SEISMICITY AND FAULT PLANE SOLUTIONS OF INTERMEDIATE DEPTH EARTHQUAKES IN THE PAMIR-HINDU KUSH REGION

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Abstract. Relocations of earthquakes, recorded by a local network of stations in Afghanistan and Tadzhikistan in 1966 and 1967, indicate a narrow seismic zone (width ≈ 30 km) dipping steeply into the mantle to a depth of 300 km beneath the Pamir and Hindu Kush ranges. Very low seismicity was observed at depths less than about 70 km, the approximate depth of the Moho. Clear gaps in activity exist also within the zone of intermediate depth seismicity. One gap, about 50 km wide near 37°N and at depths greater than 100 km, separates a steeply northward dipping zone to the southwest from a steeply southeastward dipping zone to the northeast. This gap probably marks either a tear in the downgoing slab or a gap between two oppositely dipping slabs. Fault plane solutions, determined for events between 1960 and 1967, generally show steeply plunging T axes approximately within the planar seismic zone. They therefore are grossly similar to those at island arcs where no deep earthquakes occur and presumably result from gravitational body forces acting on a relatively dense slab of lithosphere. At the same time there is a very large variation in the fault plane solutions, much larger than is common at island arcs.

Introduction

Although it does not have an island arc structure, the Pamir-Hindu Kush region is the source of very high intermediate depth seismicity. This region is one of the most active sources of earthquakes felt within the USSR, even though most of it lies outside of the USSR, in Afghanistan. Accordingly, Soviet seismologists have devoted considerable attention to its study. An extensive network of stations has been operated in Tadzhikistan for 20 years by the Tadzhik Institute of Seismo-Resistant Construction and Seismology (TISSS) of the Academy of Sciences of the Tadzhik SSR and by the Institute of Physics of the Earth (IPE) of the Academy of Sciences of the USSR (in Moscow). Moreover, in 1966 and 1967 a special network was installed in Afghanistan and along the Soviet-Afghan boundary by the IPE to study the seismicity and structure of this region. The data in

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1966 and 1967 allowed the most precise determinations of hypocenter that were possible at that time [Lukk and Nersesov, 1970]. These hypocenters defined an approximately planar zone that dips steeply into upper mantle and extends in an east-west direction for nearly 700 km. With careful analytical and graphical techniques, but without the aid of high-speed computers, Lukk and Nersesov [1970] simultaneously determined a velocity structure for the crust and upper mantle and located the earthquakes. In the present paper we extend their study and present relocations of these same events using a computer.

The data obtained with this network were also used to infer a high-velocity zone surrounding the seismic zone [Vinnik and Lukk, 1973, 1978; Vinnik et al., 1977; Malamud, 1973, 1974; Chatelain et al., 1977, 1980; Nowroozi, 1971, 1972] suggested a corresponding high Q zone [Khalutin et al., 1977; Molnar et al., 1976]. These studies and others [Billington et al., 1977, Chatelain et al., 1977, 1980; Malamud, 1973; Nowroozi, 1971, 1972] suggested a variety of possible configurations of slabs of oceanic or continental lithosphere that had been subducted in the region.

In addition, the longer-term recording in Tadjikistan has allowed the determination of numerous fault plane solutions of earthquakes with magnitudes ranging from about 4 to 7 [Soboleva, 1968a, b, 1972]. Because of the close proximity of many stations, much smaller events were studied than was ordinarily possible with data from the World-Wide Standardized Seismograph Network (WSSN) alone. Soboleva [1968a] discussed the orientations of the P, T, and B axes and their relationships to the seismic zone, but her interpretation preceded the recognition of plate tectonics and more modern ideas about such relationships [Isacks et al., 1968, 1969; Isacks and Molnar, 1969, 1971]. Moreover, locations of these events which occurred between 1960 and 1967 were sufficiently imprecise to reveal systematic relationships between solution and location, such as those observed by Chatelain et al. [1980]. In the present paper we use either Nowroozi's 1971 relocations of the events or hypocentral determinations given by the International Seismological Center (ISC) to relate the solutions to the seismic zone defined by the well-located earthquakes determined here for smaller events in 1966 and 1967. We then discuss the results in light of the ideas given by Isacks et al. [1968, 1969] and Isacks and Molnar [1969, 1971]. (Nersesov and Lukk take no responsibility for the interpretation given in that discussion.)

Seismicity

Three-component short-period seismograph stations, equipped with Soviet 85D seismometers...
were operated at locations shown in Figure 1 (and at other sites not used in this study). These instruments have a flat frequency response for displacement between about 5 and 30 Hz. Recording speeds were typically 120 mm/min, and signals were usually impulsive. Consequently, P wave arrival times could be determined with uncertainties less than a few tenths of a second, and S waves arrival times could be identified with somewhat larger uncertainties, about 1 s. These times were measured by A. A. Lukk and I. L. Nersesov. When possible, the data were supplemented by published arrival times from stations at Warsak Dam, Pakistan (WRK), and Kabul, Afghanistan (KBL).

We relocated the earthquakes recorded by this network in 1966 and 1967 using the computer program HYP071, written by Lee and Lahr [1975], assuming a modification of the velocity structure determined by Lukk and Nersesov [1970]. A more complete discussion of the velocity structure, of the location procedure, and of the various uncertainties is given in the companion paper [Chatelain et al., 1980]. Much of the analysis given in that study deals with networks with some stations in approximately the same places as Soviet stations were in 1966 and 1967. Therefore the precision of the locations is probably comparable. The Soviet network, however, is concentrated to the north of the seismic zone, and the temporary networks employed by Chatelain et al. [1980] in 1976 and 1977 were largely south of the zone. We found a systematic northward displacement (of about 10 km) of the seismic zone using the Soviet data compared with the data from 1976 and 1977, and we infer that pronounced lateral variation in velocity in the region may be the cause of systematic differences between the locations of events. Nevertheless, the uncertainties in the relative locations of events (their precision) are likely to be approximately the same for either

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Fig. 1. Map of region showing position of stations (solid diamonds) and epicenter of earthquakes at various depths: solid triangles, 50-100 km; open triangles, 100-150 km; inverted triangles, 150-200 km; pluses, 200-250 km; and Y's, 250-300 km.
configuration of stations. For the majority of the events we estimate that uncertainties in the precision of the depths and hypocenters are about 1.0 km and that there could also be systematic errors of the same amount.

All locations with Fms residuals less than 0.7 sec [Chatelain et al., 1980] are plotted in Figure 1 and are listed in Table 1. Maps for separate depth ranges are shown in Figure 2, and cross sections are shown in Figure 3. This arrangement of plots is the same as in Chatelain et al. [1980], and the general features of the seismicity are similar. As noted in other studies, the seismic zone dips steeply (Figure 3) and is oriented approximately east-west (Figures 1 and 2) [Billington et al., 1977; Chatelain et al., 1977; Lukk and Herscov, 1970; Malamud, 1973; Novroco, 1971]. West of approximately 71°E the zone trends east-west, but to the east it trends more nearly north-southwest. As the data from the studies referenced above show, at depths greater than about 150 km, the east-west zone dips steeply to the north, and the northeast-southwest zone dips steeply to the southeast (Figure 3).

Because of the greater number of more precisely determined hypocenters than for the previous studies, there are also some features that were less clearly resolved in most of these earlier studies. At shallower depths (70-150 km), both zones appear to dip at shallower angles than at greater depths (Figure 3), a result also obtained by Billington et al. [1977]. At the same time there is a very low level of seismicity at depths shallower than about 70 km (Figure 3). This is not a consequence of inaccurate locations but reflects much lower seismicity in the crust than in the underlying mantle.

The seismicity is not a continuous planar zone with uniformly distributed seismicity but instead contains pronounced gaps in activity and tight clusters of concentrated activity. One gap, near 37°N, is clear at all depths (Figure 2 and section FF' in Figure 3). This gap, approximately 50 km wide, seems to separate the zones that dip north and southeast (Figures 1 and 3), and it is tempting to suggest that the slab of lithosphere in which the earthquakes presumably occur is discontinuous there. This gap in activity is also clear in the data discussed by Chatelain et al. [1980].

A less well-defined gap in the western part of the zone between depths of about 150 and 180 km separates regions of shallower and deeper activity (profiles BB', CC', and HH' in Figure 3). Although there may not be enough events to convincingly demonstrate its existence here, this gap is particularly clear in the data described by Chatelain et al. [1980]. There is a suggestion also of a narrow gap in activity between 200 and 250 km at about 70.5°E (Figure 2 and profile HH' in Figure 3) which is very clear in the data from 1977 [Chatelain et al., 1980, Figure 5].

Along most of the zone and below about 150-km depth the width of the zone is about 30 km, a result similar to that of Billington et al. [1977] but much narrower than the data from most previous studies suggest [e.g., Lukk and Herscov, 1970; Malamud, 1973; Novroco, 1971]. Given the uncertainties in the locations, the width could be narrower in most regions, except possibly near 71°E, and at depths greater than 200 km. There the zone seems to divide into two separate zones separated by a gap in activity about 30 km wide (Figure 2 and profile DD' in Figure 3). Events in both clusters were located with the same stations, and our estimation of the errors in locations suggests that this separation is real. Nevertheless, with a more favorable station distribution the southern branch is not apparent in the data of Chatelain et al. [1980].

Because most of the gaps and clusters in the

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seismicity in 1966 and 1967 are evident in the data obtained in 1976 and 1977 [Chatelain et al., 1980], we do not consider them to be artifacts of short time periods of recording. At the same time the data are clearly inadequate to show that these features are representative of much longer periods of time. A close correlation of peculiarities in fault plane solutions with hypocentral positions [Chatelain et al., 1980], however, suggests that these clusters and gaps reflect variations in the state of stress and therefore may be representative of the seismicity for longer time periods than considered here.

Fault Plane Solutions

Since most of the data used to determine the fault plane solutions were radiated into the upper hemisphere of the focal sphere, upper hemisphere diagrams for all of the solutions are given in Appendix A. Pertinent parameters are listed in Table 1. To facilitate comparison with data in other studies, however, lower hemispheres given in abbreviated balloon format in Figure 2 for earthquakes at different depths, and back hemispheres are given in Figure 3 in the cross sections. These solutions were determined by Soboleva [1968a,b, 1972, new unpublished data,
mediate and of deep earthquakes are usually very vertical in most cases, a result noted by Soboleva [1968a, 1972] and observed by Billington et al., [1977; Chatelain et al., 1980; Isacks and Molnar, 1971; Novicrozi, 1972]. Among Soboleva’s better constrained solutions, those used here, the T axis is in all but two cases more nearly vertical than the F axis.

Perhaps the most notable feature in Figure 2 is the wide variety of fault plane solutions. This contrasts markedly with island arc structures, where fault planes of intermediate and of deep earthquakes are usually very similar to one another within the arc and in the same depth range [Isacks and Molnar, 1971]. Solutions for events 71, 78, 80, and 82 were obtained both from Soviet recordings, most of which were radiated into the upper hemisphere [Chatelain et al., 1980, Table 1, Appendix A]. In general, the parameters differ by less than 10° and always less than 15°, their approximate uncertainty. This suggests that locally heterogeneous velocity structures do not cause the large observed variation in the solutions and that there is real variation in the orientation of the fault planes.

Variation in fault plane solutions was noted for the larger events (M > 5.5) in the Hindu Kush region, but much of this variation is systematic [Chatelain et al., 1980]. Near 70.6°E most of the F axes trend northeast-southwest, becoming more nearly north-south near 70.8°E and approximately northwest-southeast farther east near 71.0°E (Figure 2). Although many of the solutions presented here fit this general pattern, particularly the larger events, there is still a very large scatter. Although the solutions presented here are not as well constrained as those determined with the WWSSN, the variation in the observed first motions of the P waves requires large differences among the solutions (see Appendix A). We think that the variability within localized regions may not be real but is simply a consequence of large errors in the locations of the events. Chatelain et al. [1980] found very large differences in fault plane solutions of earthquakes only 20-30 km apart. Therefore errors in locations of this amount, which are difficult to eliminate, could introduce an apparently random scatter of solutions, whereas in fact there is a simple regional variation.

The fault plane solutions for the shallower events (70-150 km) include large components of
thrust faulting, therefore with steeply dipping T axes, and with P axes oriented approximately northwest-southeast (Figure 2). The dip of the seismic zone is not well defined in this depth range (Figure 3) but seems to increase with depth. It is possible that for some of these events one of the nodal planes is parallel to the seismic zone (event 53 in AA'; event 77 in DD'; events 38, 41, 43, 44, 58, and 73 in EE'; and event 65 in GG' of Figure 3). In such a case the slip during earthquake might represent displacement along a fault parallel to the seismic zone [Vinnik and Lukk, 1973, 1974; Vinnik et al., 1977]. Such occurrence is unusual for earthquakes at these depths, but perhaps in Asia the plates are thicker than at island arcs [e.g., Vinnik et al., 1977]. These earthquakes would then result from relative plate motion, not internal deformation of the downgoing slab as at island arcs [Isacks and Molnar, 1971].

The approximately horizontal northwest-southeast P axes for these events (Figures 2 and 3) are similar to those of shallow, crustal events further south [Frazov et al., 1980]. At the same time the solutions in Figure 2 are sufficiently different that the slip vectors definitely differ from one another. Therefore only some, if any, of these events between 70 and 150 km could reflect slip of one plate past another. They might reflect more diffuse deformation resulting from northwest-southeast compressive stress due to the India-Eurasia collision.

Alternatively, the nearly vertical T axes for the deeper of these events (near 150-km depth) could indicate internal deformation of the downgoing slab, as is typical of intermediate depth events at island arcs. The uncertainties in the locations of these events and in the configuration of the seismic zone do not allow this to be resolved.

Summary

A study of earthquakes occurring in 1966 and 1967 in the Pamir-Hindu Kush region and recorded by a relatively dense network of local stations reveals several unusual patterns in the seismicity. Seismicity in the crust is very low so that the intermediate depth zone does not continue to the earth's surface along any clear zone. Two possible explanations are either that convergence between India and Eurasia continues, with deformation in the crust occurring aseismically, or that convergence is absorbed farther north (or south), with the intermediate depth earthquakes occurring in a slab of lithosphere hanging in the mantle. These two explanations are not mutually exclusive.

To a first approximation the seismicity is confined to a narrow (width <30 km) planar zone that dips steeply into the mantle. The data suggest a pronounced gap near 37°N that separates a steeply north dipping zone in the west from a steeply southeast dipping zone in the northeast. This gap in activity could represent a discontinuity in the downgoing slab of lithosphere or even a gap between two lithospheric slabs [see Chatelain et al., 1980]. There is a suggestion of a decrease in the dip of the zones at shallower depths (<100 km), but because of the lack of continuity of seismicity to the surface, it is difficult to trace either inferred zone to a place at the earth's surface, where the subduction would have occurred. The dips of the seismic zone suggest a southerly source of the western zone and a northerly source for the eastern zone, an idea expressed by others from the faulting and geologic structure along the northern margin of the Pamir [Khalturin et al., 1977; Malamud, 1973; Molnar et al., 1973; Ulomov, 1974; Vinnik and Lukk, 1973, 1974; Vinnik et al., 1977]. This interpretation is certainly not required by the data, and Billington et al. [1977] give other possible scenarios.

The gap in activity at 37° is not the only gap, and clusters of activity also occur. Since these gaps and clusters are evident in data obtained during short periods of recording 10 years later, we think that they are representative of the seismicity for at least tens of years. Perhaps they have persisted hundreds or thousands of years [Chatelain et al., 1980].

We used fault plane solutions of earthquakes in 1960-1967, determined by Soboleva [1968a, 1972], but assumed the locations given in Novoosi [1971] and ISC. The T axes, in general, plunge at steep angles and lie approximately within the plane of the seismic zone. Thus they conform to the gross pattern for intermediate depth events at island arcs where there are no deep events or where there is a gap in seismicity between intermediate and deep events [Isacks and Molnar, 1969, 1971]. Therefore most of them presumably result from stress in a downgoing (or hanging) slab of lithosphere. The important parameters would be the orientation of the P, T, and B axes, not the nodal planes or slip vectors. The downdipping T axes imply that gravitational body forces tend to pull the slab down [Isacks and Molnar, 1969, 1971].

The only exception to this pattern might be for events at shallower depths (70-150 km), where the seismic zones seem to dip less steeply. Solutions for some but not all of these events show that one plane could be parallel to the seismic zone. If the plane of seismicity marks a fault, then the displacement might represent slip of one plate with respect to another. The data do not require this interpretation, however.

Fault plane solutions of deeper events (180-230 km) also show considerable variability. Although the regional variation in solutions discussed by Chatelain et al. [1980] describes much of the variation in the data presented here, the scatter is still very large. We suspect that the scatter is only apparent and is due to errors in the locations.

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