SEISMO TECTONIC ASPECTS OF THE MARKANUS VALLEY, TAJIKISTAN,
EARTHQUAKE OF AUGUST 11, 1974

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Abstract. The Markansu Valley earthquake of August 11, 1974 (m b = 6.4), occurred in a structurally complex area of the northern Pamir. It was followed by more than 80 teleseismically recorded aftershocks, 13 with m b > 5.0. Fault plane solutions for the three largest aftershocks differ from one another and from the main shock and indicate both thrust and strike slip faulting. Geological mapping and after shock locations suggest that the strike slip faulting occurred on both north and northwest trending faults. The region is one in which large northwest trending strike slip faults converge. To the north and south these faults are very clear topographic features. As they approach the northeastern Pamir, they become less distinct on the Landsat imagery, although they remain recognizable geologic features on the ground. The strike slip faults become less distinct toward their ends perhaps because the north-south motion is taken up progressively by east-west striking thrusts. It is not possible to fit orthogonal nodal planes to all of the observed first motions of the P waves from the main shock. This earthquake is located at the intersection of two inferred fault systems and appears to be a multiple rupture. The disconform P wave first motions are all nodal in character. If faulting occurred on more than one fault plane during the main shock, then the apparent first motions in the nodal directions of the first rupture may be anomalous and actually belong to a rupture later than the first one. We are aware of one other similar occurrence: the 1967 Mudurnu, Turkey, earthquake, for which the few anomalous P wave first motions were also nodal and for which the fault plane solutions of the main shock and the largest aftershock are very different. The concentration of large earthquakes near the intersection of two systems is also observed in Iran. The seismic moment of the main shock of the Markansu Valley sequence is about 5 x 10^26 dyn cm.

Introduction

Recent studies of continental deformation in the Alpine-Himalayan belt show that large-scale horizontal motions often take place on narrow strike slip systems of considerable length such as the north Anatolian fault and Altyg Tagh fault, which may bound relatively aseismic blocks (e.g., McKenzie, 1972; Molnar and Tapponnier, 1975, 1978; Tapponnier and Molnar, 1977, 1979). These large strike slip faults may move in place along their length, sometimes motion changes from pure strike slip to include a compressional or extensional dip slip component. Where deformation occurs primarily by strike slip faulting, it is often confined to narrow zones. However, where crustal extension or compression takes place, such as in western Turkey, northwest Iran, the Pamir, and Yunnan, deformation appears to be spread out over large areas, and motion is not confined to a single narrow fault system. Of particular interest is how one style of continental deformation changes into the other. Complexities are seen where well-defined strike slip systems meet or pass into regions of thrust or normal faulting, such as in Yunnan and Szechwan of China [Tapponnier and Molnar, 1977] and at the eastern end of the north Anatolian fault in Iran and Turkey (McKenzie, 1972). This paper discusses the deformation associated with an earthquake sequence in a structurally complex region in the northern Pamir. This area is one of active thrust faulting toward which the large Altyg Tagh, Karakorum, and Talasso-Fergana strike slip fault systems converge (Figure 1).

Regional Structure

Burtman et al. [1963] and Rashentsev [1963] discuss in some detail the geology and structure of the southern Tien Shan and eastern Pamir. The main structural features are the large northwest trending right lateral strike slip faults which cross the region (Figure 2). To the northwest the Tien Shan-Kun Lun fault (TS-KL) of Burtman et al. [1963] includes the Talasso-Fergana fault [Burtman, 1963], which is particularly active further north and stands out well on Landsat imagery [Tapponnier and Molnar, 1979]. As it enters the area of Figure 2, it becomes less distinct on Landsat imagery and may not be active south of about 41°N. It is possible that its motion is then taken up by other northwest trending strike slip faults further south. The Karakorum fault (Figure 1), a right lateral strike slip fault [Feihe et al., 1964] and a remarkably clear feature on Landsat imagery [Molnar and Tapponnier, 1978] and topographic maps, lies to the southeast of the region in Figure 2. It
seems to continue into the southeast corner of Figure 2 as a group of subparallel faults including the Pamir-Karakorum fault (P-KK) and Kunug fault (KF) of Burtman et al. [1963].

On Landsat imagery, none of these are as obvious as the Karakorum fault itself further south. Since the installation of the World Wide Standard Seismograph Network (WSSN), there have been no earthquakes on either the southern part of the Talasso-Fergana fault or the northern part of the Karakorum fault large enough for a fault plane solution to be determined, although the seismicity of the region is high [e.g., Barasangal and Dorman, 1969]. To the west of the Pamir-Karakorum fault in Figure 2 a number of east-west trending thrust faults dominate the structure of the Pamir. Most of them dip to the south [Burtman et al., 1963; Ruzhentsev, 1963]. In addition, a series of right lateral strike-slip faults branches off to the west of the Pamir-Karakorum fault at angles of 20°-40° (Figure 2). The relationship between the strike slip and thrust faults of the central Pamir was clarified in a detailed investigation in the Murgab region (about 38.5°N, 74°E) by Ruzhentsev [1963]. He noticed that toward the northwest the strikes of the northwest trending strike slip faults became more westerly and that motion changed into thrusting. This change was accompanied by a decrease in displacement on the strike slip faults. Burtman et al. [1963] describe a decrease in displacement toward the southeast along the Tien Shan-Kun Lun fault and toward the northwest along the Pamir-Karakorum fault. It seems that as the strike slip systems approach the southern Tien Shan and Pamir from the northwest and southeast, they can be mapped as geologically continuous, but displacement along them diminishes and is taken up by a number of thrust faults over a wide region. This may explain why they are indistinguishable on Landsat imagery of this region (Figure 3), whereas to the northwest and southeast they are clear [Molnar and Tapponnier, 1978; Tapponnier and Molnar, 1979].

Two prominent faults are observed in Figure 3. A major break of slope in the alluvial fan at 39.22°N, 74.5°E may be a thrust fault dipping northward on the curved continuation of the Kunug fault (Figure 2). About 5 km farther north is another fault (Figures 2 and 3), also marked on the map of Burtman et al. [1963]. Near 38.7°N, 74.2°E the Karakul thrust is visible and dips northward [Burtman et al., 1963]. Further south, short segments of more northerly aligned drainage may perhaps indicate the smaller strike slip faults referred to by Ruzhentsev [1963].

Aftershock Locations

The Markansu Valley earthquake of August 11, 1974 (11.8.74a, $M_b = 6.4$, $M_s = 7.3$), was
Fig. 2. Geological and structural map of the southern Tien Shan and Pamir, modified from Bartman et al. [1963] and Ruzhentsev [1963]. Solid circles indicate the relative locations of the main events in the 1974 sequence (see Figure 4), and the cluster of epicenters could be displaced up to about 25 km. Thrust faults marked with solid sawteeth are from published reports, and those with open sawteeth are inferred from Landsat imagery. The area where the Pamir-Karakorum fault (P-KK) meets the Pamir Thrust (PT) is marked schematically. It is not clear from published work or from Landsat imagery whether the Pamir Thrust is continuous east of the Pamir-Karakorum fault, which is also indistinct in this area. Molnar and Tapponnier [1975] mark a southerly dip for the western part of the Pamir Thrust, whereas a northerly dip is inferred from Figure 3 for the thrust east of the Pamir-Karakorum fault. It is significant that the shock of 14.9.69 has a well-controlled, steeply dipping southerly plane, whereas further west, 11.8.74 has a shallow dipping plane to the south (Figures 4 and 5). The dashed line indicates the area of Figure 3. The Tien Shan-Kun Lun fault (TS-KL) includes the Talasso-Fergana fault of Figure 1. The Pamir-Karakorum and Kungur (KF) faults continue southeast into the Karakorum fault. The Karakul Thrust is marked by KT, Lake Karakul by LX, and Kashgar by K.

Located at 39.34°N, 73.76°E by the International Seismological Center (ISC). It was followed by more than 80 teleseismically recorded aftershocks, 13 of which had magnitudes (Mw) greater than or equal to 5.0. The main shock and three of the aftershocks were large enough for fault-plane solutions to be determined from first motions of P waves recorded by the long-period WWSSN instruments. These solutions differ from one another and show both strike slip and thrust faulting (see below).

The main shock and its aftershocks were relocated using a technique, described in detail by Jackson and Fitch [1979], which locates earthquakes in relation to a master event. Relative locations are not affected by systematic errors in absolute locations that arise from azimuthal heterogeneities in the upper mantle. The Pamir region is known to be heterogeneous, and ray paths are very likely to be perturbed by the deep structure of the nearby Hindu Kush [Khalturin et al., 1977] as well as by other deep structures in the Himalayan belt. The method used pays careful attention to the assumption behind all relative locations: that ray paths between source and receiver are essentially the same for different events. The source area of the 1974 aftershocks is small (Figure 4), and we did not relocate any earthquakes with initial epicenters farther than 70 km from the master event. The technique is very effective in places where teleseismic travel time anomalies are high, as shown by Fitch and Jackson [1979] in the Tonga arc.
Jackson et al.: Markansu Earthquake, August 11, 1974

Fig. 3. Landsat imagery of the area marked in Figure 2. Latitude-longitude crosses marked on the photograph are approximate.

The pattern of relative locations can be positioned in space only when some a priori location for one of the events is known. The Markansu Valley earthquake occurred in a very mountainous and sparsely populated region, and we are not aware of any detailed reports of epicentral damage, surface faulting, or isoseismal mapping that might constrain the location. The main shock (11.8.74a) was a complicated rupture producing complex seismograms (see Figure 6 and Zakharova and Chepiknas [1977]). The event of August 27, 1974 (17.8.74), was chosen as a master because impulsive P wave onsets from it were reported at many stations. Relocations are shown in Figures 4 and 5 and listed in Table 1. We have no a priori information for the location of any of the shocks, so the locations are drawn in Figure 2 assuming the ISC location of 39.52°N, 73.80°E for the master event.

All the earthquakes appear to be shallow, but depths are not well constrained. The ISC reports a depth of 19 km for the master, and no large event was relocated more than 20 km below it. Surface wave analysis shows that depths for three shocks in this area are less than about 15 km [Patton, 1978]. No Pp phases were unambiguously reported, and we are not aware of evidence for subcrustal seismicity in the Markansu Valley region.

Fault Plane Solution of the Main Shock

We were unable to fit two orthogonal nodal planes to the P wave first motions of the main shock. As the radiation patterns of the three main aftershocks and of 11.5.67, which occurred near the main shock, all differ from one another and from the pattern of the main shock (Figures 6 and 7 and Table 2), it is tempting to conclude that slip occurred on more than one plane during the main shock. Before discussing this possibility, let us first discuss in more detail the radiation pattern of the main shock.

Figure 6 shows the lower-hemisphere equal-area projection of the radiation pattern and some key seismograms. Three possible solutions are also shown - one with essentially pure strike slip motion as for 11.5.67 (Figure 7), a second with essentially pure thrust faulting as for the first large aftershock (Figure 7), and a third given by Ni [1978] for the main shock, showing oblique thrusting. The latter solution is crudely what one would expect if two earthquakes with the other two solutions occurred simultaneously. Notice that all three solutions shown in Figure 6 violate some of the first motions. Because the dilatations recorded at stations to the south (in India and Pakistan) are clear, the pure thrust solution can be rejected.

The main difference between the pure strike slip solution and Ni's oblique slip is from stations to the north (in northern Europe, Greenland, and Alaska). The first half cycle is clearly weak for all of them, but at STU, VAL, KGN, GDE, and COL it is clearly compressional (Figure 6). At the closer stations, NUR, KEW, and KBS we have interpreted the first motions as very weak dilatations, followed by very small compressions, suggesting radiation near a nodal plane. In all cases our choices of the first motions were made from the long-period records, as shown in Figure 6. The arrival times of the P waves on the short-period records, however, agreed with the arrival times of the P waves that we picked on the long-period records. If the later, larger signals were chosen for the first motions, they would have arrival times later than the first arrivals on the short-period records.

We also disagree with Ni [1978] on the first motions at QUE and LEM. We think that we can see a very small dilatation preceding the large compression at QUE. We think that the first motion at LEM is dilatational, but we can see where one might pick the half cycle before it as a compression. Our choice of a dilatation is based in part on the arrival time of the P wave determined from the short-period record, but this short-period record is not particularly clear. Even if Ni's interpretation of the recordings were correct, a similar strike slip solution could be found consistent with compressions at these two stations.

We favor the strike slip solution principally because of the first motions of S waves. There are many fewer first motions for S waves than P waves, because we could not reliably pick them at most stations. Those that we did determine, however, agree with the strike slip solution, and those at COL and PMO, in particular, are inconsistent with Ni's oblique slip solution.

As a further check, we analyzed the surface waves at several stations. The results, which are reported in the appendix, show a large scatter and do not provide any additional constraint on the possible fault plane solutions.
Fig. 4. Relocations of major events \( m_b \geq 5.0 \) relative to 27.8.74 (number 51). All except 11.5.67 used more than 100 stations in the relocation (Table 1). Standard errors, checked by Chi squared tests, are less than 5 km in any direction for these events (see Table 1). Station distributions are good for events of this size, and so systematic errors in relative locations should be small. Sequence numbers identify the events in 1974 in Table 1. Earlier events are marked by open circles; 29.8.63 and 14.9.69 were not relocated. Their locations are those given by the ISC, and the fault plane solutions are from Tappornier and Molnar [1979]. New fault plane solutions are shown in Figures 6 and 7, and parameters are listed in Table 2. No P wave solution is available for 24.7.71, and the solution shown is from a linear moment tensor inversion by Patton [1978]. Dashed lines mark trends of aftershocks corresponding to one of the fault planes in the fault plane solution (see text).

Discussion of the Main Shock

The Markansu Valley earthquake was unusual in that it was impossible to fit two orthogonal nodal planes to the P wave first motions. The July 22, 1967, Maduru earthquake in western Turkey is another example [McKenzie, 1972, Figure 26d]. In common with the Markansu Valley shock, it was followed by large aftershocks with different fault plane solutions from the main shock. At Maduru the change in mechanism was from strike slip to normal faulting [McKenzie, 1972]. Thus in both these sequences more than one fault plane was active. The Markansu Valley shock appears to be a multiple rupture, as can be seen on the seismograms in Figure 6 [see also Zakhurov and Chepkunas, 1977]. While this is not uncommon for large crustal earthquakes, ruptures are usually assumed to have occurred on the same fault plane, with substantially the same mechanism as the initial event [e.g., Wyss and Brune, 1967; Fukao, 1972]. For the Markansu Valley event it is possible that the first rupture was closely followed by a second that ruptured a fault with a different trend. This is especially plausible, since the main shock occurred very close to the intersection of two belts of aftershocks, each of which is parallel to one nodal plane of one of the larger events in the sequence (Figure 4). If the two ruptures nucleated very close together in space and time, then P waves radiated to stations close to a node in the radiation pattern of the first might be lost in the noise, and the larger onset of the second event would be picked as the first motion. The discrepant observations radiated to the north.
TABLE 1. Location of Major Earthquakes

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Date</th>
<th>Origin Time, UT</th>
<th>Position</th>
<th>Depth, km</th>
<th>Stn.</th>
<th>Errors, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.8.74</td>
<td>0113:55</td>
<td>39.381°N, 73.806°E</td>
<td>23</td>
<td>6.4</td>
<td>1.9</td>
</tr>
<tr>
<td>2</td>
<td>11.8.74</td>
<td>0512:33</td>
<td>39.397°N, 73.711°E</td>
<td>34</td>
<td>5.4</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>11.8.74</td>
<td>0523:52</td>
<td>39.403°N, 73.750°E</td>
<td>20</td>
<td>5.6</td>
<td>2.4</td>
</tr>
<tr>
<td>4</td>
<td>11.8.74</td>
<td>0702:08</td>
<td>39.453°N, 73.816°E</td>
<td>31</td>
<td>5.1</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>11.8.74</td>
<td>0908:55</td>
<td>39.333°N, 73.859°E</td>
<td>118</td>
<td>5.2</td>
<td>1.9</td>
</tr>
<tr>
<td>6</td>
<td>11.8.74</td>
<td>2005:30</td>
<td>39.178°N, 73.662°E</td>
<td>23</td>
<td>5.8</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>11.8.74</td>
<td>21:21:33</td>
<td>39.192°N, 73.664°E</td>
<td>28</td>
<td>5.9</td>
<td>0.6</td>
</tr>
<tr>
<td>8</td>
<td>27.8.74</td>
<td>1256:03</td>
<td>(39.520°N, 73.820°E)</td>
<td>19</td>
<td>5.8</td>
<td>3.3</td>
</tr>
<tr>
<td>9</td>
<td>27.8.74</td>
<td>1733:58</td>
<td>39.412°N, 73.848°E</td>
<td>17</td>
<td>5.3</td>
<td>0.8</td>
</tr>
<tr>
<td>10</td>
<td>3.9.74</td>
<td>1941:19</td>
<td>39.466°N, 73.709°E</td>
<td>22</td>
<td>5.7</td>
<td>1.2</td>
</tr>
<tr>
<td>11</td>
<td>16.9.74</td>
<td>1645:57</td>
<td>39.538°N, 73.582°E</td>
<td>16</td>
<td>5.0</td>
<td>0.3</td>
</tr>
<tr>
<td>12</td>
<td>11.5.74</td>
<td>1450:37</td>
<td>39.466°N, 73.774°E</td>
<td>8</td>
<td>5.5</td>
<td>1.6</td>
</tr>
<tr>
<td>13</td>
<td>11.4.71</td>
<td>1143:39</td>
<td>39.405°N, 73.208°E</td>
<td>56</td>
<td>5.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Events in Figure 4 relocated in relation to number 51. The sequence number identifies the event in the ISC bulletin.

(Figure 6) are close to nodal planes of each of the three possible solutions shown. This may account for the curious character of the records at NUR, KEV, and KBS, which seem to have double-nodal onsets. It is significant that at Mudurnu the discrepant readings are also nodal [see McKenzie, 1972, Figure 264]. The explanation offered above would be unlikely to apply to discrepant observations far from the nodal planes of the first rupture because the second rupture would presumably be triggered by the arrival of energy from the first and the signal from the first rupture would clearly be recorded before the second. Only near a nodal plane is the arrival from the first rupture likely to be too small to be seen.

From Figure 6 it might appear possible that the closer stations such as NUR, KEV, and KBS recorded the first motion of the initial rupture. Then at the more distant DH and COL the weak nodal signal of the first rupture may have been lost in noise, and instead only a later rupture with a different mechanism was recorded. If this were so and the two ruptures were sufficiently separated in time, the distant stations should show a positive (late) travel-time residual in relation to the closer stations. Figure 7 shows the travel time residuals from the ISC location for the main shock for northern stations in the azimuth range 300°-20°.

Unfortunately, the data scatter, and no particular trend is observed. Both the Markam Valley and Mudurnu earthquakes are too small for the second and subsequent ruptures to be

![Fig. 6. Lower-hemisphere, equal-area projection of first motions and selected seismograms for the main shock 11.8.74a. Fault planes drawn as solid lines represent our preferred solution. The dashed lines are a pure thrusting solution, and the dotted lines the solution of HI [1978]. Seismograms are all from the long-period instruments of the WESN. Upward first motions are compressional and are plotted as solid symbols. Dilatations are open symbols, crosses denote nodal readings, and arrows give first motion of S waves. P and T show positions of the P and T axes of the preferred solution.](image1)

![Fig. 7. New fault plane solutions of other earthquakes. Symbols same as in Figure 6. All were assumed to have occurred in the crust with a focal velocity of 6.5 km/s. Table 2 lists the parameters of the solutions.](image2)
relocated in relation to the first, as done by Wyss and Brune [1967] and Fukao [1972].

An alternative explanation for the discrepant observations is that laterally heterogeneous velocity structures have refracted teleseismic ray paths and therefore the stations are not plotted in Figure 6 in their correct positions on the focal sphere. This effect was inferred for earthquakes at ocean ridges [Solomon and Julian, 1974; Thatcher and Brune, 1971], and the upper mantle structure under the Pamir and western Tien Shan is thought to be anomalous [e.g., Khalturin et al., 1977].

Faulting in the Source Region

The fault plane solutions from five earthquakes in the source region show three types of faulting. The preferred solutions for the main shock and for 11.5.67 show strike slip faulting on northwest-southeast or northeast-southwest planes. The trend of aftershocks (Figure 4) suggests a northwest-southeast fault plane, therefore with right lateral motion parallel to the Pamir-Karakoram Fault [Burtman et al., 1963]. If the ISC location for the master event (27.8.74), by which the pattern in Figures 2 and 4 is positioned, was in error by 25 km, the northwest trend of aftershocks could lie on the extension of this fault. A systematic error of 25 km in the ISC location is possible.

The two largest aftershocks (8.11.74b and 8.11.74e) show thrust faulting, but in both, the strike slip component is not well resolved. The shallow dipping planes of Figures 4 and 7 are essentially those given by Patton [1975]. We inverted Rayleigh wave spectra to obtain moment tensors for these events, and the corresponding fault plane solutions agree remarkably well with the P wave first motions. It is possible, however, that a small component of strike slip motion is also present. Ni [1975] shows fault plane solutions for these aftershocks, among which 11.8.74b is in general agreement with ours. We disagree about 11.8.74e, which he regards as a normal fault. This is principally because he read the onsets at some southeastern stations (e.g., BAO and LDM) as dilatational and so they appear to be compressional. Three other thrust solutions of earthquakes from this general area are also known (Figure 4). The three westernmost solutions of Figure 4 all show a shallow

southward dipping nodal plane consistent with southward underthrusting at the northern margin of the Pamir (Figure 4).

The fault plane solution for the master event (26.8.74) shows predominantly strike slip faulting on either north-south or east-west planes and is clearly different from those of the main shock (11.8.74a) and 11.5.67. A northerly trend of aftershocks (Figure 4) suggests a north-south fault plane, therefore with left lateral motion.

The two thrusting aftershocks are on an extension of the northwest-southeast strike slip trend, a phenomenon observed for many continental earthquakes, e.g., Dasht-e-Bayaz, Iran [Jackson and Fitch, 1979]. Such intersections of fault trends appear to be areas of intense aftershock activity and stress concentration (Figure 5). Figure 5 shows that the smaller aftershocks do not closely follow the trends delineated by the larger shocks. This is not necessarily because they are mislocated but seems to be a general phenomenon where faulting is not confined to a single strike slip system. Jackson and Fitch [1979] mention this effect at Gediz, Turkey, and it has also been observed by local networks [e.g., Whitcomb et al., 1973]. The smaller aftershocks may represent internal deformation in blocks whose overall motion is controlled by larger faults.

Fig. 8. ISC residuals (in seconds) from the main shock versus epicentral distance for stations in the azimuth range 320°-20°. Solid circles are those whose arrivals were reported as impulsive. Open circles were emergent or of unspecified quality.
Conclusions

The region affected by the August 11, 1974, event and its aftershocks is small. Thirteen shocks with $M_b > 5.0$ were concentrated in an area about 30 km in diameter. The inferred faulting during the 1974 Markansu Valley sequence is similar to that described by Burtman et al. [1963] and Ruzhentsev [1963] for the northeast Pamir. In particular, right lateral strike slip faulting on northwest striking planes is intimately associated with thrusting on east-west planes. Although we are not aware of persuasive evidence for northsouth faulting, as is inferred for one trend of aftershocks, Mi [1978] interprets a north-northeast structure through the center of Lake Karakul (LK in Figure 2) as an active fault (Figure 3).

In contrast to most regions, thrust faults are more clearly seen on land-based imagery of the Pamir-Tien Shan region than are the strike slip faults. An explanation of this effect may be that at the ends of the strike-slip faults, displacement decreases and is taken up on not one but several thrusts [Ruzhentsev, 1963]. This may cause the strike slip fault to become a less distinct topographic feature toward its ends.

The main shock occurred at the intersection of the two trends of aftershocks, and more than one type of faulting was active during the sequence. Motion on two or more fault planes during the main shock may have contributed to the complexity of its seismograms and made it impossible to fit orthogonal planes to the mixed P wave first motion. Such a situation is rare but was noticed for an earthquake at Madura, Turkey [McKenzie, 1972]. There too the fault plane solutions of the principal aftershocks differed from those of the main shock, and the discrepant first motions were nodal in character. The seismic moment of 11.874a is about 5 x 10^26 dyn cm (see the Appendix).

Appendix

Here we report the analysis of surface waves from the main shock. This analysis was frustrating because R1 and G1 were usually too large to be analyzed. Only at stations with very low magnifications and apparently near nodes in the radiation patterns were R1 and G1 small enough to be digitized. At the same time, G2 and G3 were clear at a few stations with high magnifications and, apparently, in most cases, near maxima in the assumed radiation patterns. Our policy was to analyze all Rayleigh waves (R1) that were not too large and any G wave that could be seen on the seismograms. Thus the data analyzed are a mixture of Love and Rayleigh waves with varying path lengths (Table A1). We Fourier-transformed the surface wave signal and estimated the spectral density at 100 s (and in a few cases, 150 and 200 s). For this estimate we used the mean of the spectral density between 80 and 120 s (or between 130 and 170 s or 180 and 220 s). From Ben-Menahem et al. [1970] the amplitude spectral density $|\tilde{u}(T)|$ at a particular period $T$ can be written as

$$|\tilde{u}(T)| = \frac{M_o}{\mu} \frac{T}{2\pi} F(A)$$

where $M_o$ is the seismic moment, $\mu$ is the shear modulus, and

$$F(A) = \frac{1}{a} (\sin \frac{A}{a})^{1/2} \exp(\gamma(T)^{1/2})$$

where $A$ is the epicentral distance in kilometers, $a$ is the radius of the earth, and $\gamma(T)$ is a measure of attenuation. Ben-Menahem et al. [1970] tabulate $F(A)$, and we used their values. $G(f.p.s., h, Az.)$ depends upon the parameters describing the fault plane solution (f.p.s.), the azimuth to the station (Az.), and the focal depth ($h$). It can be written for Rayleigh waves as

$$G = [(cR_T^2 + sR_R^2)^2 + (qR_Q^2)^2]^{1/2}$$

or for Love waves as

$$G = [(cL_L^2 + sL_R^2)^2 + (qL_Q^2)^2]^{1/2}$$

where lowercase letters contain information about the fault plane solution and azimuth and uppercase letters contain information about the depth of focus and earth structure. They are defined and tabulated by Ben-Menahem et al. [1970]. We used their tabulated values for a depth of 15 km in a continental earth structure.

For each of the three possible fault plane solutions we calculated $M_o$ (Table A1) from

$$M_o = \frac{2\mu |\tilde{u}(T)| F(A) G}{T}$$

We assumed that $\mu = 3.3 \times 10^{11}$ dyn/cm². If the data were free of error and one of the assumed fault plane solutions were correct, then in principle, the calculated values of $M_o$ would be the same for each station. In fact, for each assumed fault plane solution the calculated values scatter a great deal and do not support any of the solutions. Figure A1 shows the range of scatter. Part of the scatter is probably due to the proximity of some stations (e.g., TRN or ALQ) to nodes in one or more of the radiation patterns. Therefore slight errors in azimuth cause large errors in calculated spectral densities and moments. The data are probably of mixed quality also. The estimates of $|\tilde{u}(T)|$ are surely better for the recordings of G2 and G3 than for R1 and G1. However, because of the longer paths the values of $F(A)$ and their uncertainties are larger for G2 and G3. Because of the scatter, the surface waves do not help much to discriminate among the possible fault plane solutions.

Table A1 lists the calculated values of $M_o$ for each station and for each of the three possible fault plane solutions in Figure 6. Although the scatter in values is large, the averages for each solution are comparable. Ignoring the high value from TRN for the strike slip solution, the geometrical average of 18 estimates is $4.3 \times 10^{26}$ dyn cm. The very small value of $G(f.p.s., h, Az.)$ for TRN makes the uncertainty in $M_o$ determined from it so large that it is excluded from the average. For
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<th>U(Δ), cm s</th>
<th>F(Δ)</th>
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<th>U19, cm x10^(-26)</th>
<th>Mo**</th>
<th>U10, cm x10^(-26)</th>
<th>U19, cm x10^(-26)</th>
<th>Mo***</th>
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*All R1 from vertical components, ALQ-EX (back azimuth, 0°), ATU-NS (back azimuth, 232°), KON-WS (back azimuth, 27°), NUR-NS (back azimuth, 102°), SPA-NS (back azimuth, 129°), and STU-NS (back azimuth, 76°).

*Pure strike slip faulting. Strike = 129°, dip = 90°, slip = 180°.

**Pure thrust faulting. Strike = 77°, dip = 22°, slip = 90°.

Fig. A1. Moments for the main shock calculated from Love and Rayleigh waves at different stations, assuming different focal mechanisms (see Table A1). The scatter does not support any particular solution. This may simply indicate that rupture occurred on more than one fault plane during this earthquake.

the pure thrust solution the geometrical average of 19 estimates is $6.2 \times 10^{26}$ dyne cm, and for $M_0$'s [1978] oblique slip solution it is $5.2 \times 10^{26}$ dyne cm. Zakharcova and Chepukauskas [1977] estimate the moment to be $1.3 \times 10^{26}$ dyne cm, from recordings made at Obninsk, USSR. Let us assume that $M_0 = 5 \times 10^{26}$ dyne cm. For a fault length $l = 30$ km and width $w = 20$ km and with $\mu = 3.3 \times 10^{11}$ dynes/cm$^2$, the average slip would be $\delta = 2.5$ m. The stress drop given by Kneepkens [1978],

$$\delta = \frac{1}{2} \frac{\mu}{\delta}$$

would be 21 bars. Given the uncertainty in $\delta$, alone, this estimate is uncertain by at least a factor of 4.

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