukk and Nersesov, 1970] clearly require more complicated Q and/or velocity distributions in the crust and upper mantle than are assumed here but do not contradict a broad high-Q zone surrounding the seismic zone.

Because in the mantle, Q for S waves is usually lower than Q for P waves, if attenuation strongly affects the observed spectra of the deeper events, the ratio of S wave to P wave spectra should decrease rapidly at high frequencies. In Figure 11, P and S wave spectra for several of the deeper events are shown with their ratios. The fact that the ratio does not decay rapidly at high frequency but instead becomes flat supports the contention that attenuation is not the cause of the lower frequencies observed for the deeper events.

One other observation is consistent with a somewhat broader zone associated with the Pamir-Hindu Kush earthquakes than island arc earthquakes. Although the seismic zones at well-studied island arcs are only 15 to 20 km wide [Ansell and Smith, 1975; Dewey and Algermissen, 1974; Engdahl, 1971, 1973; Mitronovas et al., 1969; Sykes et al., 1969], they are 50 to 60 km wide in the Hindu Kush (Figure 2) [Lukk and Nersesov, 1970].

From this evidence we infer that the high-Q zone surrounding the intermediate depth events is broad and not confined to the immediate vicinity of the earthquake zone (Figure 12). We therefore conclude that the stress drops for events between about 50 and 180 km are larger than those deeper than 180 km. The fact that high frequencies are well recorded from some deeper events (h ∿ 200 km) in the Pamirs implies that the inference about the shape of the high-Q zone is valid for this region. The evidence from the Hindu Kush, however, is less convincing, and more detailed work is likely to reveal complexities not yet defined.

Discussion

The basic observations made in this study are of relatively high frequencies of both P and S waves from intermediate depth earthquakes in the Pamir-Hindu Kush region recorded at stations in the immediate vicinity of the earthquakes, a few hundred kilometers to the north and several hundred kilometers to the south (Figure 12). The most detailed analysis is for recordings at Garm, Tadzhikistan (about 200 km north of the seismic zone), where frequencies as high as 10 Hz are well recorded. Some of the large events are even heard there. Further north at Toktogul, Kirgizia (about 600 km north of the seismic zone) frequencies as high as 5 Hz are well recorded. Seismograph stations nearly directly above the seismic zone also record strong signals with predominant periods of about 5 Hz [Lukk and Nersesov, 1970]. Higher frequencies may be

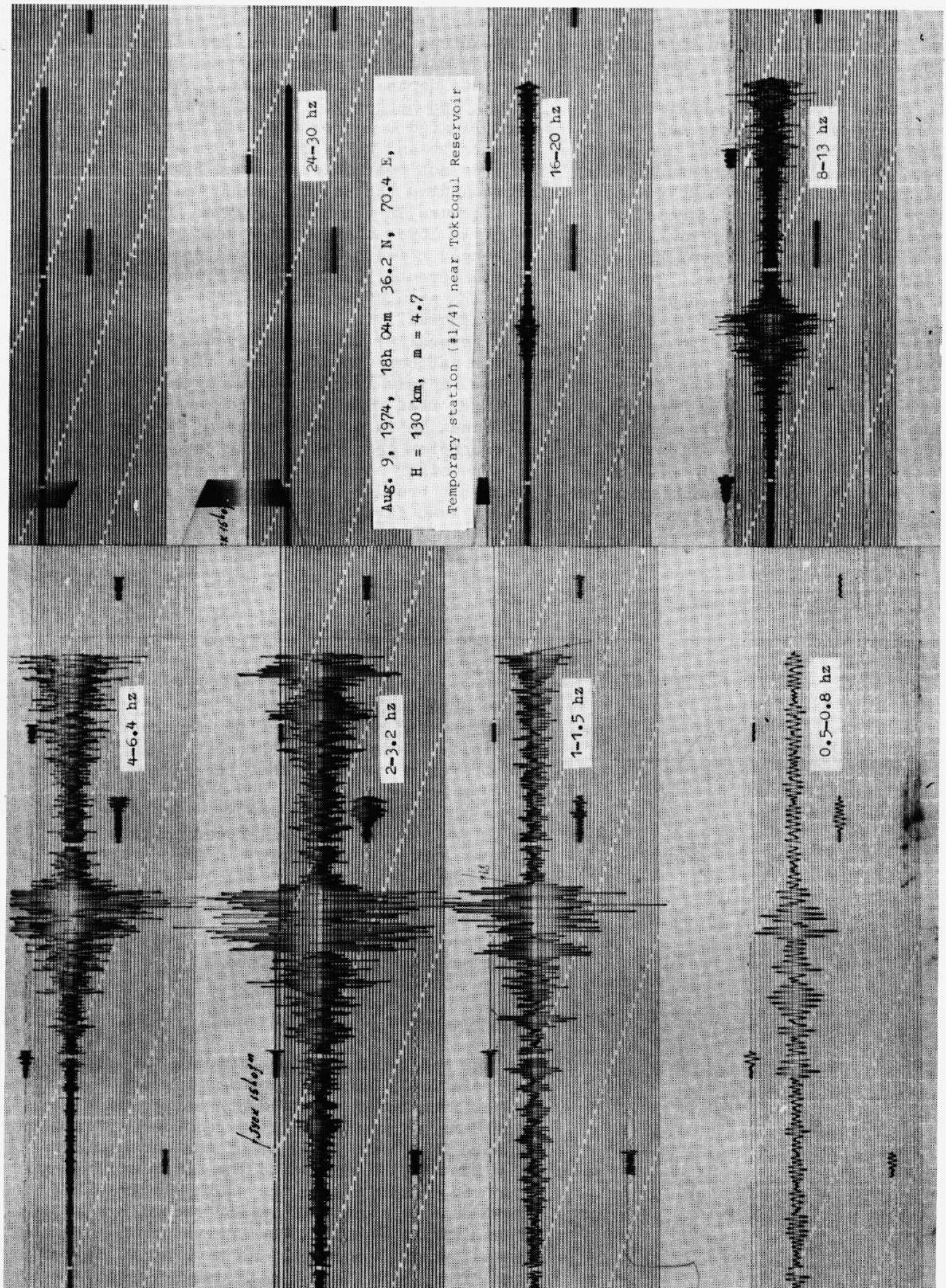

Fig. 6. Seismograms recorded by ChISS at a station near Toktogul for an intermediate depth event in the Pamir-Hindu Kush region.

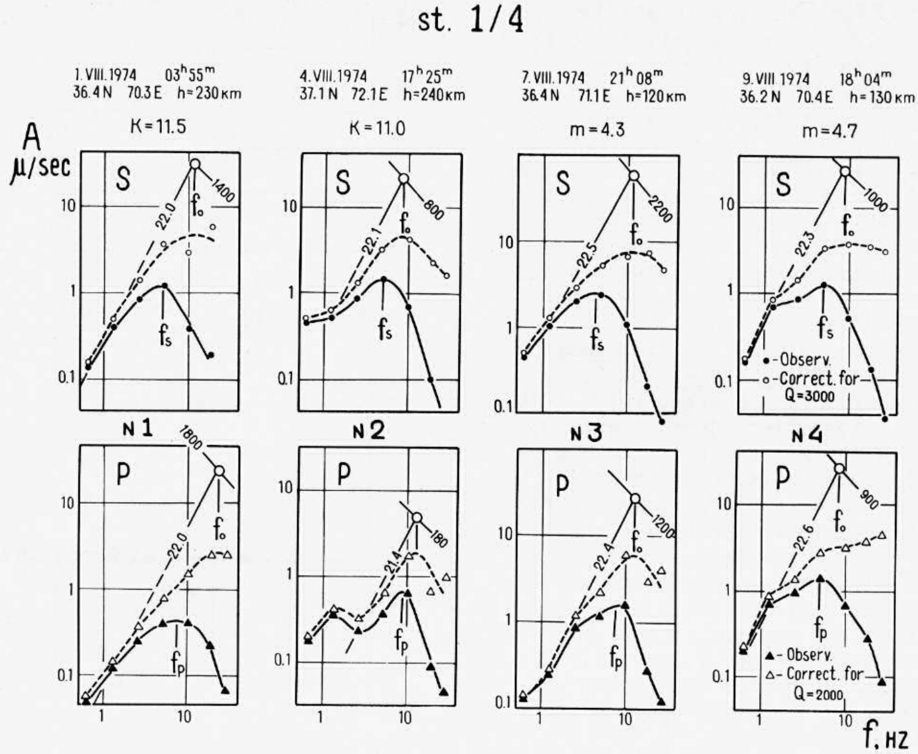

Fig. 7. ChISS spectra for selected events (Table 3, on microfiche) recorded at the station near Toktogul Reservoir. Solid symbols show observed ChISS spectra, and open symbols show ChISS spectra after corrections for attenuation. Sloping lines parallel to low-frequency slope give the logarithm of the calculated seismic moment. Intersecting this line at f_o, the peak frequency, is the line of constant stress drop (in bars) appropriate for the calculated M_o and f_o. For instance, for event N1, both P and S yield a value of $M_o = 10^{22}$ dyn cm, and stress drops are calculated to be 1400 and 1800 bars, respectively.

transmitted to these stations, but they are difficult to recognize on the seismogram. To the south, S_n propagates efficiently with predominant frequencies of 1.5 Hz to stations in India and in Pakistan from intermediate depth events. Again, higher frequencies may be transmitted. Thus in nearly all directions from the intermediate depth events, relatively high frequencies propagate efficiently.

Regardless of the spectrum radiated by the earthquakes, these observations imply relatively high Q ($\gtrsim$1000) for these paths. Thus the lithosphere appears to be continuous at the seismic zone, and a zone of high Q seems to extend into the asthenosphere at the seismic zone. At the same time, regardless of the average value of Q for these paths, the stress drops of the intermediate depth earthquakes seem to be larger than those at shallow depths. Either Q is very high (several thousand) or the calculated stress drops are unusually high (several hundred bars) or both. If the calculated stress drops are less than 1 kbar, Q in the lithosphere must be greater than about 3000.

The precise configuration of the high-Q zone cannot be determined unambiguously. We infer that the high-Q zone is not a narrow tongue that penetrates the asthenosphere, for example,

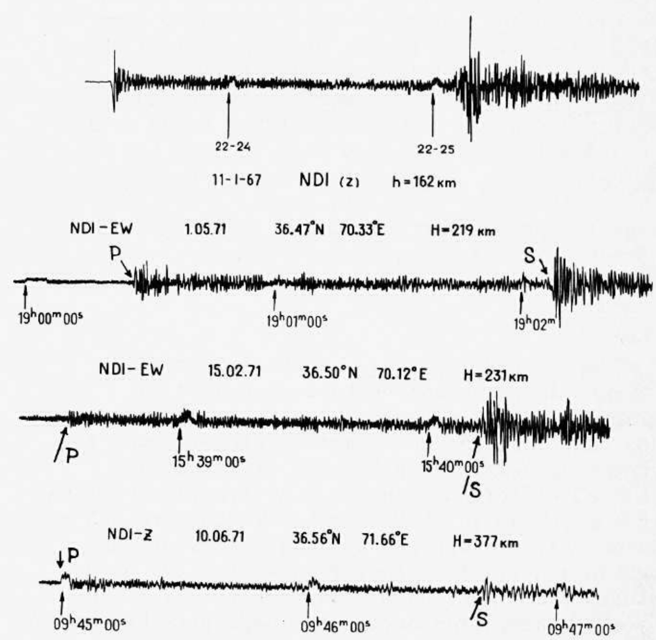

Fig. 8. Short-period seismograms recorded at New Delhi for four intermediate or deep events in the Pamir-Hindu Kush region.

at island arcs, but instead is a relatively broad zone (Figure 12). Perhaps only at depths greater than 250 km is it a narrow tongue. At the same time we tentatively infer that the stress drops of events at depths between about 40 and 180 km are typically somewhat larger than those at greater depths and perhaps 10 times or more larger than those at shallower depths.

The high Q probably indicates lower than usual temperatures. Several authors have suggested that at least part of the Pamir Hindu Kush intermediate depth earthquake zone represents oceanic lithosphere that has underthrust southward [Malamud, 1973; Molnar et al., 1973; Molnar and Tapponnier, 1975; Ulomov, 1973, 1974; Vinnik and Lukk, 1973, 1974]. If correct, since intermediate depth events do not occur along the entire length of the old Tethys Ocean that formerly lay between India and Eurasia, the intermediate depth earthquakes probably occur in oceanic lithosphere either from an isolated part of the Tethys Ocean or from an inner arc basin, perhaps that formed much earlier than the collision between India and Eurasia. A possible explanation for the broad zones of earthquakes and of high Q is that much older (Paleozoic?) thicker lithosphere recently descended into the asthenosphere than presently does so at island arcs.

At the same time, convergence between India and Eurasia seems to be occurring by deformation over a broad zone, and subduction of oceanic lithosphere has presumably stopped in the Pamir-Hindu Kush region. At island arcs, although the down-going slab cools the surrounding asthenosphere, it also drags the surrounding asthenosphere along, maintaining a rather narrow long cold zone. In the Pamir-Hindu Kush region a cold slab may simply be hanging in the asthenosphere and cooling it. By not descending rapidly, perhaps a broader cold region can form in the upper mantle beneath the Pamir-Hindu Kush region than at island arcs.

Fault plane solutions of earthquakes show that the T axis is nearly always vertical and therefore parallel to the seismic zone [Soboleva, 1968a]. The earthquakes would then be a consequence of the gravitational force acting on the weight of the cold slab [Isacks and Molnar, 1971]. Perhaps the larger calculated stress drops for events between 50 and 180 km than for deeper events results from higher stresses in the slab, where a greater load must be supported.

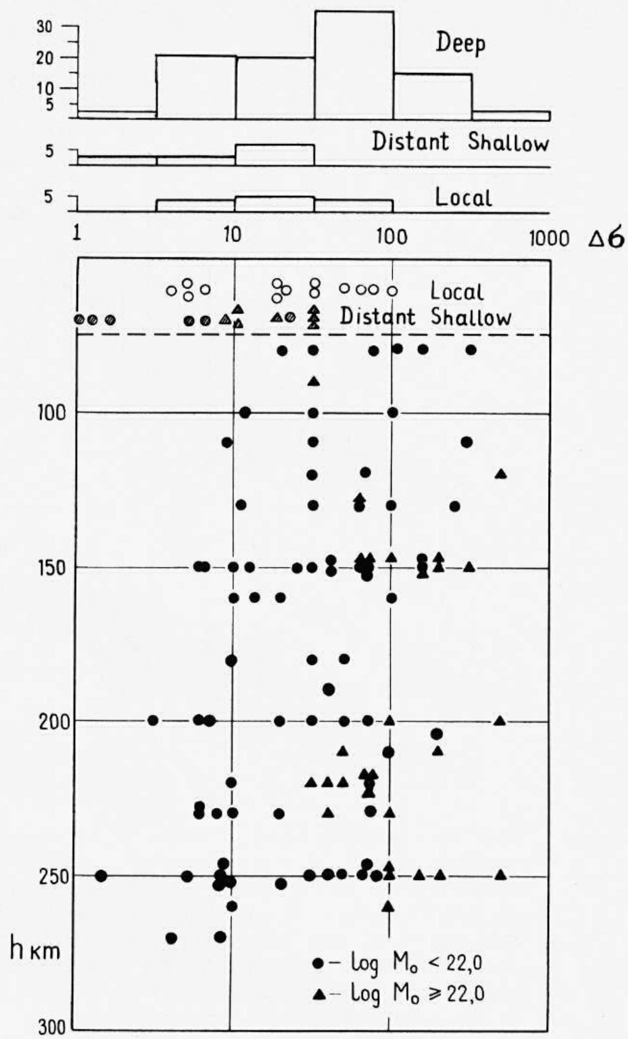

Fig. 9. Calculated stress drops of earthquakes as a function of depth. Each point represents the analysis of the spectrum of either P or S from one earthquake recorded at Garm. Shallow earthquakes (h < 50 km) are not distinguished by depth, but local earthquakes at Garm and distant shallow earthquakes are separated. No correction for attenuation was made.

Note added in proof. ChISS (chastotno-izbinatelnaya seismicheskaya stantsia) is translated as frequency selection seismic station. The output of the seismometer, proportional to ground velocity, is band pass filtered into several different channels. At frequencies less than or equal to 10 Hz the bandwidths are 60% of an octave, and the center frequencies are an octave apart. At higher frequencies the bandwidths are 25% of an octave, and ratios of adjacent center frequencies are separated by a fifth. The ChISS specrum is a plot of the logartithm of the maximum ground velocity recorded on the seismogram as a function of the logarithm of the center frequency (Figure 4). Because of the linear dependence of the bandwidth on the center frequency and because of the flat velocity response, an impulsive ground motion with a flat Fourier displacement spectrum gives a ChISS spectrum that increases with a slope equal to 2; that is, the peak amplitude on the seismogram is proportional to the square of the center frequency. For pulses of finite width the displacement spectrum decreases at high frequencies, and the ChISS spectrum becomes flat and often decreases depending upon the coherency and duration of the signal.

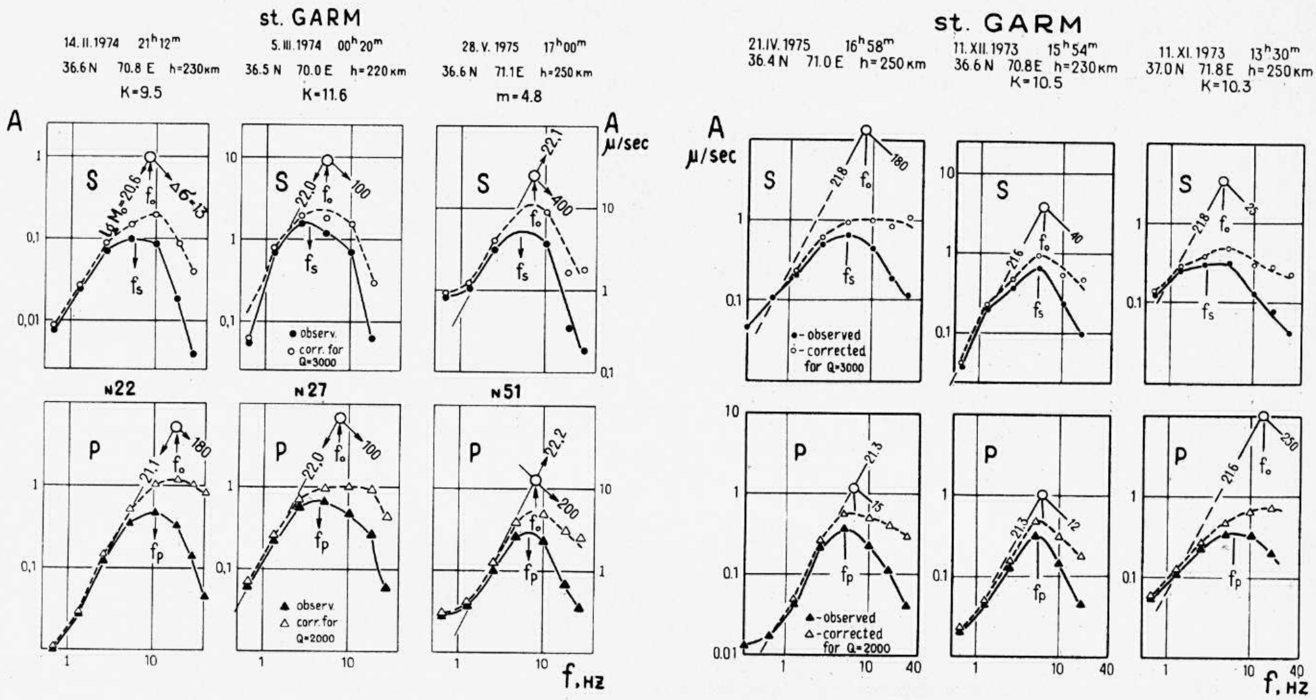

Fig. 10. ChISS spectra, corrected for attenuation, for selected events (Table 1, on microfiche) recorded at Garm. Calculated values of log M_0 and $\Delta\delta$ are shown. Symbols are the same as those in Figure 7.

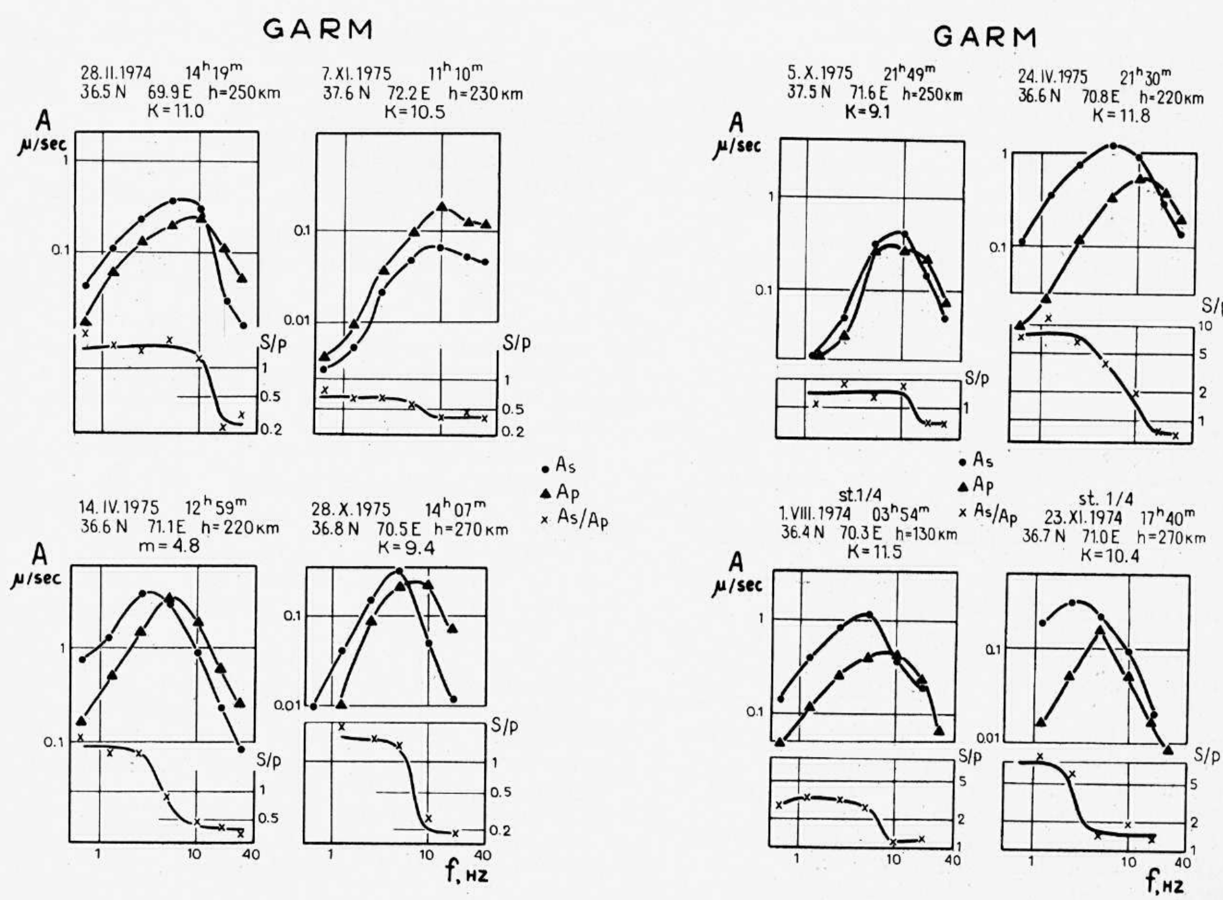

Fig. 11. ChISS spectra of selected events (Table 1, on microfiche) and the ratio of S to P wave spectra.

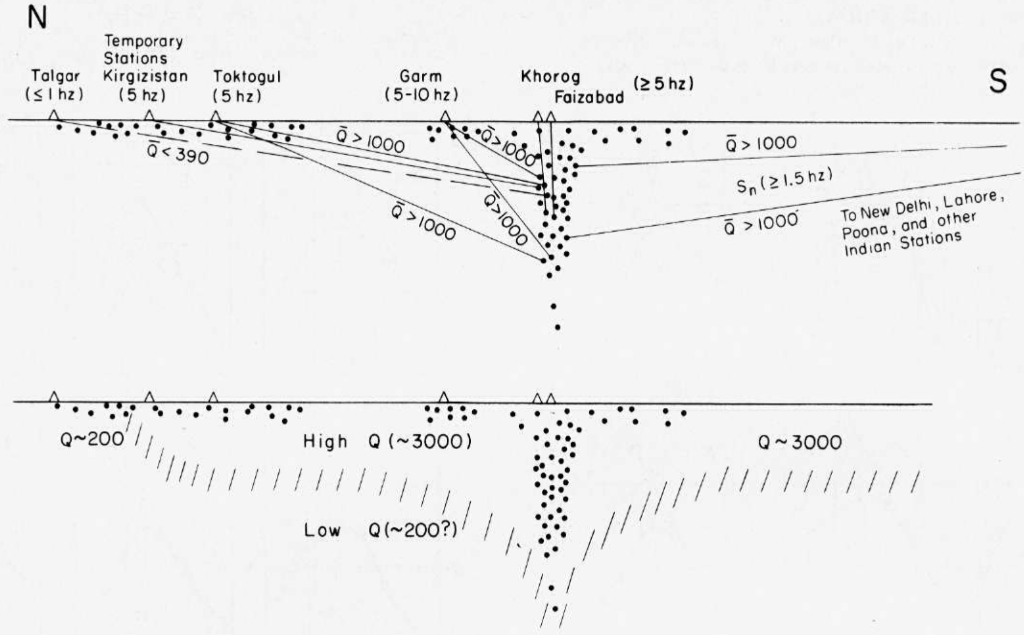

Fig. 12. Cartoons summarizing observations (top) and interpretation (bottom). Dots schematically show seismic areas. Paths to stations are only approximate.

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References

Aki, K., Generation of propagation of G waves from the Niigata earthquake of June 16, 1964, 2, Estimation of earthquake moment, released energy, and stress-strain drop from the G wave spectrum, Bull. Earthquake Res. Inst. Tokyo Univ., 44, 73-88, 1966.

Aki, K., Scaling law of the seismic spectrum, J. Geophys. Res., 72, 1217-1231, 1967.

Ansell, J. H., and E. G. C. Smith, Detailed structure of a mantle seismic zone using the homogeneous station method, Nature, 253, 518-520, 1975.

Barazangi, M., and B. Isacks, Lateral variations of seismic wave attenuation in the upper mantle above the inclined earthquake zone of the Tonga arc: Deep anomaly in the upper mantle, J. Geophys. Res., 76, 8493-8516, 1971.

Barazangi, M., B. Isacks, and J. Oliver, Propagation of seismic waves through and beneath the lithosphere that descends under the Tonga arc, J. Geophys. Res., 77, 952-959, 1972.

Barazangi, M., W. Pennington, and B. Isacks, Global study of seismic wave attenuation in the upper mantle behind island arcs using pP waves, J. Geophys. Res., 80, 1079-1092, 1975.

Brune, J. N., Tectonic stress and the spectra of seismic shear waves from earthquakes, J. Geophys. Res., 75, 4997-5009, 1970.

Dewey, J. W., and S. T. Algermissen, Seismicity of the Middle America arc-trench system near Managua, Nicaragua, Bull. Seismol. Soc. Amer., 64, 1033-1048, 1974.

Engdahl, E. R., Explosion effects and earthquakes in the Amchitka Island region, Science, 173, 1232-1235, 1971.

Engdahl, E. R., Relocation of intermediate depth earthquakes in the central Aleutians by seismic ray tracing, Nature, 245, 23-25, 1973.

Isacks, B. L., and M. Barazangi, High frequency shear waves guided by a continuous lithosphere descending beneath western South America, Geophys. J. Roy. Astron. Soc., 33, 129-140, 1973.

Isacks, B., and P. Molnar, Distribution of stresses in the descending lithosphere from a global survey of focal mechanism solutions of mantle earthquakes, Rev. Geophys. Space Phys., 9, 103-174, 1971.

Isacks, B. L., J. Oliver, and L. R. Sykes, Seismology and the new global tectonics, J. Geophys. Res., 73, 5855-5899, 1968.

Katsumata, M., The effect of seismic zones upon the transmission of seismic waves, Quart. J. Seismol., 25, 89-95, 1960.

Keilis-Borok, V. I., On estimation of the displacement in an earthquake source and of source dimensions, Ann. Geofis., 12, 205-214, 1959.

Khalturin, V. I., T. G. Rautian, V. L. Golubyatnikov, and T. F. Byelikova, The dependence of spectral-temporal characteristics of Hindu Kush earthquakes on the depth of origin, in Problems of Quantitative Estimation of Seismic Risk, pp. 130-136, Nauka Publishing House, Moscow, 1975 (in Russian).

Kinyapina, T. A., The earthquake of 14 November 1937, Collection of papers on seismology, Trans., 12, 111-120, Tadjik Inst. of Anti-seismic Eng. and Seismol., Acad. of Sci., Tadjik SSR Publishing House, Dushanbe, 1964 (in Russian).

Lukk, A. A., Attenuation of seismic waves in the focal zone of deep Pamir-Hindu Kush earthquakes, in Experimental Seismology, pp. 87-97, Nauka Publishing House, Moscow, 1971, (in Russian).

Lukk, A. A., and I. L. Nersesov, The deep Pamir-Hindu Kush earthquakes, in Earthquakes in the USSR in 1966, pp. 118-136, Nauka Publishing House, Moscow, 1970 (in Russian).

Malamud, A. C., Several regularities of the spatial distribution of Pamir-Hindu Kush deep focus earthquakes, Izv. Akad. Nauk. Tadzh. SSR Otd. Fiz. Matematicheskikh Geol. Khim. Nauk, 4, 70-73, 1973 (in Russian).

McKenzie, D. P., Speculations on the consequences and causes of plate motions, Geophys. J. Roy. astron. Soc., 18, 1-32, 1969.

Mitronovas, W., B.L. Isacks, and L. Seeber, Earthquake locations and seismic wave propagation in the upper 250 km of the Tonga island arc, Bull. Seismol. Soc. Amer., 59, 1115-1135, 1969.

Molnar, P., and J. Oliver, Lateral variations of attenuation in the upper mantle and discontinuities in the lithosphere, J. Geophys. Res., 74, 2648-2682, 1969.

Molnar, P., and P. Tapponnier, Cenozoic tectonics of Asia: Effects of a continental collision, Science, 189, 419-426, 1975.

Molnar, P., T. J. Fitch, and F. T. Wu, Fault plane solutions of shallow earthquakes and contemporary tectonics in Asia, Earth Planet. Sci. Lett., 19, 101-112, 1973.

Mooney, H. M., Upper mantle inhomogeneity beneath New Zealand: Seismic evidence, J. Geophys. Res. 75, 285-309, 1970.

Nersesov, I. L., V. F. Pisarenko, T. G. Rautian, N. A. Smirnova, and V. I. Khalturin, An application of methods of pattern recognition for statistical separation of shallow and deep earthquakes from dynamic characteristics of recording, in The Tsunami Problem, pp. 63-74, Nauka Publishing House, Moscow, 1968 (in Russian).

Nowroozi, A. A., Seismic-tectonics of the Persian Plateau, eastern Turkey, Caucasus and Hindu Kush regions, Bull. Seismol. Soc. Amer., 61, 317-341, 1971.

Oliver, J., and B. Isacks, Deep earthquake zones, anomalous structures in the upper mantle, and the lithosphere, J. Geophys. Res., 72, 4259-4275, 1967.

Soboleva, O. V., Special features of the directions of the principal stress axes in the foci of Hindu Kush earthquakes, Izv. Phys. Solid Earth, Acad. Sci. USSR, 1, 71-78, 1968a, (in Russian).

Soboleva, O.V., Influence of radiation asymmetry on the displacement distribution around epicenters of the deep earthquakes, Izv. Phys. Solid Earth, Acad. Sci. USSR, 10, 45-56, 1968b, (in Russian).

Sykes, L. R., B. Isacks, and J. Oliver, Spatial distribution of deep and shallow earthquakes of small magnitudes in the Fiji-Tonga regions, Bull. Seismol. Soc. Amer., 59, 1093-1113, 1969.

Tsujiura, M., Spectra of body waves and their dependence on source depth, 1, Japanese arc, J. Phys. Earth, 20, 251-266, 1972.

Ulomov, V. I., Dynamics of the earth's crust of central Asia and a method of study of its horizontal movement, Inform. Commun. 81, 20 pp. Inst. of Seismol., Akad. of Sci., Uzbek, SSR, 1973, (in Russian).

Ulomov, V. I., Dynamics of the Earth's Crust and Prediction of Earthquakes, pp. 44-106, Fan Publishing House, Tashkent, 1974 (in Russian).

Utsu, T., Regional differences in absorption of seismic waves in the upper mantle as inferred from abnormal distribution of seismic intensities, J. Fac. Sci., Hokkaido Univ., Ser., 7, 2, 359-374, 1966.

Utsu, T., Seismological evidence for anomalous structure of island arcs with special reference to the Japanese regions, Rev. Geophys. Space Phys., 9, 839-890, 1971.

Vinnik, L. P., and A. A. Lukk, Velocity inhomogeneities of the upper mantle of the Central Asia, Dokl. Akad. Nauk SSSR, 213(3), 580-583, 1973, (in Russian).

Vinnik, L. P., and A. A. Lukk, Lateral inhomogeneities in the upper mantle under the Pamir-Hindu Kush, Izv. Acad. Sci. USSR Phys. Solid Earth, 1, 9-22, 1974, (in Russian).

Wyss, M., Stress estimates for South American shallow and deep earthquakes, J. Geophys. Res., 75, 1529-1544, 1970.

Wyss, M., and P. Molnar, Source parameters at intermediate and deep focus earthquakes in the Tonga Arc, Phys. Earth Planet. Interiors, 6, 279-292, 1972.

Wyss, M., T. C. Hanks, and R. C. Liebermann, Comparison of P-wave spectra of underground explosions and earthquakes, J. Geophys. Res., 76, 2716-2729, 1971.

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