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A PRELIMINARY STUDY OF FOCAL MECHANISMS OF SMALL EARTHQUAKES IN THE CENTRAL NEVADA REGION

by

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FOREWORD

Throughout this paper, terms such as "focal mechanism," "auxiliary plane," "fault plane," and "first arrival" will be found. Although these terms will not be confusing to the seismologist, the vocabulary of seismology may be new to others, and it is for this reason that the following remarks are made. For a more complete discussion, the reader is referred to the Appendix.

In the area surrounding an earthquake epicenter, the ground is often observed to move in a particular fashion under the first impulse of the disturbance. Detailed observations of these "first motions" have come to be the principal means by which the processes at the focus of an earthquake, or "focal mechanisms" are investigated. The initial disruption at the heart of an earthquake sends seismic waves propagating into the space around it that are characteristic of the nature of the disturbance. An underground explosion, for instance, would result in compressions being radiated into all the space around it, and an observer at the surface would feel the ground move upward under his feet. If the cavity produced by the explosion were later to collapse, the same observer would feel the ground move downward. In these two cases, the sense of first motion would be the same, no matter where in the immediate area of the explosion the observer was standing.

Earthquakes, on the other hand, are often observed to produce compressions in some areas around the epicenter, and downward motion, or dilatations, in others. In many cases, compressions and dilatations are found to occupy alternate quadrants of the surface, and it is this observation on which much of modern focal mechanism theory is based.

An early (and still widely held) belief was that earthquakes are the result of breakage and abrupt movement on a fault. One can easily visualize how dilatations might be observed on the downdropped side of a fault, and compressions on the uplifted side. If relative movement between the fault faces is entirely horizontal, then it can be reasoned that a quadrant distribution of motion alternately toward and away from the epicenter would be observed, and that dilatations could be separated from the compressions by two nodal planes -- the plane of the fault and an "auxiliary plane" at right angles to it, and passing through the focus of the earthquake.

In the actual case, these nodal planes may have any orientation. For some earthquakes, a simple plane does not suffice to separate the regions of different first motion, and it is further possible (particularly in volcanic areas) to observe earthquakes which result in motion of only one type.

In the study of focal mechanisms, therefore, it is the task of the seismologist to compile "readings" of an earthquake, to find if any discernable pattern exists in the distribution of compressions and dilatations, and from this, deduce the mechanism that produced the earthquake.

Abstract

Preliminary data are given for a group of nearly 400 small earthquakes that occurred on a short section of the Fairview Fault in Central Nevada during the summer of 1966. These earthquakes occurred at a rate of about 11 per day, although there was some fluctuation in the daily rate of occurrence and the earthquakes do not appear to have occurred randomly in time. Most of the activity appears to have been concentrated along a short section of the fault near the southern end, and, although the relative density over the active zone is about the same when the entire recording period is considered, there was a tendency for earthquakes to occur in only limited volumes of the zone for periods of a day to several days. Observations of first motion patterns are not enough to confirm a consistent, repeating mechanism, although similar appearing earthquakes were found to recur in the same general areas repeatedly throughout the recording period. Most often, first arrivals suggested that normal and right-lateral movement was occurring on the Fairview Fault, except at the southern end, where it appears that reverse faulting is occurring. The possibility of a scissors fault in this area is suggested.

INTRODUCTION

In recent years, the state of Nevada has come to be a region of interest to an increasing body of seismologists. The central part of the state, where observations of many earthquakes during each recording day can be obtained, provides as rich a collecting ground for seismic data as can be found in the conterminous United States. However, the remoteness of most of the better recording sites is such that increased emphasis need be placed on the development of portable seismic recording gear. The staff of the University of Nevada Seismological Laboratory is one of the groups currently engaged in the design and construction of such equipment. At the date of this writing, four back-portable seismic event recorders are in the final stages of completion (D. P. Hunt, oral comm.) and should see service during the spring of 1967.

The purpose of this investigation is to provide a preliminary study of the seismic activity in the region of interest, in order to further direct the usage of the portable gear. Data for the study were obtained from a six-component seismic array operated in an active earthquake zone in Central Nevada during May, June, and July, 1966.

One of the primary areas of research toward which the use of the new portable recording gear will be directed is an investigation into earthquake focal mechanisms in this region. It is desirable, in a study of this sort, to have recordings from many stations in the epicentral area. Owing to the limited number of recording units that will be available, it will be necessary to move them periodically, in order to obtain records from a large number of locations within the zone of interest. A primary aim of this paper is to determine whether or not the mechanism producing earthquakes remains similar enough over a period of days or weeks to justify using observations from different earthquakes obtained from various recording sites, and treating these observations as if they were all obtained from a single event.

I METHOD OF INVESTIGATION

Description of Equipment

To obtain data for this investigation, recordings of nearly 400 small earthquakes were made in Central Nevada during the summer of 1966. The system used to record and play back these events was assembled by the staff of the University of Nevada Seismographic Laboratory during late 1965 and early 1966.

The field seismic unit is mounted on a ½ ton trailer, constructed to accomodate the various components. A rear compartment is designed to hold eight twelve-volt batteries and the power distribution unit. The trailer is so designed that re-charging may be accomplished without opening the compartment or removing the batteries. The rear compartment also contains storage space for 10 reels of field wire, 500 meters each, and a reel carrier to aid in laying out and picking up the wire. When the unit is moved, four Electro-Tech EV-17 amd two EV-17-H seismometers are also carried here.

The recording equipment is mounted in a larger, forward compartment. To aid in temperature stabilization, the various electronic components are enclosed in a large, insulated stainless steel box, which is permanently mounted in this forward compartment. In an experiment during the winter of 1965-66, total outside temperature fluctuation during one 15 hour period (overnight) was 42 degrees, while fluctuation inside the box was 27 degrees for the same period. The box is divided into two compartments; one compartment contains a Geotechnical Corporation seven channel tape recorder, Model 17373, and the other houses six Model 1755 seismic signal amplifiers, designed and built to specification by the California Electronic Manufacturing Company. The amplifiers share this second compartment with a Develco Model 3202A time signal receiver, which receives a time signal broadcast continuously from Radio Station WWVB in Fort Collins, Colorado. The six amplified seismic signals and the time signal are recorded simultaneously on the tape recorder.

Signals from outlying seismometers are fed into the amplifiers through a monitor panel on the front of the trailer, which contains a meter for monitoring the seismic signal at the amplifier outputs, and reproduced from the tape.

Total power consumption for the system is about one ampere. Once set up, the field seismic unit is capable of ten days' continuous, unattended operation.

The playback system for the magnetic tapes is located at the seismographic laboratory in Reno. An Ampex seven channel tape recorder/reproducer, Model SP-300, is used to play back the tapes obtained in the field, and the signals from the various channels are fed through a variable resistance gain-control panel into a Honeywell Model 906 Visicorder, on which permanent records are obtained. The visicorder is equipped with the option of several different paper speeds. Since relatively fast paper speeds are desirable in interpreting the seismograms, it would be impractical to play out the entire tape on a visible record. To date, the most satisfactory method of obtaining paper recordings of events has been to play back the tape at 80 times recording speed while observing the light spots from the Visicorder galvanometers. Seismic events are easily seen as "blips", even at this high playback speed. A technique presently being investigated is that of listening to the signal from one of the channels as it is being played back. The frequency at the high playback speed is within the audio range, and it appears that this method may prove more reliable in detecting small events than watching the light spots. After an earthquake is found, the tape is then rewound to a point just before the event, and played out at a slower speed as a visible recording. Most earthquakes are initially run off at a time scale of 1 second to $\frac{1}{2}$ inch on the record (Plate 1). Events selected for special analysis can be replayed at 1 second to $2\frac{1}{2}$ inches of record.

In the process of observing the light spots produced by the galvanometers, one soon learns to distinguish between seismic events, wind or traffic noise, and sonic booms, which are quite common at the recording site.

The Recording Site

All records used in this analysis were obtained from a recording site at Slate Mountain, just south of Fairview Peak in West-Central Nevada (Fig. 1). This area is the site of extensive fault breakage which occurred during the

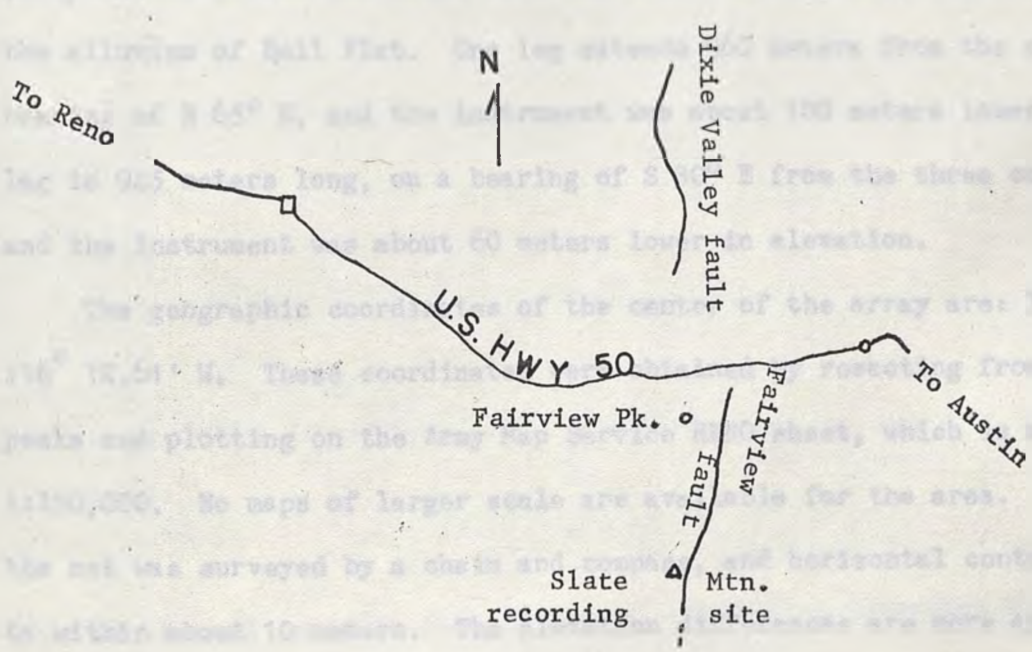


Figure 1 . Location sketch of recording site

Fairview Peak-Dixie Valley earthquakes of December 16, 1954, (Slemmons, 1957, p. 360; Larson, 1957, p. 377) and is near the southern end of the visible scarp. A preliminary study (Oliver et al., 1966) indicated that small earthquakes in this area occur at an exceptionally high rate, and, in personal communication, Roger Greensfelder of the U.S. Geological Survey suggested Slate Mountain because it was central to a seismographic net being operated in Nevada by that agency.

The instruments in the array were arranged in the form of a three-legged star, with vertical seismometers at the end of each leg (Fig. 2). A three-component set of seismometers (vertical, east-west, north-south) was situated at the recording unit, 100 meters west of the 1954 surface breakage of the Fairview fault. One leg extended westward, toward the mountain, and the instrument was located 680 meters distant, in an abandoned mine tunnel which is 200 meters higher in elevation than the recording unit. This leg is at a bearing of N 75° W from the three-component set. The other two legs of the array extend across the fault from the center of the net, and are located on the alluvium of Bell Flat. One leg extends 960 meters from the center, at a bearing of N 65° E, and the instrument was about 100 meters lower. The other leg is 945 meters long, on a bearing of S 30° E from the three component set, and the instrument was about 60 meters lower in elevation.

The geographic coordinates of the center of the array are: 39° 06.67' N., 118° 12.61' W. These coordinates were obtained by resecting from surrounding peaks and plotting on the Army Map Service RENO sheet, which is at a scale of 1:250,000. No maps of larger scale are available for the area. Internally, the net was surveyed by a chain and compass, and horizontal control is accurate to within about 10 meters. The elevation differences are more approximate. However, since arrival times on the records are to be read, at best, to the

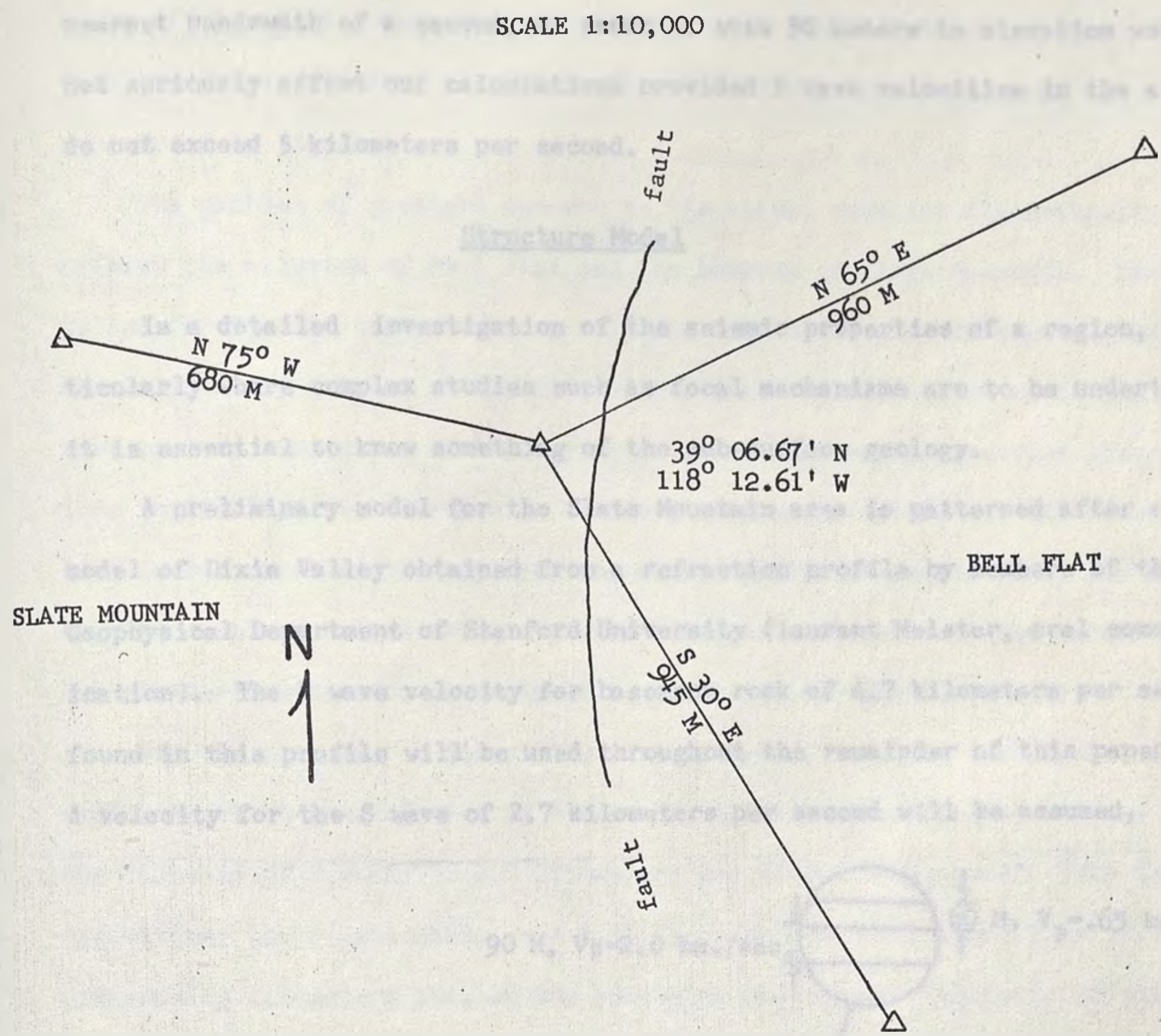


Figure 2. Map of array at Slate Mountain - Bell Flat recording site

nearest hundredth of a second, an error of even 50 meters in elevation would not seriously affect our calculations provided P wave velocities in the area do not exceed 5 kilometers per second.

Structure Model

In a detailed investigation of the seismic properties of a region, particularly where complex studies such as focal mechanisms are to be undertaken, it is essential to know something of the sub-surface geology.

A preliminary model for the Slate Mountain area is patterned after a model of Dixie Valley obtained from a refraction profile by members of the Geophysical Department of Stanford University (Laurent Meister, oral communication). The P wave velocity for basement rock of 4.7 kilometers per second found in this profile will be used throughout the remainder of this paper. A velocity for the S wave of 2.7 kilometers per second will be assumed,

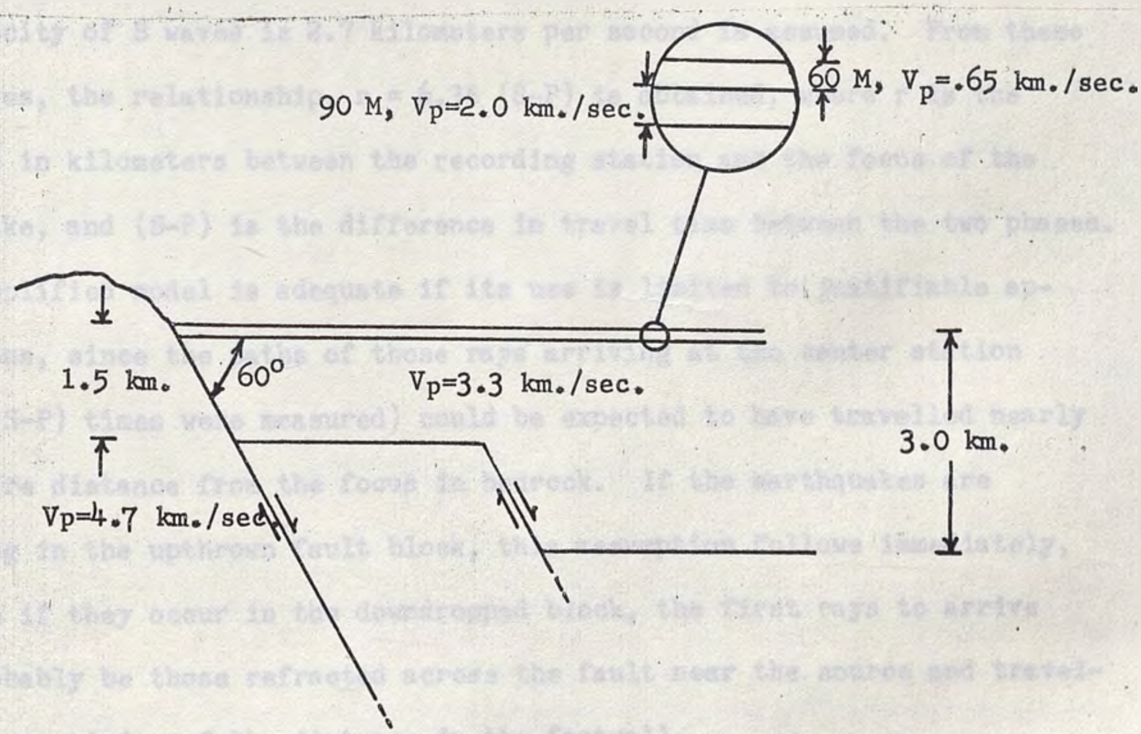


Figure 3. Preliminary structure model

being of the right order of magnitude for rocks with a Poisson's ratio of 0.25 and P wave velocity as above. The preliminary structure model is reproduced in Figure 3 .

The problem of greatest concern is the abrupt velocity discontinuity between the alluvium of Bell Flat and the bedrock of Slate Mountain. Station delays for the two instruments on alluvium must be found with some degree of accuracy in any attempt at hypocenter location, and refraction at the interface must be considered if the rays are travelling in any direction other than vertically. An increase in velocity with depth within the alluvium will lead to curvature of the ray, and the relationship between velocity and depth must be resolved before more complex studies are undertaken. The nature of the shattered zone around the fault is still another unknown factor.

For the purposes of the preliminary analysis, however, a homogeneous medium in which the velocity of P waves is 4.7 kilometers per second and the velocity of S waves is 2.7 kilometers per second is assumed. From these velocities, the relationship, $r = 6.35$ (S-P) is obtained, where r is the distance in kilometers between the recording station and the focus of the earthquake, and (S-P) is the difference in travel time between the two phases. This simplified model is adequate if its use is limited to justifiable applications, since the paths of those rays arriving at the center station (where (S-P) times were measured) could be expected to have travelled nearly the entire distance from the focus in bedrock. If the earthquakes are occurring in the upthrown fault block, this assumption follows immediately, but even if they occur in the downdropped block, the first rays to arrive will probably be those refracted across the fault near the source and travelling the remainder of the distance in the footwall.

Inspection of the seismograms obtained reveals that, in practically every case, the first instrument in the net to record the P wave was the vertical seismometer at the center of the net. That arrivals at the two instruments on alluvium were later, even though they may have been closer to the foci, must be attributed to lower seismic velocities in alluvium. This tends to confirm that rays arriving at the three-component set must have travelled in bedrock. The fact that velocities probably increase with depth in the alluvium does not alter the above argument. If the assumed velocities of P and S are in error, only the dimensions of the problem are altered.

II FINDINGS

Discussion of Data Obtained

The field seismic unit was operated at Slate Mountain during the time periods of 15-18 May, 26 May-3 June, and 26 June-12 July, 1966. Over this time, 342 local seismic events were recorded, and others of very small magnitude probably escaped detection in the playback process. Utilizing the travel time versus distance relationship of the last section, it is seen that all these events must have occurred within 25 kilometers of the net, since all (S-P) times were 4 seconds or less. Of the 342 earthquakes, 309 had S-P times of 2.5 seconds or less and were therefore within about 16 kilometers of the recording site. Numbers of earthquakes grouped according to (S-P) time

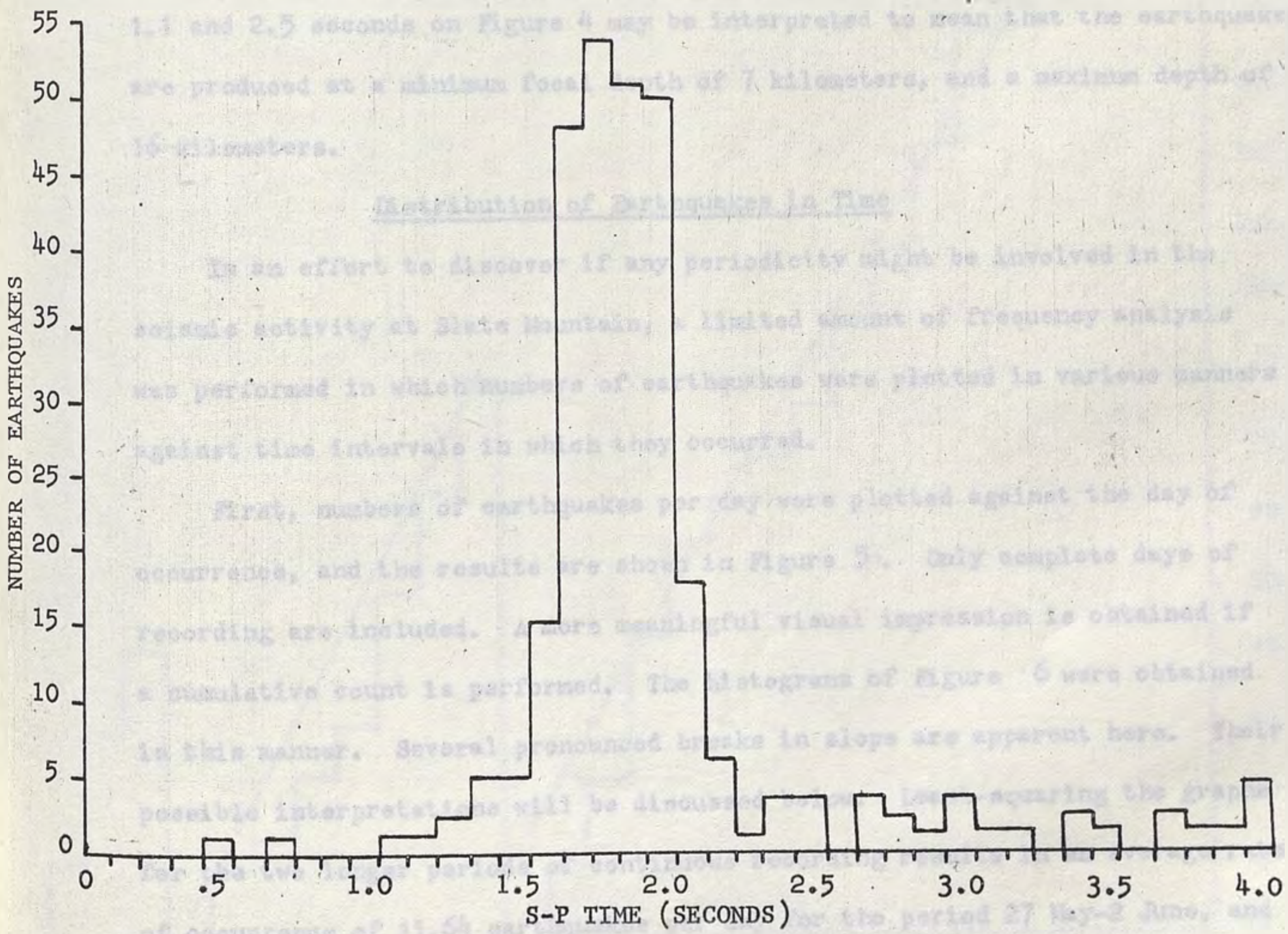


Figure 4. Numbers of earhquakes grouped by S-P times

are shown in Figure 4. It is surprising that so many of the earthquakes recorded are represented by S-P times over such a limited range. Although a sharp lower limit might be expected since a minumum focal depth of at least several kilometers is likely, a more gradual decay of the number of recorded earthquakes with distance would seem to be prescribed if the earthquakes are occurring randomly within the active zone. Instead, the sharp cutoff at just over 2 seconds implies that most events are occurring in a very restricted zone, and that the Slate Mountain recording site must be located very near the epicentral area.

If it is assumed that the observed travel times are due largely to focal depth, rather than to lateral hypocentral distances, the cutoffs at 1.1 and 2.5 seconds on Figure 4 may be interpreted to mean that the earthquakes are produced at a minimum focal depth of 7 kilometers, and a maximum depth of 16 kilometers.

Distribution of Earthquakes in Time

In an effort to discover if any periodicity might be involved in the seismic activity at Slate Mountain, a limited amount of frequency analysis was performed in which numbers of earthquakes were plotted in various manners against time intervals in which they occurred.

First, numbers of earthquakes per day were plotted against the day of occurrence, and the results are shown in Figure 5. Only complete days of recording are included. A more meaningful visual impression is obtained if a cumulative count is performed. The histograms of Figure 6 were obtained in this manner. Several pronounced breaks in slope are apparent here. Their possible interpretations will be discussed below. Least-squaring the graphs for the two longer periods of continuous recording results in an average rate of occurrence of 11.64 earthquakes per day for the period 27 May-2 June, and

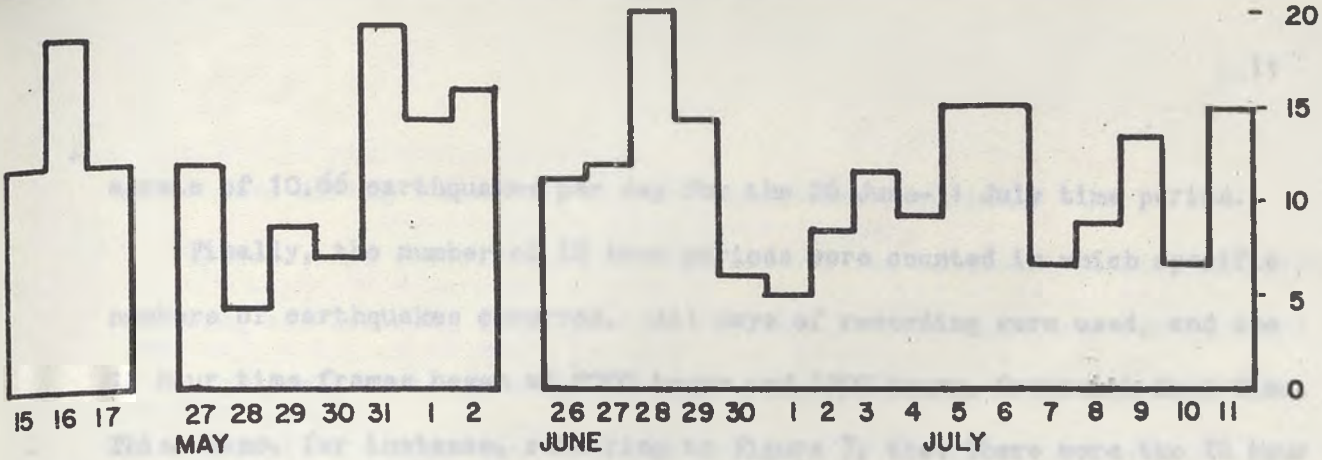


Figure 5. Number of earthquakes with S-P times of 2.5 seconds or less

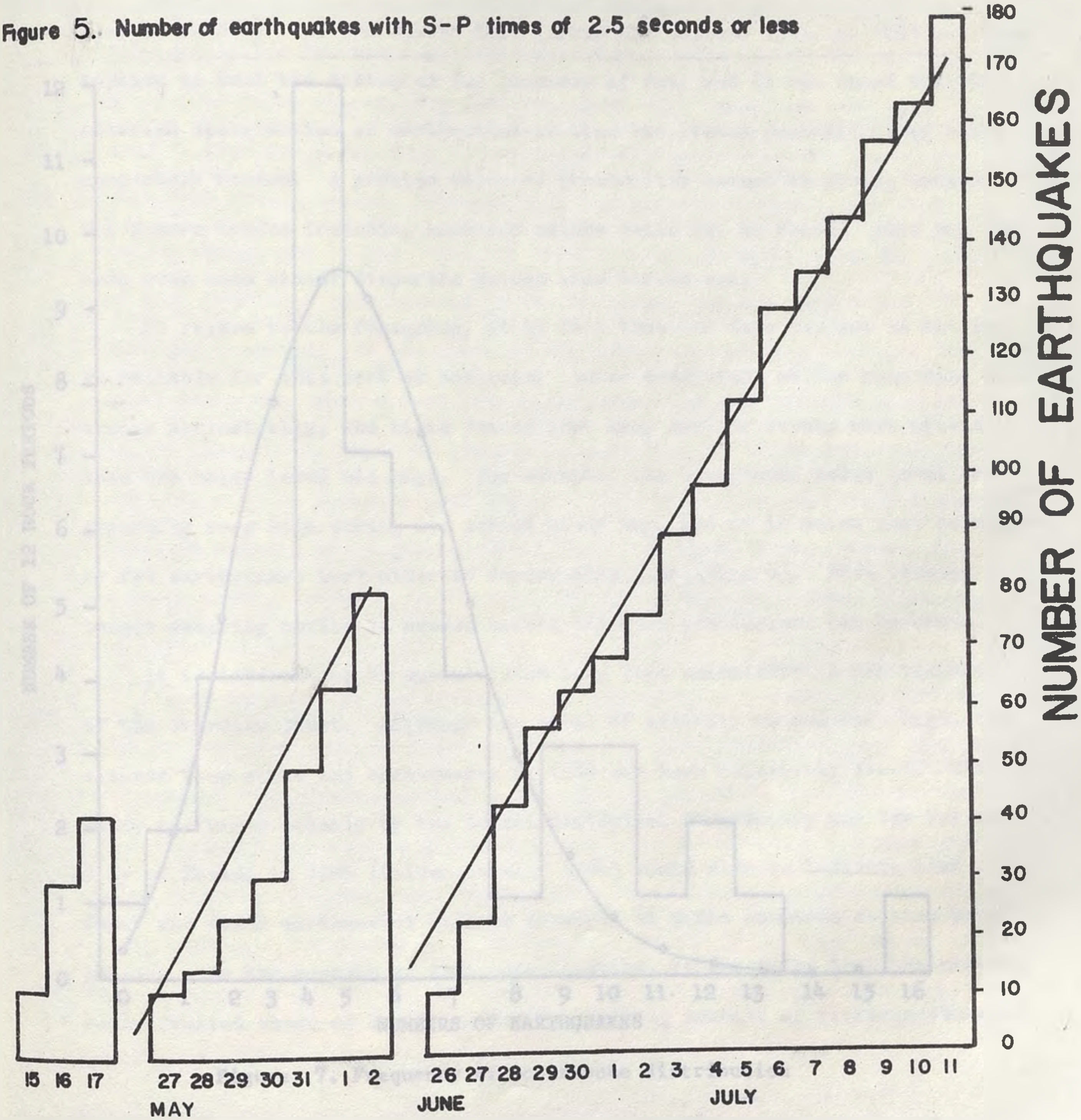


Figure 6. Cumulative count

a rate of 10.66 earthquakes per day for the 26 June-11 July time period.

Finally, the number of 12 hour periods were counted in which specific numbers of earthquakes occurred. All days of recording were used, and the 12 hour time frames began at 0000 hours and 1200 hours, Greenwich Mean Time. This means, for instance, referring to Figure 7, that there were two 12 hour

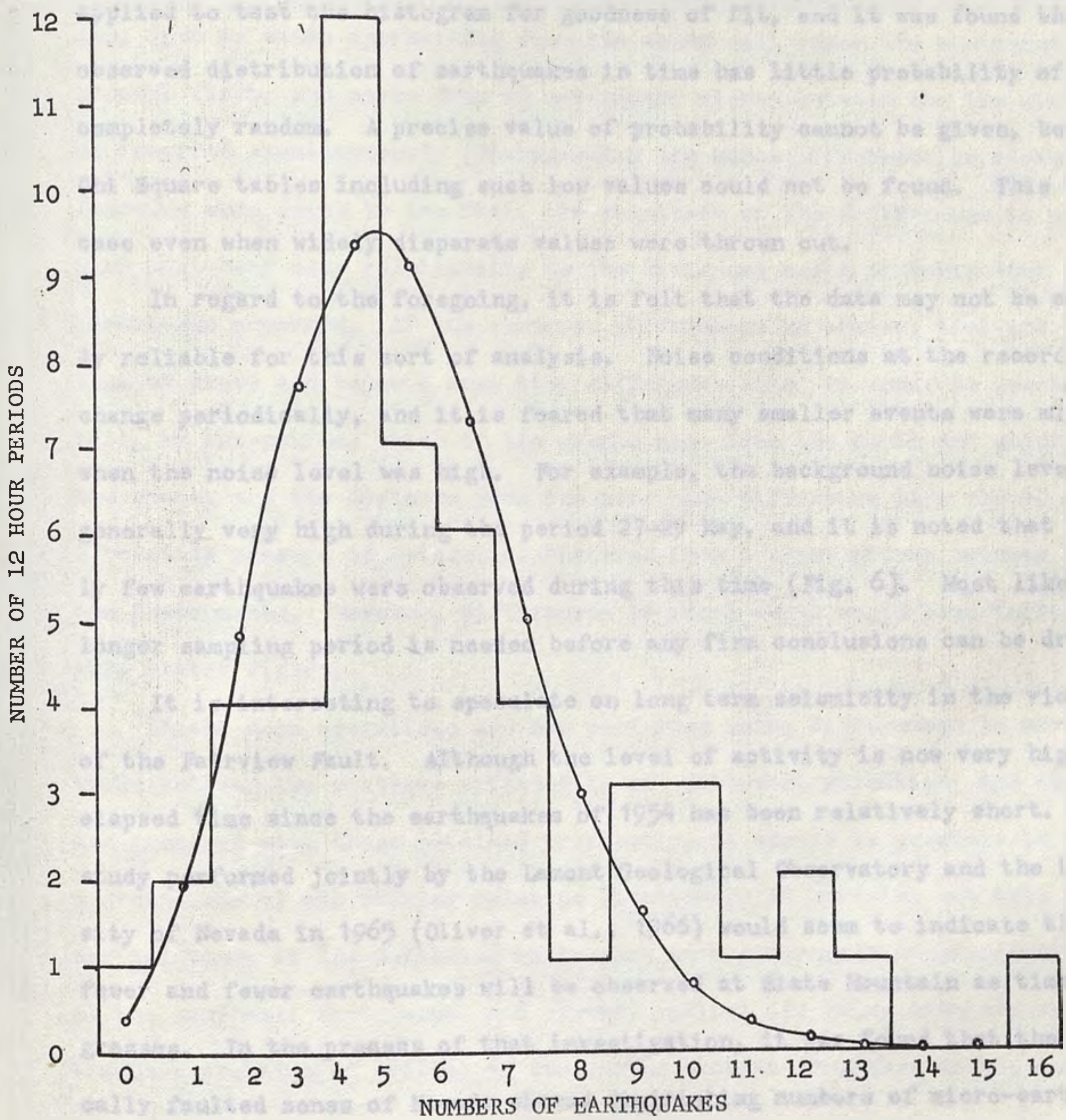


Figure 7. Frequency of occurrence distribution

time frames during which only one earthquake was recorded.

To test this distribution for randomness, the Poisson distribution curve (Worthing and Geffner, 1943, p. 174) for this set of events was computed and is superimposed on the histogram. The points plotted on this curve reflect the theoretical values that would be observed if the distribution were completely random. The Chi Square test (Arkin and Colton, 1931, p. 109) was then applied to test the histogram for goodness of fit, and it was found that the observed distribution of earthquakes in time has little probability of being completely random. A precise value of probability cannot be given, because Chi Square tables including such low values could not be found. This was the case even when widely disparate values were thrown out.

In regard to the foregoing, it is felt that the data may not be entirely reliable for this sort of analysis. Noise conditions at the recording site change periodically, and it is feared that many smaller events were missed when the noise level was high. For example, the background noise level was generally very high during the period 27-29 May, and it is noted that relatively few earthquakes were observed during this time (Fig. 6). Most likely, a longer sampling period is needed before any firm conclusions can be drawn.

It is interesting to speculate on long term seismicity in the vicinity of the Fairview Fault. Although the level of activity is now very high, the elapsed time since the earthquakes of 1954 has been relatively short. The study performed jointly by the Lamont Geological Observatory and the University of Nevada in 1965 (Oliver et al., 1966) would seem to indicate that fewer and fewer earthquakes will be observed at Slate Mountain as time progresses. In the process of that investigation, it was found that the historically faulted zones of Nevada showed diminishing numbers of micro-earthquakes as the age of the fault increased.

Distribution of Earthquakes in Space

Although the dimensions of the net are too small to permit precise locations, a map of relative locations can be constructed by strictly empirical means.

Waves approaching from the north will obviously reach the instrument at the end of the northeast leg before they reach the one at the southeast leg; just as waves approaching from the south will reach the southeast instrument first, and waves from an earthquake midway between the two should be recorded simultaneously (disregarding the minor difference in elevation). Assuming some depth to the foci, the magnitude of the differences in arrival time must bear some relationship to the distances north or south that the earthquake occurred. If the observed differences in arrival time are then plotted above and below a zero time difference line, it would be possible to tell, by inspection, which of the events came from the north and which from the south, and the distance from the zero time difference line should provide a relative measure of epicentral distance from a point midway between the two instruments. However, differences in focal depth would also influence this latter figure.

If the same operations are now performed using differences in arrival times between two stations extended in an east-west direction, and the results are combined with those obtained previously, it should be possible to construct a 2-dimensional map showing relative locations. In carrying out this procedure, arrival times at the northeast instrument were subtracted from arrival times at the southeast instrument, and plotted against the value obtained by subtracting the time of arrival at the center station from that at the end of the west leg. In this manner, events approaching from, say, the northeast will be plotted in the first quadrant, and the analogy with a geographical map will thus be retained.

Of course, locations on the map will bear no direct relationship to locations on the ground, but such a representation should at least indicate which events could be expected to have occurred within close proximity of each other. There are two factors which limit the validity of such a construction. The first is that no account is taken of differences in focal depth. Since the time-of-arrival differences depend generally on the angle of approach of the wave front, vertical as well as horizontal hypocentral distances are influential. Secondly, there is the ambiguity that is introduced by combining observations made on alluvium with those from bed rock. If the simplified travel paths suggested on page 7 are assumed, i.e., if the rays arriving at the two stations used to determine the east-west time differences lie entirely in bed rock; and if it is further assumed that the rays arriving at the two stations on the alluvium travelled entirely in alluvium, then the lower seismic velocities in the latter would tend to expand the relative dimensions of the earthquake zone in a north-south direction. However, this effect may be wholly or partially offset by greater curvature of the ray in alluvium, leading to steeper angles of emergence and greater apparent velocities.

Two maps were constructed. In the first (Fig. 8(A)), the recording periods 15-18 May and 26 May-3 June were grouped. The second (Fig. 8(B)) shows the period 26 June-12 July. On these figures, the large triangle indicates the approximate position that an earthquake would be plotted if it occurred directly under the center of the net. For this purpose, the time difference of .04 seconds between the west and center stations was chosen, primarily because of the difference in elevation.

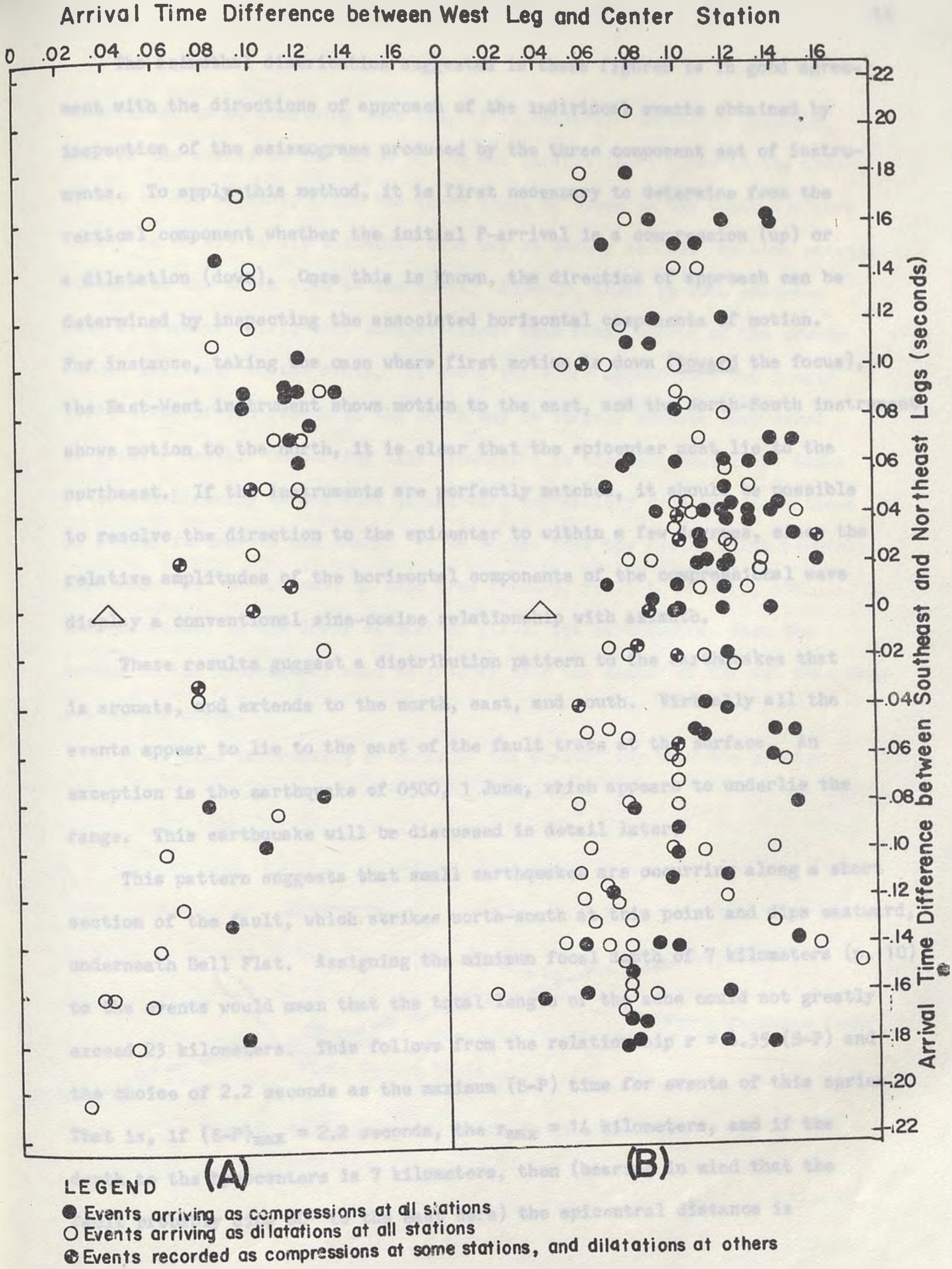


Figure 8. Spatial distribution of earthquakes (for explanation, see text)

The azimuthal distribution suggested in these figures is in good agreement with the directions of approach of the individual events obtained by inspection of the seismograms produced by the three component set of instruments. To apply this method, it is first necessary to determine from the vertical component whether the initial P-arrival is a compression (up) or a dilatation (down). Once this is known, the direction of approach can be determined by inspecting the associated horizontal components of motion. For instance, taking the case where first motion is down (toward the focus), the East-West instrument shows motion to the east, and the North-South instrument shows motion to the north, it is clear that the epicenter must lie to the northeast. If the instruments are perfectly matched, it should be possible to resolve the direction to the epicenter to within a few degrees, since the relative amplitudes of the horizontal components of the compressional wave display a conventional sine-cosine relationship with azimuth.

These results guggest a distribution pattern to the earthquakes that is arcuate, and extends to the north, east, and south. Virtually all the events appear to lie to the east of the fault trace at the surface. An exception is the earthquake of 0500, 1 June, which appears to underlie the range. This earthquake will be discussed in detail later.

This pattern suggests that small earthquakes are occurring along a short section of the fault, which strikes north-south at this point and dips eastward, underneath Bell Flat. Assigning the minimum focal depth of 7 kilometers (p. 10) to the events would mean that the total length of the zone could not greatly exceed 23 kilometers. This follows from the relationship r = 6.35 (S-P) and the choice of 2.2 seconds as the maximum (S-P) time for events of this series. That is, if $(S-P)_{max}$ = 2.2 seconds, the r_{max} = 14 kilometers, and if the depth to the hypocenters is 7 kilometers, then (bearing in mind that the fault probably dips 60° to the east here) the epicentral distance is constrained to be something less than 13 kilometers. Generally speaking, most of the events to the north of the net exhibit (S-P) times on the order of 1.9 to 2.2 seconds, while the (S-P) times of those to the south are more likely to be 1.7 to 1.9 seconds. This may be merely because the zone extends further to the north than to the south. However, there is some evidence (Wm. J. Stauder, S.J., oral communication) that focal depths of the events become shallower to the south. It would therefore appear that the longer (S-P) times of the events to the north may be largely because they occur at greater depth. Supporting this hypothesis is the fact that (S-P) times of events directly to the east do not vary appreciably from the (S-P) times of events further to the south. If we assume that the fault, which probably dips about 60° to the east in this area (Romney, 1957; L. Meister, oral communication) is the locus of most or all of the earthquakes, then the depths to the hypocenters must be greater near the center of the net than they are to the south.

It is also interesting to consider the possibility that the greater

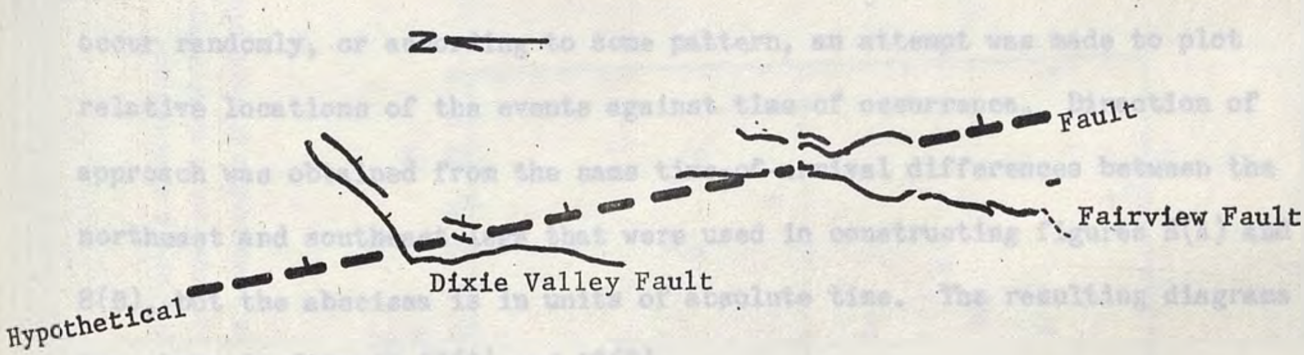


Figure 9. Hypothetical fault at greater depth

number of earthquakes here at the end of the fault might be attributed to greater stresses here, exactly in the manner that the greatest stresses in any tension crack are concentrated near the ends (cf., Richards, 1961, p. 227). This would imply that the Fairview Fault is a tension crack, and evidence that this is so is not entirely lacking. A fault plane solution by Romney of the 1954 earthquake (1957, p. 36) suggests that the Dixie Valley Fault and the Fairview Fault are the surficial expression of a major fault at greater depth (Fig. 9). Measurements of geodetic changes after the earthquake (Whitten, 1957, p. 322) seem to bear out the fault plane solution. Further, it is noted that, during the summer of 1966, Dr. James Brune of the California Institute of Technology was engaged in a study, similar in some respects to this one, of the Dixie Valley Fault. One of his findings (oral communication) was that the Dixie Valley Fault appears to be more seismically active at the northern end. If the Dixie Valley-Fairview Peak fault system is a coherent tension feature, as these findings would imply, it would be expected that any further surface breakage would extend the Dixie Valley Fault to the north, and the Fairview Fault to the south.

Spatial Distribution of Earthquakes with Time

In a further effort to determine whether the earthquakes at Slate Mountain occur randomly, or according to some pattern, an attempt was made to plot relative locations of the events against time of occurrence. Direction of approach was obtained from the same time-of-arrival differences between the northeast and southeast legs that were used in constructing figures 8(A) and 8(B), but the abscissa is in units of absolute time. The resulting diagrams are shown in figures 10(A) and 10(B).

Recall that the two instruments lie on a line nearly paralleling the surface breakage of the fault, and that they rest on the downdropped block,

LEGEND

- o Events arriving as dilatations at all stations
- ● Events arriving as compressions at all stations
- ⊙ Events recorded as compressions at some stations, and dilatations at others

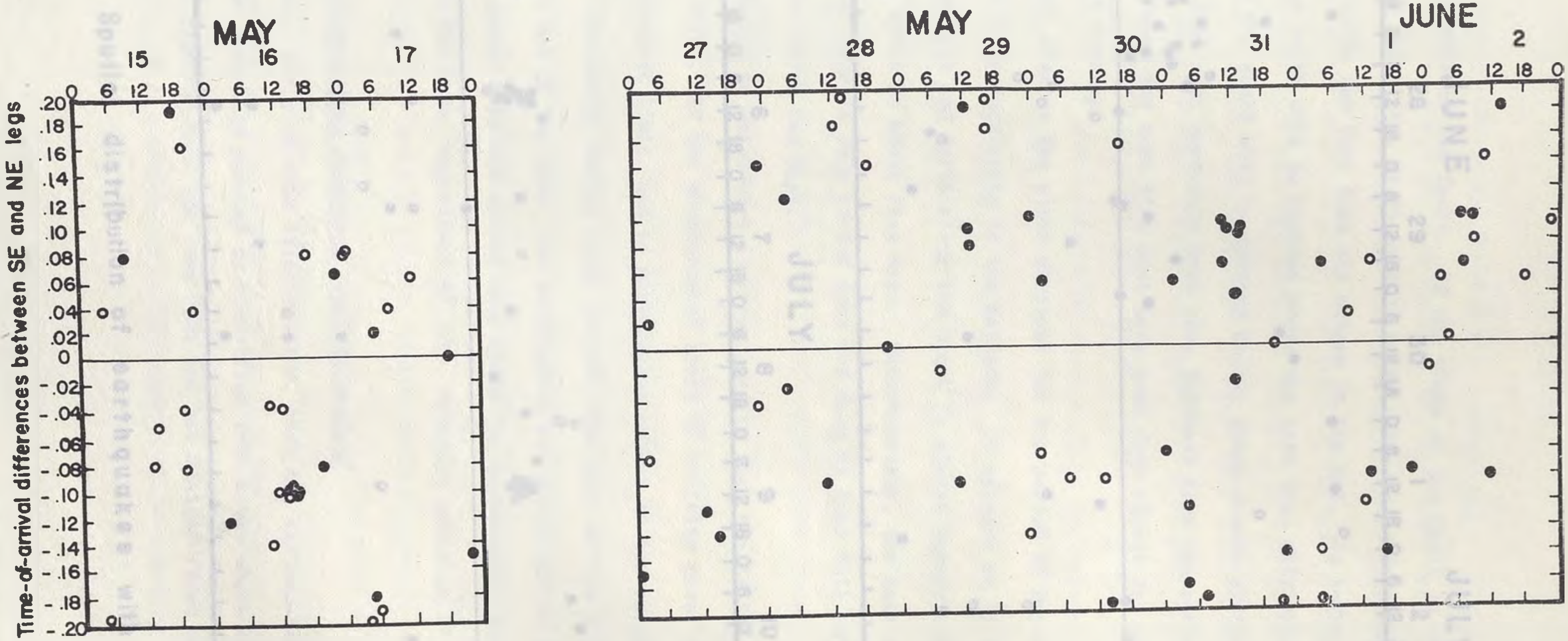


Figure 10(A). Spatial distribution of eartquakes with time

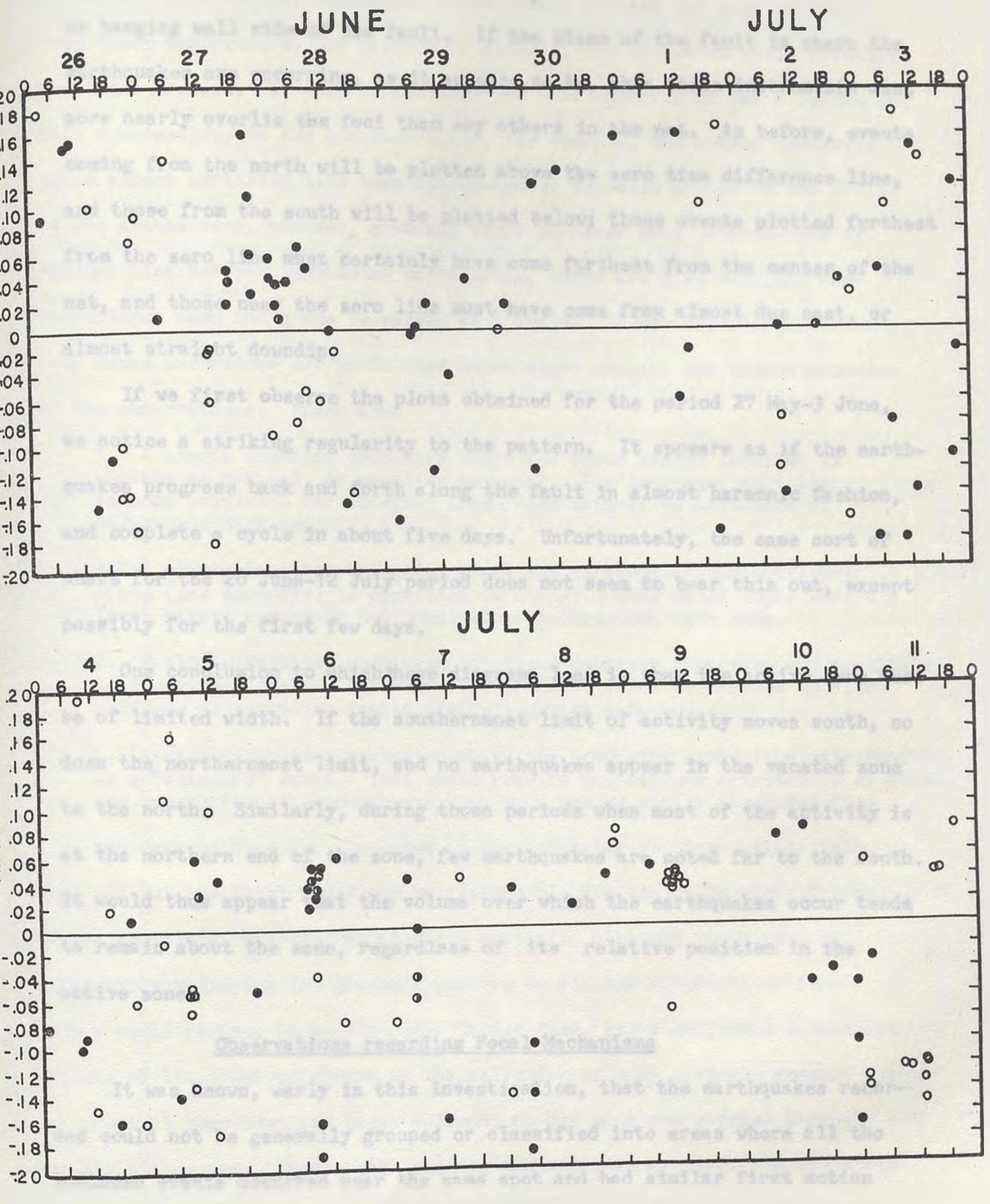


Figure 10(B) Spatial distribution of earthquakes with time or hanging wall side of the fault. If the plane of the fault is where the earthquakes are occurring, as it appears to be, then these instruments must more nearly overlie the foci than any others in the net. As before, events coming from the north will be plotted above the zero time difference line, and those from the south will be plotted below; those events plotted furthest from the zero line must certainly have come furthest from the center of the net, and those near the zero line must have come from almost due east, or almost straight downdip.

If we first observe the plots obtained for the period 27 May-3 June, we notice a striking regularity to the pattern. It appears as if the earthquakes progress back and forth along the fault in almost harmonic fashion, and complete a cycle in about five days. Unfortunately, the same sort of chart for the 26 June-12 July period does not seem to bear this out, except possibly for the first few days.

One conclusion to which these diagrams lead is that the active zone must be of limited width. If the southernmost limit of activity moves south, so does the northernmost limit, and no earthquakes appear in the vacated zone to the north. Similarly, during those periods when most of the activity is at the northern end of the zone, few earthquakes are noted far to the south. It would thus appear that the volume over which the earthquakes occur tends to remain about the same, regardless of its relative position in the active zone.

Observations regarding Focal Mechanisms

It was known, early in this investigation, that the earthquakes recorded could not be generally grouped or classified into areas where all the included events occurred near the same spot and had similar first motion patterns. If a simple, consistent first motion pattern had been observed from these earthquakes, the problem of deducing the mechanism would probably have been trivial. If only dilatations had been observed on the alluvium and only compressions on the mountain block, for example, the source mechanism could almost certainly have been attributed to dip-slip motion on the fault. In the actual case, however, although there do occur many coincidences or similarities between individual earthquakes, there are some puzzling contradictions when the group is viewed as a whole. In the following sections, four focal mechanisms are postulated which might explain the inconsistencies of the observations. These are:

1. A simple faulting mechanism where the force system involved is capable of partial, or complete reversal. For instance, that there is some provision for changing from right-lateral to left-lateral stress and back again.

2. A simple faulting mechanism where the attitude of the auxiliary plane (see Appendix) is permitted to change. This would imply that the local stress system is not consistent in direction with time.

3. A simple faulting mechanism involving constant direction and magnitude to the stress system, but where the geologic model is altered to allow slippage on secondary faults, as well as the main one.

4. A simple faulting mechanism where the producing agent (the main fault) is a "scissors" fault. This would require non-uniform orientation of stresses across the aftershock zone, but in a manner easily accounted for.

For reasons that are presented in the following sections, it is felt that all but the first model may be responsible for the production of some of the anomalous observations at Slate Mountain, although the wisdom of extensively modifying the geologic picture to fit the observations from such a small net may be questioned. In any case, it is difficult to account for all of the observed events by the selection of only a single model.

Several important and basic assumptions are made and carried throughout the discussion. First, the faulting mechanism is assumed. To speculate on the focal mechanism responsible for earthquakes at Slate Mountain by considering merely the recorded data, and without regard or consideration of the tectonic setting, would be to use only part of the information available to a study that is already hampered by the scarcity of pertinent raw data. It is known that the earthquakes of 1954 were accompanied by large-scale surface faulting at Slate Mountain, where the faulting was normal and in some areas had a strike-slip component. The small aftershocks that were recorded for this study must certainly be related to the force system that produced the main fault, and a faulting mechanism would thus appear to be prescribed. The lack of general accord among seismologists on the nature of source mechanisms for major tectonic earthquakes is outlined in the Appendix.

Further, it is assumed that when all the instruments of the net record the same direction of first motion, the first arriving ray originated on the footwall side of the main fault (or on the side of the fault nearest the net where multiple faults are considered). This reasoning is explained as follows: In inspection of the records, one of the more puzzling discoveries was that many of the events did not show a distribution of compressions and dilatations across the net. Whereas it might be expected that, for most earthquakes, arrivals on one side of the fault would be compressions, while those at the other two stations would be dilatations, nearly all of the events (over 95%) arrived at all the instruments of the net with the same sense of first motion. The probable reason for this is that the sense of first motion observed at all the stations is that which occurred on the footwall side of the fault; and that the first rays arriving at the stations on the alluvium have been refracted across the fault and thus do not bear the true sense of first motion that was observed in the hanging wall at the hypocenter. Since the minimum focal depth for these events has been shown to be around 6 kilometers, and considering that the alluvium is probably around 1½ kilometers thich (Fig. 3) and that the two legs extending onto Bell Flat are located somewhat less than 1 kilometer from the fault trace at the surface, the necessary conditions for this sort of refraction appear to be at least possible, if not probable.

The problem when trying to apply the foregoing assumption to the observations on Figures 8 and 10 is immediate and obvious. One quickly runs into trouble in trying to explain the patterns of first motion distribution in terms of presumed motion on the fault. For instance, the observation that certain series of earthquakes arrive as dilatations both from the north and the south seems unreasonable. This would suggest that earthquakes are the result of movement of the footwall away from the recording site in both directions -- an absurd implication.

a. The Reversing Mechanism

The enigma described in the preceding paragraph could be explained if there were such a thing as an earthquake mechanism that would periodically reverse. Of course, dilatations from the footwall could also mean that the mountain block was sinking -- an unlikely proposition, and one that brings us back to the reversing mechanism anyway, when one considers that there are places on the charts where compressions, also, are recorded both to the north and south during the same interval of time. A force system with the ability of abrupt reversal is hard to explain. This would allow the interpretation of a good many of the inconsistent observations, but introduces a proposition that is harder to conceive than the problem it purports to solve. Further discussion on the consistency of local stress systems is presented in the next section.

b. Tilting of the Auxiliary Plane

A more reasonable explanation of the anomalous observations is that the orientation of the auxiliary plane (which is assumed to be at right angles to the fault plane) is not constant from one earthquake to the next. This is equivalent to saying that slippage on the fault is not always in the same direction. For example, normal faulting with a left-lateral component at the northern end of the zone would be observed as a compression over the entire net. If a strong right-lateral component is present, however, the auxiliary plane will be tilted so that the area covered by the array would lie in a quadrant of dilatation. Since the same argument may be applied to the southern end of the fault, most desired combinations of compressions and dilatations may be obtained by manipulation. The absolute values of rotations of the auxiliary plane that would be required for a specific case are easily obtained by trigonometry or graphic methods. For example, an earthquake at the northern end of the zone (taken to be 11½ kilometers from the center of the net, p. 16) which occurred at a focal depth of 7 kilometers and resulted from combined dip-slip and right-lateral offset would be received as a compression at all the points of observation if the ratio of strike-slip to dip-slip were less than about 7 to 10 (that is, if the rake of the null vector were less than about 35^{o}). For higher strike-slip to dip-slip ratios, the first arrivals would all be dilatations. Compressions from events at the southern end of the fault are easily obtained from the same faulting components, i.e., normal faulting and right lateral offset, and this set of circumstances may explain the periods of time when compressions were noted from both the north and south. However, unless reverse faulting or left-lateral offset occur here, <u>there is no way for a dilatation to be received from the south</u>. To achieve the same changeover effect in the worked example above at the southern end of the zone, faulting would have to be of the opposite sense of that to the north, and the problem is again reduced to explaining a force system that acts in opposite directions.

Since, in the actual case, inspection of Figures eight and ten reveals that most of the events to the south are actually received as dilatations, it appears that still another mechanism for them must be postulated.

It is felt that, for some of the events that were investigated (in particular, a series that occurred on July 6th -- to be discussed later), a slight deviation in the orientation of the auxiliary plane is actually experienced. These few examples, though, lie very near to each other and almost directly down-dip. In this case, the auxiliary plane need be tilted only a few degrees in order to cut the array in a different manner, and large variations in its attitude need not be explained.

Since the apparent reversal of mechanism keeps recurring, the principal objections to this concept should perhaps be stated. First, if the basic principles of the Reid mechanism (see Appendix) are strictly applied, the idea of reversal of mechanism does not sound entirely unreasonable. Reid proposes that the entire stress surrounding a fault is released at the moment of faulting -- that the sides of the fault snap forward into a new strain-free position. This suggests that some "overshoot" can occur, and that the reversal of mechanism might be attributed to the final adjustments of the fault face to the point of static equilibrium. Orowan (1960) traces the development of the growing dissatisfaction with this concept. Briefly, the reason that modifications to the Reid mechanism are needed is this: It is unlikely that the entire stress supported by the rock body surrounding the focus of an earthquake is released at the time of the earthquake. This means that slippage of the same fashion would be expected to repeatedly occur, and that reversal would not be observed.

Press (1966) outlines laboratory and experimental results that tend to substantiate these objections to the Reid mechanism. Brace and Byerlee (1966) have found that rock samples under stress may be observed to undergo repeated stress drops by fracturing during the deformation process. No single fracture, however, releases the entire stress that is sustained by the sample.

For these reasons, it is felt that in the Slate Mountain area (or in any small aftershock zone) the stresses that are responsible for producing the earthquakes are, in general, uniformly aligned throughout the area, that slippage occurs in much the same manner on all the earthquake-producing faults of the same parallel set, and that the orientation of the auxiliary plane does not vary appreciably.

c. Modification of the Geologic Model

Since there seems to be no consistent faulting mechanism for the main fault that will satisfactorily explain all the observations, certain modifications to the geologic model are prescribed.

As a starting point, it is assumed that faulting in the Slate Mountain area is normal and right-lateral. This is the sense of faulting that was observed during the 1954 earthquake (Slemmons, 1957, p. 360; Larson, 1957, p. 379) and could reasonably be expected to be the most likely attitude of the present displacements. However, it will be seen that no consistent pattern of faulting will explain all the observations unless additional geologic features are postulated. The proposed modifications are most likely over-simplifications of what may well be a very complicated faulting system, but will serve to illustrate how different patterns of first motion can be accounted for by altering the down-dip structure. If the assumed nature of faulting is in error, a consistent pattern of slippage can still be made to fit the observations by the proper choice of structure.

Referring to the structure model on page 6, it will be assumed that earthquakes are occurring on the step fault as well as the main one. There are four cases to consider -- earthquakes occurring to the south and north of the net on both faults. These four cases will be labled as follows:

A. Earthquakes occurring to the north on the main fault
B. Earthquakes occurring to the south on the main fault
C. Earthquakes occurring to the north on the secondary fault
D. Earthquakes occurring to the south on the secondary fault

If the symbol "+" is used to represent a compression at the array, and "-" is taken to mean a dilatation, the following table of expected arrivals from events resulting from normal and right-lateral faulting can be formed.

Type of Faulting	Normal				Right-Lateral			
Case	A	B	C	D	A	B	C	D
First Arrival	+	+	+	+	-	+	-	+

Some reversals could be accounted for by postulating different components of normal and right-lateral faulting. However, the main point to be gained from the table is that this model provides no means by which to produce a dilatation from the south.

If we postulate a graben to the east of the main fault, however (Fig. 11), but still assume normal and right-lateral faulting, the following results would be observed:

Type of Faulting	Normal				Right-Lateral			
Case	A	B	C	D	A	B	C	D
First Arrival	+	+	-	-	-	+	-	+

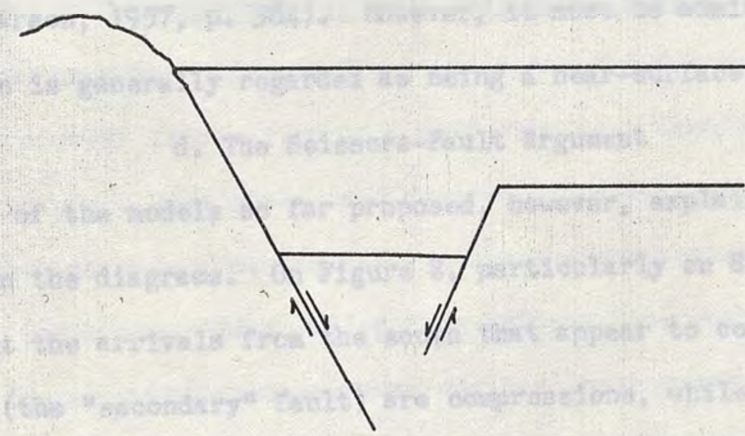


Figure 11. Hypothetical graben structure east of main fault.

Finally, we have a means by which to produce a dilatation from the south. In this case, it would result from dip-slip movement on the fault that bounds the graben on the east. In addition, this model can be used to account for every other type of first motion distribution that was observed. For instance, during the period from 1200 27 June to 1500 28 June events to the north arrived as compressions, and events to the south as dilatations (Fig. 10(B)). In this case, it is conceivable that the graben was "settling", with dip-slip motion to the south on the minor fault and to the north on the major one.

Of course, the postulated "graben" is merely a conceptual device and probably has no material counterpart. The main point to be brought out here is that anomalous first arrival patterns can be explained by modification of the down-dip structure, and need not be the result of a reversal of mechanism or significant changes in the orientation of the stress system affecting the aftershock area. There is a symmetry to the "graben and step-fault" argument that may be used to explain the observed first-arrival pattern regardless of what the direction of faulting in the area may be. The observation is also warranted that graben structures at the base of faults are not at all uncommon. Features of this sort were noted in the area following the 1954 earthquakes (Larson, 1957, p. 384). However, it must be admitted that this phenomenon is generally regarded as being a near-surface feature.

d. The Scissors-Fault Argument

None of the models so far proposed, however, explain one prominent feature on the diagrams. On Figure 8, particularly on 8(A), it is quite plain that the arrivals from the south that appear to come furthest from the east (the "secondary" fault) are compressions, while those from what is assumed to be the footwall of the main fault are dilatations. The conclusion that the footwall has thus moved either down or to the south is hard to repudiate. Although a minor amount of left-lateral offset was observed on the main fault in 1954 (Larson, 1957, p. 384), the overwhelming predominance of right-lateral offset left little doubt as to the direction of major faulting. There is also evidence (to be presented in later sections) that many of the small events presently being investigated involve right-lateral components. To explain the dilatations that are observed in the footwall to the south, it would therefore seem necessary to postulate reverse faulting. Since the fault is not visible at the surface to the south of the recording site, field evidence substantiating this concept is not available. However, the very fact that the fault dies out here may hint that different conditions are encountered.

Thus, while normal faulting occurred over the central portions, there may be a point of inflection toward the end of the fault where motion between the fault faces is rotational, and all faulting further to the south is reverse. The geologic term that is used to define this type of structure is "scissors fault." The similarity of this suggested behavior to that of a plucked string implies that Fourier analysis may some day be found to be a valid tool for the investigation of the propagation of breakage along a fault.

<u>Consideration of some Individual Events</u>

Earthquakes which showed first arrivals of different direction within the array provide information of a different sort than can be obtained by inspection of the group as a whole, and deserve individual attention. There were 17 of these events recorded, and their general characteristics are summarized in Table 1. Under the column labled "1st Motion", the numbers refer to the individual traces on the seismograms, and are interpreted as follows:

1: West Leg
2: Vertical Component at Center Station
3: East-West Component at Center Station
5: North-South Component at Center
6: Southeast Leg
7: Northeast Leg

If it is assumed that these earthquakes are the product of the main

	DATE	TIME	S-P TIME	1st MOTION 1	2	3	5	6	7
1.	17 May	05 29 57.8	2.5	D	C	W	N	C	C
2.	27 May	06 49 07.6	2.1	C	D	E			
3.	28 May	03 57 35.6	2.9	C	C	W	S	C	D
4.	28 May	22 47 28.7	1.2					C	D
5.	31 May	07 32 16.2	0.5	C	C		N	D	C
6.	31 May	22 10 ----	1.7	C	D	W	S	D	
7.	1 June	05 00 08.2	0.7	C	C	E		D	D
8.	2 June	07 09 24.2	1.7	C				D	C
9.	29 June	09 44 30.0	3.0-	C	C	W	S	C	D
10.	2 July	16 34 51.2	1.8	C	C	W	N	D	C
11.	2 July	21 10 ----	1.1	D	D	E	S	D	C
12.	5 July	09 30 03.1	1.8	C	C			D	D
13.	6 July	09 08 18.6	1.9	C	C			D	D
14.	6 July	09 09 21.9	2.0		C	W	S	D	D
15.	6 July	09 09 32.3	2.0		D	E		C	C
16.	7 July	04 33 15.0	2.0	C	C	W		C	D
17.	7 July	04 36 19.0	1.9					C	D

Table 1.

fault, it would be expected that there are two ways in which differential movement within the array might occur. If the auxiliary plane does not cut the array, the vertical motion would be of the opposite sense to either side of the fault. If the auxiliary plane does cut the array, the different first motion patterns would depend on its exact orientation, but it would be expected that the two instruments on the alluvium would show different first arrivals because of their relatively large separation in the north-south direction.

There is some degree of diversity noted in the observations for those events of the latter type. An example of several earthquakes, widely dispersed in time, which all seem to result in the same type of first motion distribution due to passage of the auxiliary plane through the array, is provided by earthquakes 3,4,9,16, and 17. All these events resulted in a compression at the southeast leg and a dilatation at the northeast leg. Where readings could be obtained for the instruments to the west of the fault trace, a compression was noted. If the observations for these five events are lumped, the suggested nature of movement on the main fault is normal and right-lateral. If this is the case, the auxiliary plane must have intersected the surface to the south of the instruments on the mountain block for those events which showed compressions here. The fact that poor readings were obtained for two of these events on the footwall side of the fault suggests that these stations may lie on, or very near, the nodal plane. Although these five earthquakes all occurred nearly due east of the array, they were not all precisely at the same location. From inspection of the time-of-arrival differences, it is seen that earthquakes 3 and 4 on 28 May occurred nearly directly downdip, earthquake number 9 on 29 June was to the north, and earthquakes 16 and 17 on 7 July were slightly to the south. This would imply changes in the orientation of the auxiliary plane of the type discussed on pages 22 and 23. However, unlike the arguments of the preceding sections, the arrivals at the two instruments on the alluvium are here being assumed to have originated in the footwall.

Other distributions of compressions and dilatations occur that are hard to explain in terms of the arguments that are being used. Earthquakes 1 and 2, for instance, occurred nearly due east of the net, and although the auxiliary plane does not cut the array between the two instruments on the alluvium, different first arrivals are noted at the other two stations. This must mean that the auxiliary plane does not strike in an east-west direction, which would infer that the main fault is not a nodal plane for these events.

There are several examples in Table 1 of the type of earthquake that showed a different sense of first motion to either side of the fault. Earthquakes 13, 14, and 15 are of this type, and form part of a remarkable series of earthquakes that occurred on 6 and 7 July. There were 11 earthquakes in this series, all quite similar in appearance, S-P times, and arrival time differences between the two stations on alluvium. The first two members of the group showed initial compressions at all instruments in the net; the second two showed initial compressions at the center station, but dilatations at the two instruments on Bell Flat; the fifth member was the exact inverse of the previous two, showing a dilatation at the center station and compressions at the two instruments on the alluvium. After this, conditions seemed to revert to their former state, and the remaining six earthquakes in the group arrived at all stations as compressions. The transition was not gradual. Earthquakes four and five of the group (which are numbered 14 and 15 in Table 1) occurred within 11 seconds of each other. These are the two that show the greatest diversity. Readings for the entire series are tabulated in Table 2, and the seismograms of earthquakes 2,4,5, and 6 are reproduced as Plates 1 through 3.

			1st MOTION					
	TIME	S-P TIME	1	2	3	5	6	7
1.	08 57 12.7	2.0	C	C	W	S	C	C
2.	09 07 32.3	1.9	C	C	W		C	C
3.	09 08 18.6	1.9	C	C			D	D
4.	09 09 21.9	2.0		C	W	S	D	D
5.	09 09 32.3	2.0		D	E		C	C
6.	09 37 15.0	2.0	C				C	C
7.	09 41 25.1	2.0	C	C			C	C
8.	10 57 23.6	1.8						C
9.	10 57 42.0	1.8	C	C				C
10.	13 00 ----	2.0	C	C	W		C	C
11.	03 02 02.9	2.0	C	C	W		C	C

Table 2.

Disregarding, for the moment, earthquakes 3,4, and 5 of the series, the remainder could all be thought of as being the product of a similar, repeating mechanism. Since the arrivals at all the stations bear the same

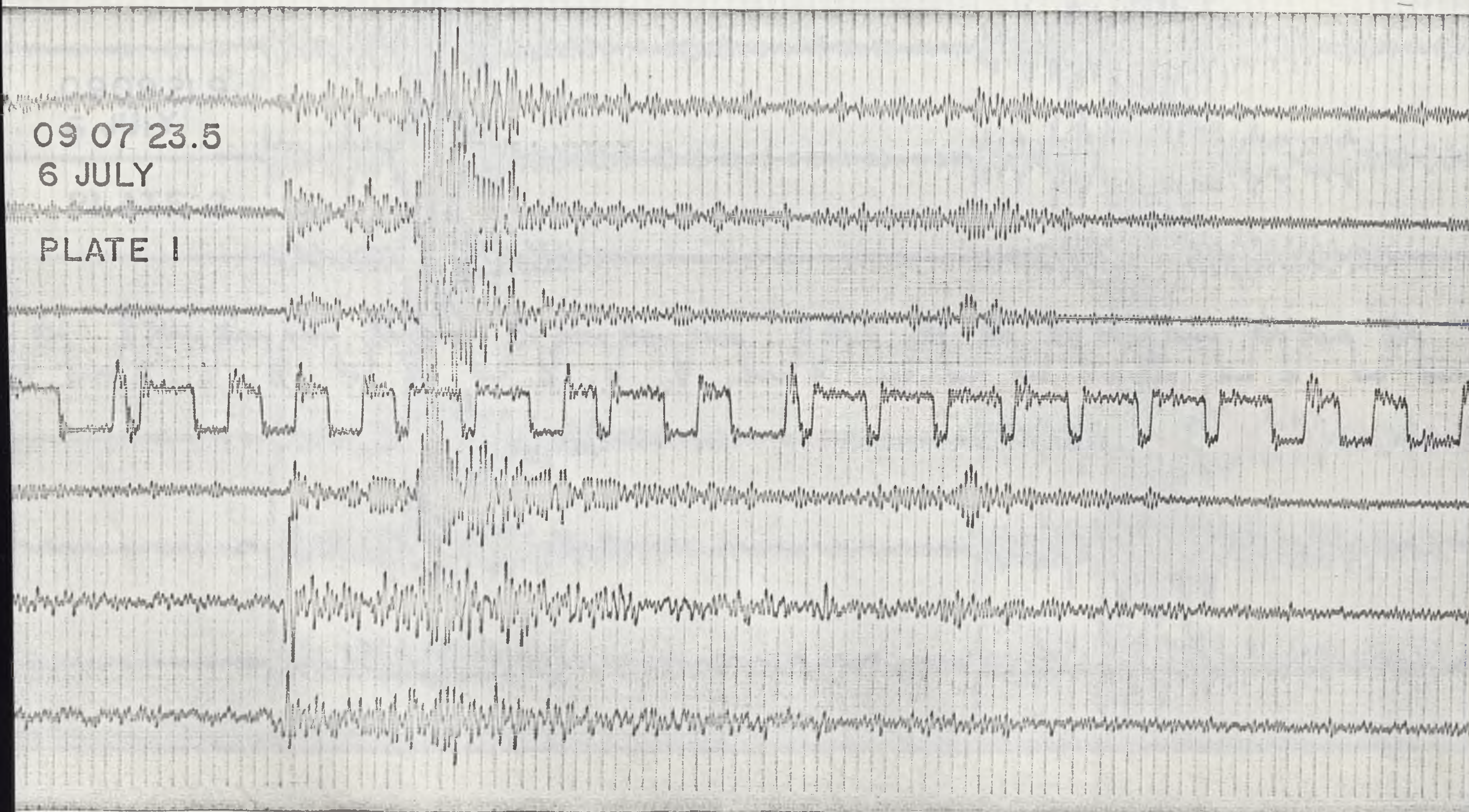


PLATE I

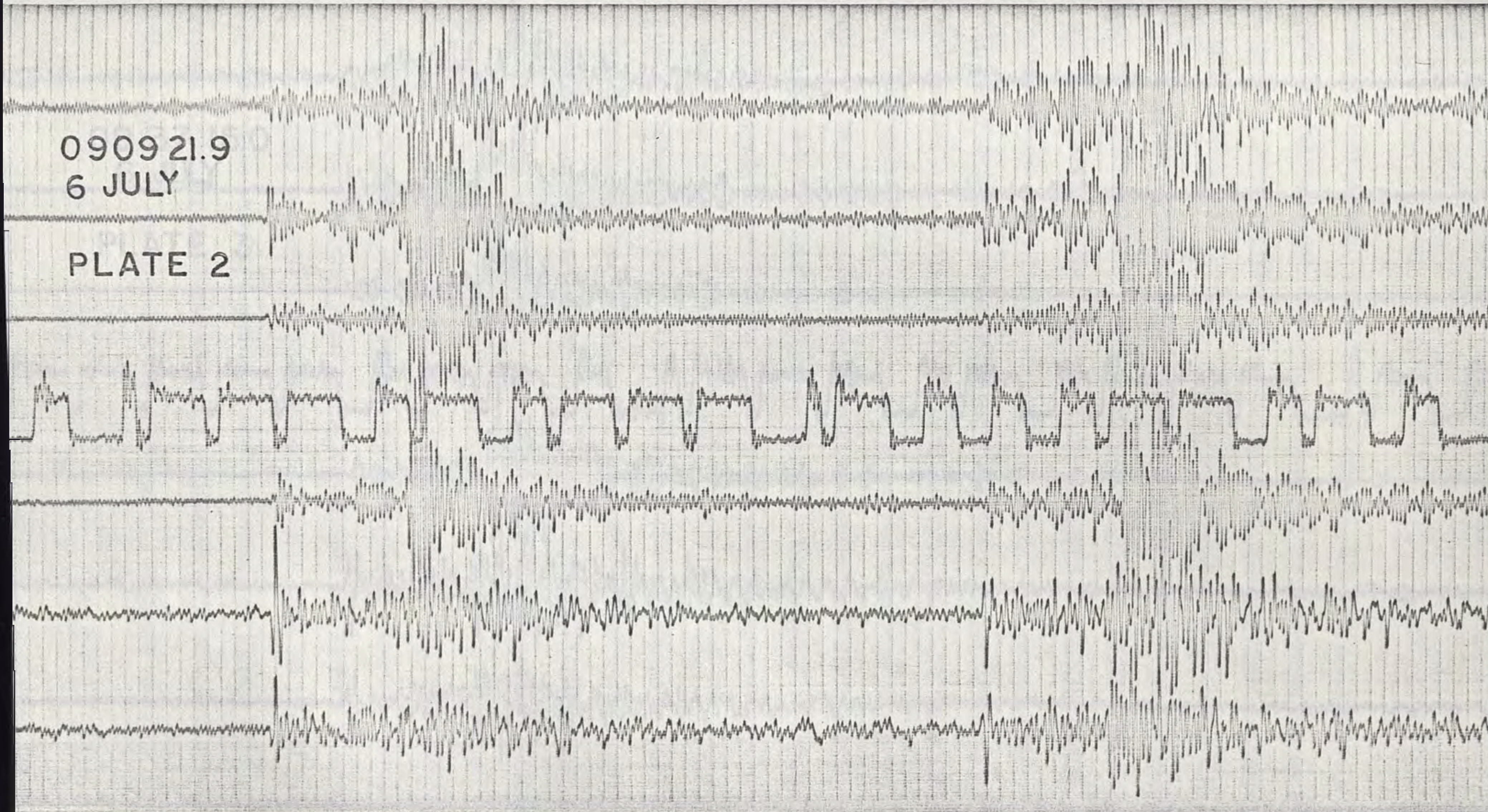


PLATE 2


09 37 15.0
6 JULY
PLATE 3

sense of first motion, it will be assumed that they all originated in the footwall, following the same line of reasoning that was presented on pages 20 and 21. Observing that the earthquakes all occurred just slightly north of the center of the net (Fig. 10(B)), the inference is that they are the product of dip-slip motion on the fault. Further, it must be conceded that some component of transverse faulting is present, or else the auxiliary plane would strike parallel to the fault and could not be expected to pass through the net. A left-lateral component seems to be ruled out if normal faulting is occurring since (bearing in mind that the epicenters are to the north of the net) the geometry of the problem would make it impossible for a dilatation to be observed under these conditions. If a right-lateral component is present, however, it would be possible for the auxiliary plane to cut the net in a different manner by only a minor change in orientation from earthquake to earthquake. This reasoning is the same as that presented on page 22.

That these conditions may be responsible for the change in the first arrival pattern of some earthquakes in this series seems logical. The auxiliary plane associated with the right-lateral mechanism suggested above would intersect the surface in a northeast-southwest direction (consider that, unless the null vector is vertical, the fault plane and auxiliary plane will not intercept perpendicularly at the surface). It would therefore seem relatively easy to account for earthquakes 3 and 4 in Table 2 by saying that the auxiliary plane passes through the net in such a manner as to separate the two stations on the mountain block from the two on the alluvium. This expediant cannot be used to explain earthquake number 5, however, since the model described can only be used to account for observations where all the arrivals are compressions, or where stations to the northwest of the auxiliary plane receive compressions and those to the southeast dilatations. In fact, it is impossible to account for earthquake number 5 of the series in terms of the present argument unless the fault trace itself suddenly becomes effective as a nodal plane, or unless the mechanism reverses. Both of these conditions are felt to be illogical.

There is remaining a very special case that might account for all 11 earthquakes. This model would require that the null vector emerge very near the center of the net, that the auxiliary plane strike nearly northeast-southwest, and that the fault itself be effective as a nodal plane at the surface, i.e,, that first arrivals on the alluvium bear the sense of motion observed in the hanging wall at the focus. In this case, all the earthquakes except numbers 3,4, and 5 could be said to result in the two stations on the mountain block lying in one quadrant of compression, and the two stations on alluvium lying in the other. Then earthquake number 3 could conceivably result from a tipping of the null vector to the south and the transition to earthquake number 5 could be due to movement of the null vector to the north, past the point of original emergence. In this case, the low amplitude at the westernmost station might be due to its proximity to the nodal plane. These hypothetical cases are graphically illustrated in Figure 12.

There are two other cases where opposite sense of first motion was observed across the fault. One of these is number 12 in Table 1. About the only thing that can be said about this earthquake is that it appears to have resulted from dip-slip motion on the fault. The other case is number 7, which is one of the very few earthquakes investigated that has no other close counterpart during the entire period of recording. This event appears to underlie the range, and to be disassociated with the fault. In this respect, it is unique for the Slate Mountain site. The seismogram for this event is

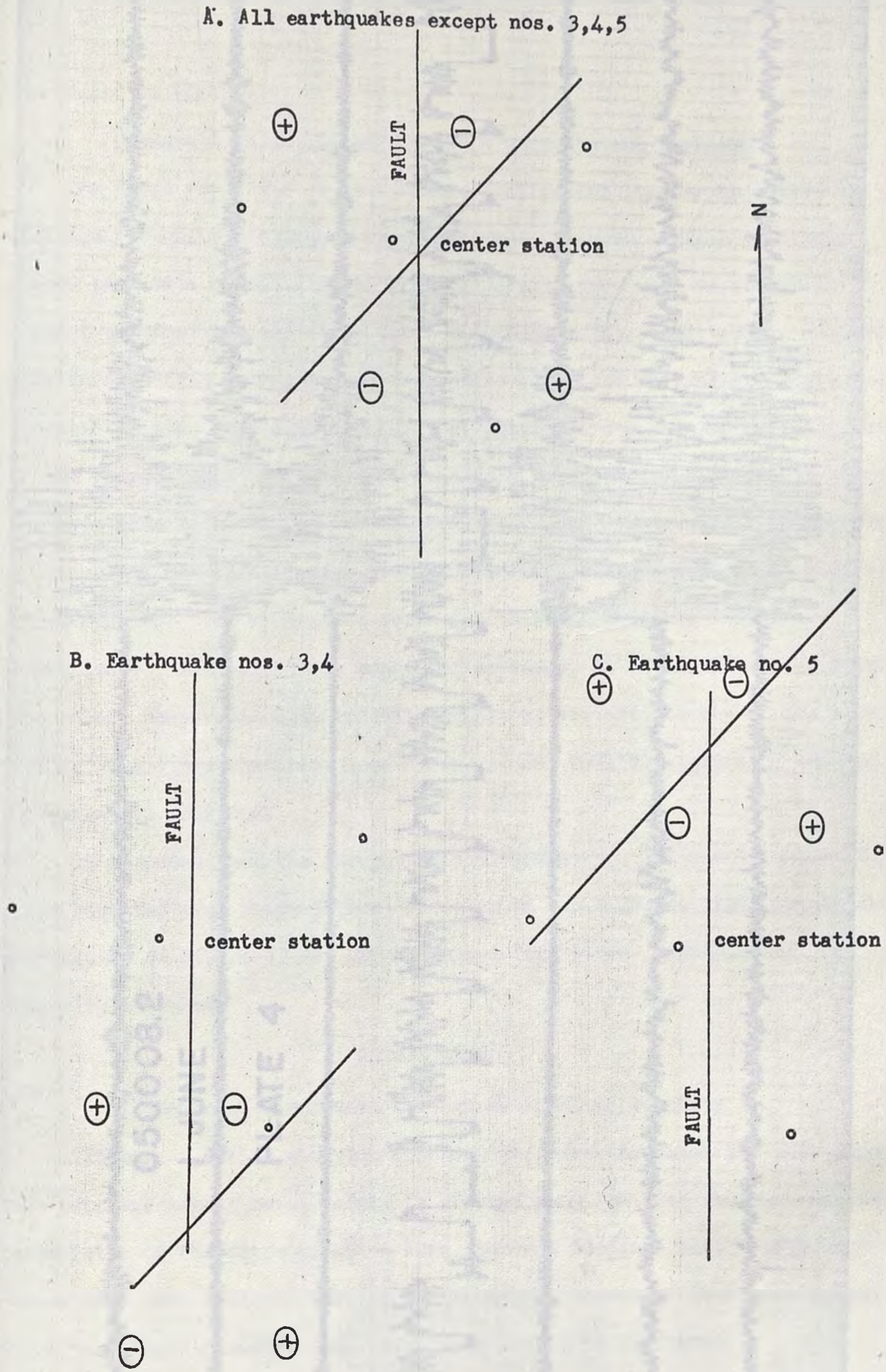
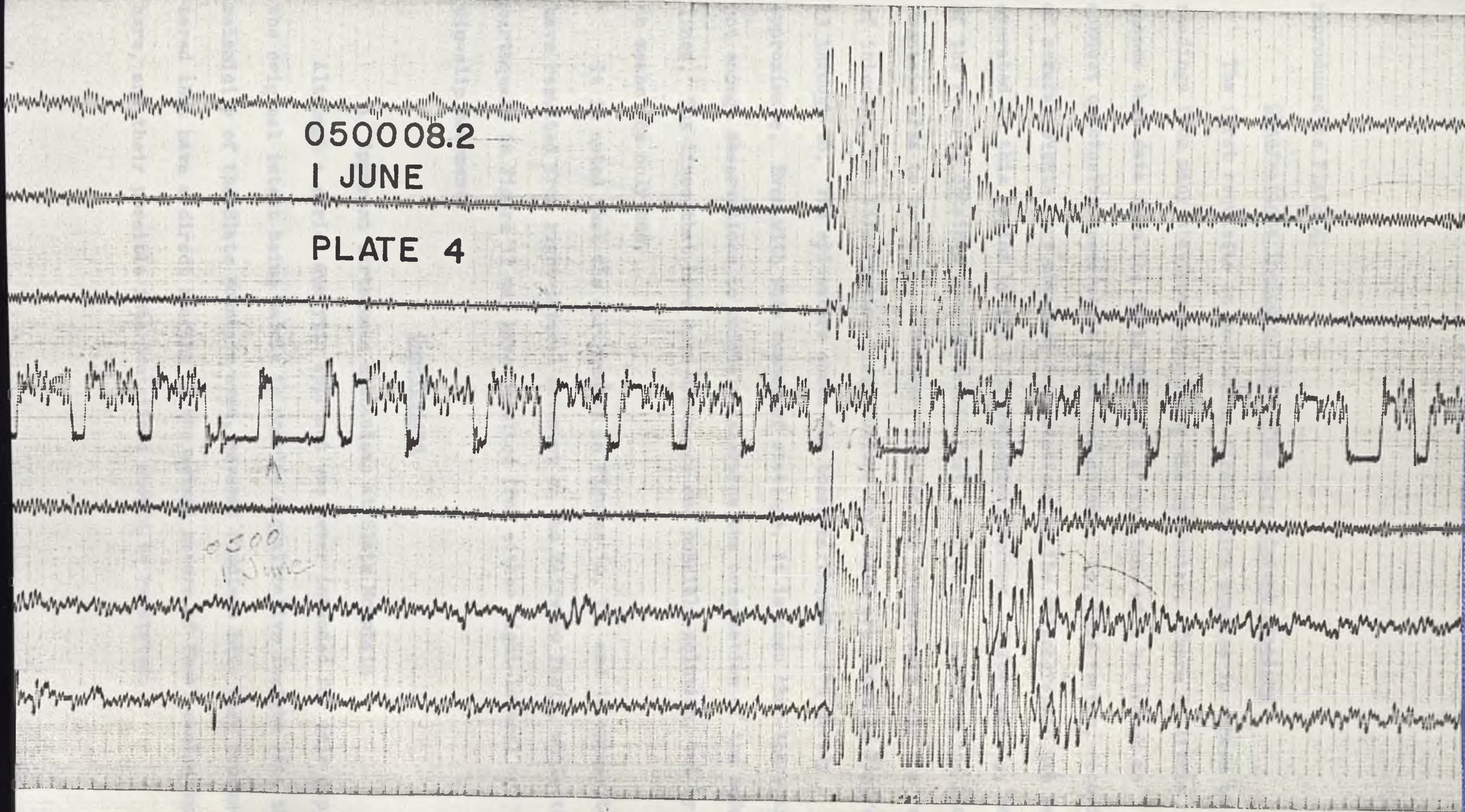


Figure 12. Hypothetical nodal plane orientations that might account for series of earthquakes on 6 July. Earthquake numbers refer to Table 2.


050008.2
1 JUNE
PLATE 4
0500
1 June

reproduced as Plate 4.

Observations including data from more distant stations

The first requisite in performing first-motion studies is access to readings from many stations surrounding the epicenter. There is little chance that data from the Slate Mountain array alone will be enough to conduct conclusive research in focal mechanisms. For this reason, records of several events were obtained from stations in the seismographic net being operated in this region by the U.S. Geological Survey. Unfortunately, most of the records obtained were of events that occurred too far from the Slate Mountain area to be of use. However, some of the events were near the region of interest, and first motion distributions for these are shown in Figures 13 through 16. The epicenters shown for these earthquakes are merely approximate. Even with this number of stations, it is seen that there are not enough observations to uniquely determine the orientation of the nodal lines. The lines that have been drawn are one possible solution, but by no means the only one.

It is noted that the earthquakes in Figures 14, 15, and 16 appear to have resulted from right-lateral movement on the Fairview Fault, while the earthquake in Figure 13 may have resulted from either right-lateral or dip-slip movement.

Conclusions

a. Apparent earthquake mechanisms at Slate Mountain

Although a strict analytic approach was never intended for this paper; the original intent being mainly to provide a qualitative insight into the seismicity of the Slate Mountain area, several findings have been encountered that have a direct bearing on the actual nature of focal mechanisms here, and their possible interpretations should be re-stated.

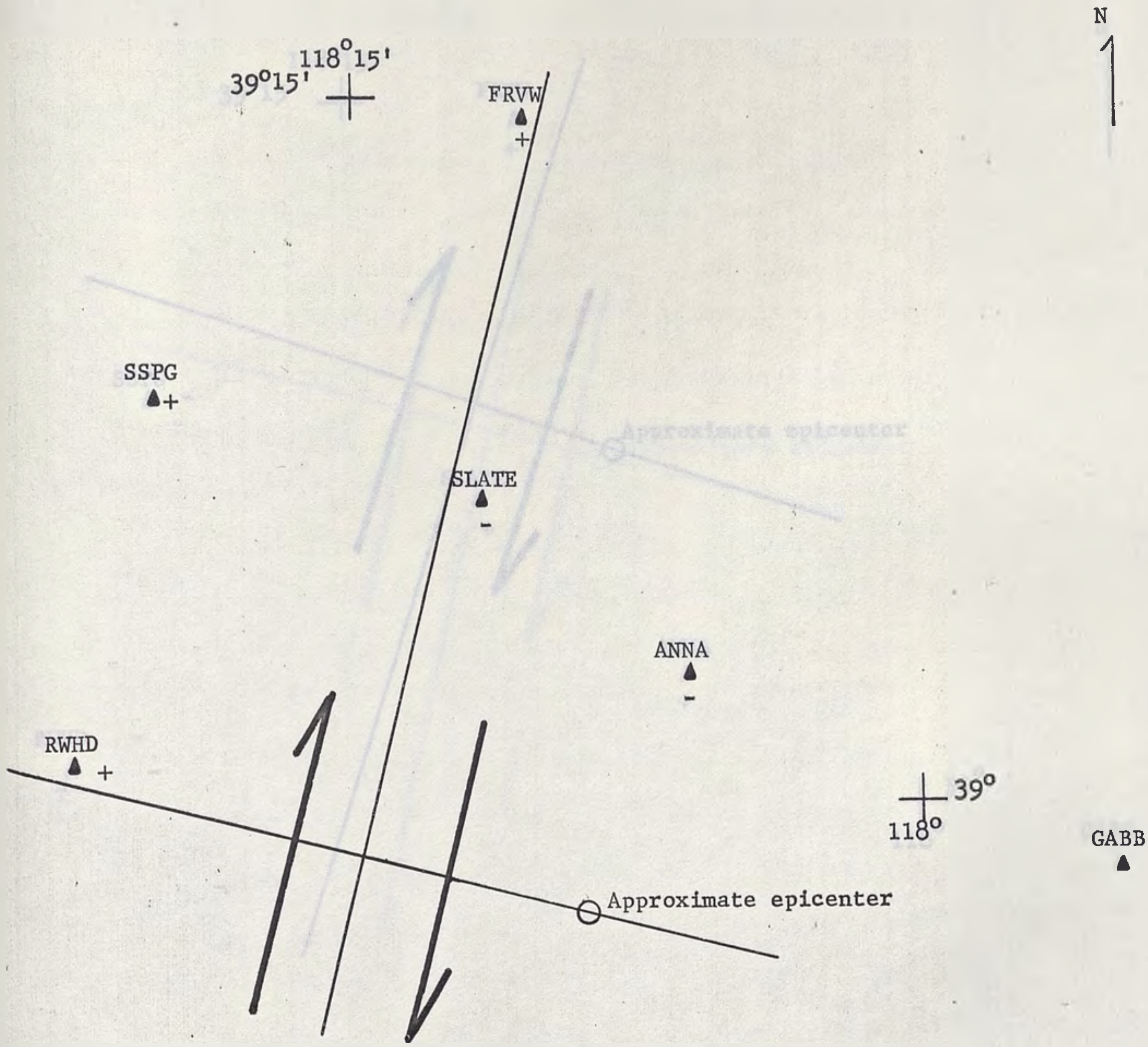


Figure 13. 15 May 1226 GMT

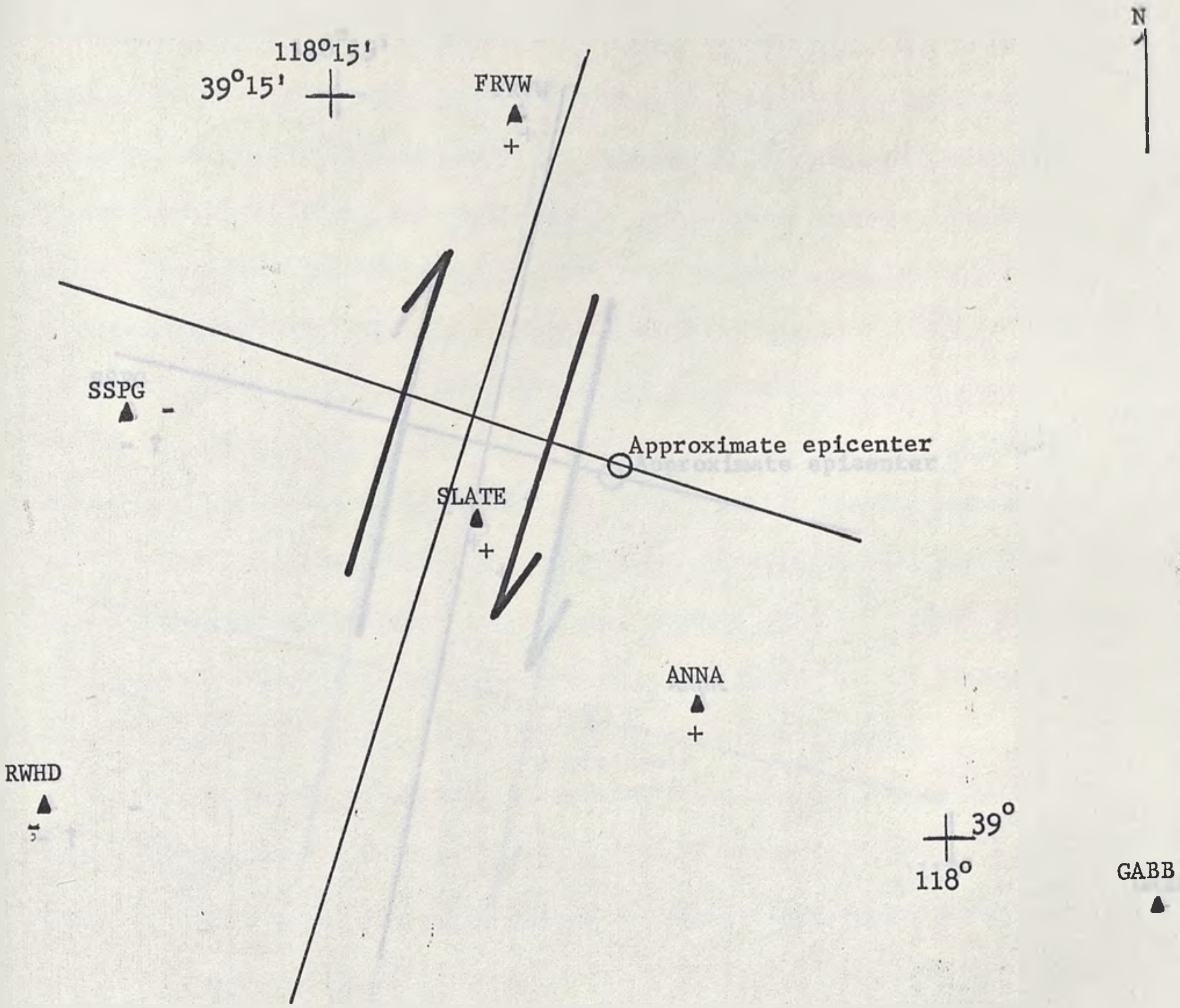


Figure 14. 15 May 1752 GMT

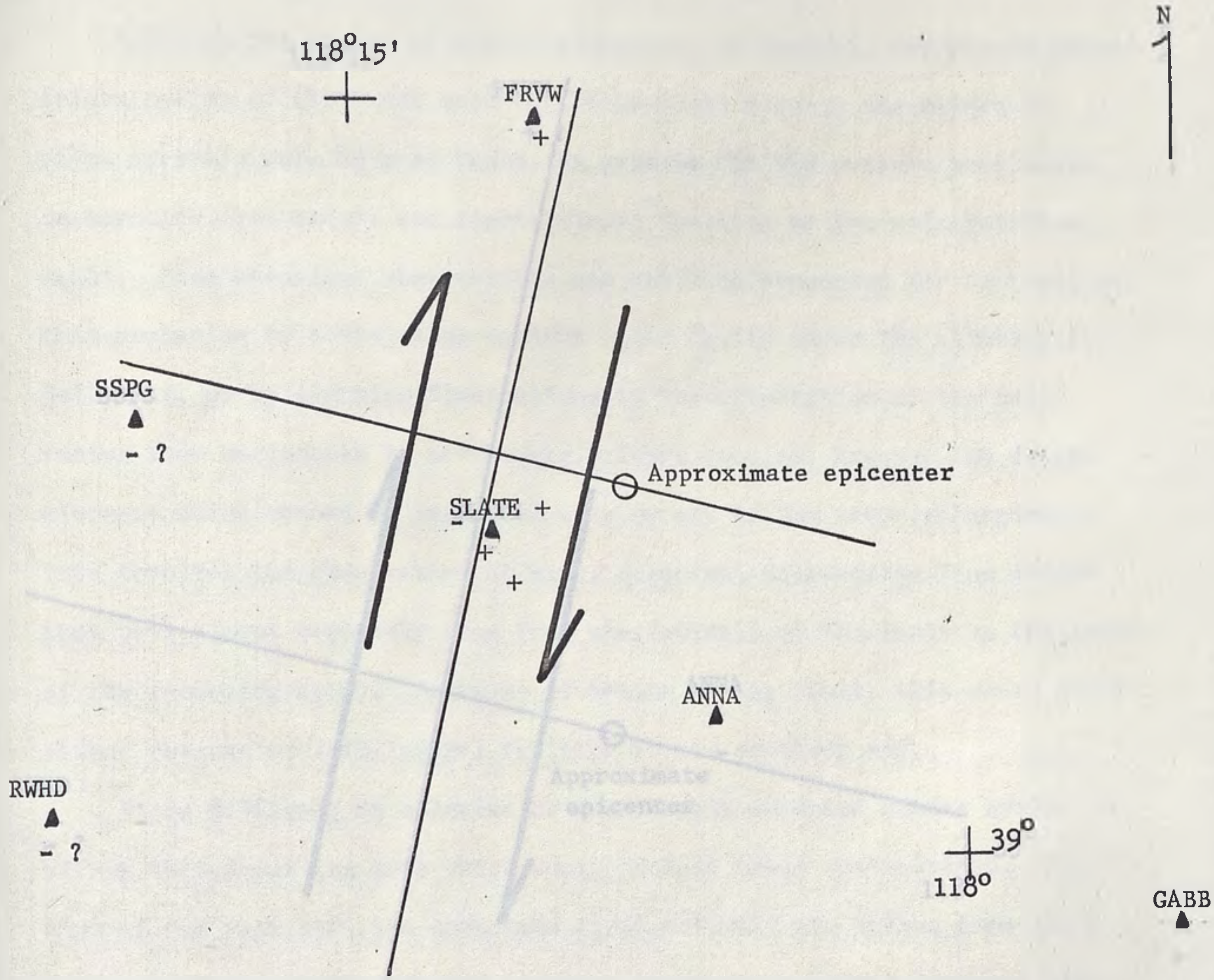


Figure 15. 17 May 0529 GMT

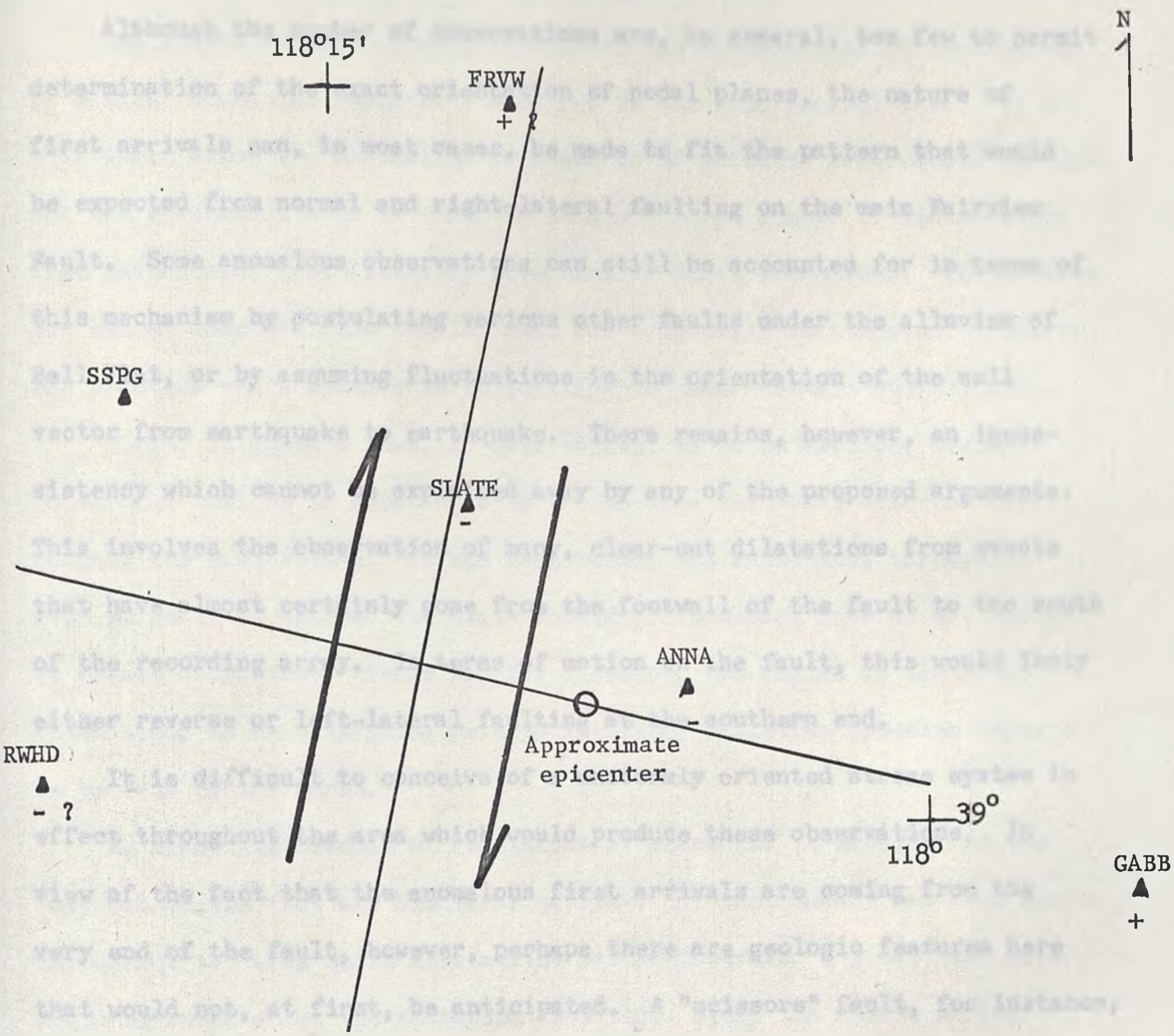


Figure 16. 27 May 0758 GMT

Although the number of observations are, in general, too few to permit determination of the exact orientation of nodal planes, the nature of first arrivals can, in most cases, be made to fit the pattern that would be expected from normal and right-lateral faulting on the main Fairview Fault. Some anomalous observations can still be accounted for in terms of this mechanism by postulating various other faults under the alluvium of Bell Flat, or by assuming fluctuations in the orientation of the null vector from earthquake to earthquake. There remains, however, an inconsistency which cannot be explained away by any of the proposed arguments. This involves the observation of many, clear-cut dilatations from events that have almost certainly come from the footwall of the fault to the south of the recording array. In terms of motion on the fault, this would imply either reverse or left-lateral faulting at the southern end.

It is difficult to conceive of a uniformly oriented stress system in effect throughout the area which would produce these observations. In view of the fact that the anomalous first arrivals are coming from the very end of the fault, however, perhaps there are geologic features here that would not, at first, be anticipated. A "scissors" fault, for instance, could produce a point of inflection in the direction of first motion that would explain the inconsistencies. Thus, while movement over the center part of the fault might be largely dip-slip, as one progresses southward he might find that the amount of normal offset diminishes to zero at a point where motion between the fault faces becomes rotational, after which reverse faulting is noted. Confirmation of this would provide a hitherto unsuspected point in the behavior of the Fairview Fault, and it is felt that further investigation is warranted.

b. Repetition of earthquake character

One of the primary aims of this paper was to determine if earthquakes of similar character repeatedly occurred in the same general area. If so, this would allow the relocation of a number of portable instruments throughout the epicentral area in order to obtain a large number of observations from earthquakes that assumably have similar focal mechanisms. The problem has become somewhat more complex than was originally anticipated. However, the practice still appears to be justifiable under certain stipulations.

First, it appears that, if this concept is to be applied, one must be careful that he is equating only earthquakes that have occurred over roughly the same volume. As has been noted, the mechanisms throughout even so small an area as the Slate Mountain aftershock zone do not appear to remain consistent. There is, for instance, the region to the south which seems to be undergoing reverse faulting, while the opposite appears to be true to the north.

An excellent example of repetition of character is provided by the July 6th series that was discussed earlier. If instruments had been moved throughout the area while this series was in progress, a great deal more would be known about the mechanism involved. Since the entire series lasted only a matter of hours, however, it is unlikely that more than one setup could have been accomplished between the time it was realized that a related sequence was occurring, and the time that it was over.

The answer, therefore, is to look for earthquakes that may represent repetition of character over a period of days or months. It is not obvious from inspection of Figures 8 and 10 that this sort of repetition occurs. Compressions seem to be intermingled with dilatations in a manner that does not immediately suggest consistent patterns. However, in inspection of the seismograms, it was noted that earthquakes, very similar in terms of all the parameters that were used to judge them, may recur in the same general area, but separated by days or weeks in time. For instance, there were many events that were recorded as compressions at all stations, and which appear to have come from only slightly to the north. Earthquakes of this same general character persist throughout the entire period, and there were few days during which at least one of this type was not recorded. The confusion arises when earthquakes of significantly different character occur in the intervening periods. However, even these intervening earthquakes can generally be associated with another or several others that were recorded at a different time. The fact is that there were very few earthquakes investigated that did not share some common characteristics with other events in the area.

It therefore appears entirely feasible to carry out the type of investigation that involves moving instruments periodically. The observation that tends most strongly to refute this argument is that it appears from Figure 8 that earthquakes having entirely different first arrival patterns occur in the same area. However, it should be borne in mind that the method used to locate these earthquakes was by no means precise. That is, earthquakes received as dilatations may have occurred at greater or less focal depth, or in a completely different volume from those earthquakes received as compressions, but plotted near the same point on Figure 8. Even if earthquakes of apparently different character actually did occur near one another, it is possible that only a minor variation in the orientation of the null vector may account for the different patterns of first arrival.

c. Suggestions for further investigations

The most serious handicap to this investigation has been that the two instruments situated on the alluvium are apparently located too close to the fault. Because of this, it is felt that the first arrivals at these stations are very often of the same sense that occurred in the footwall. An obvious recommendation for further setups is therefore to emplace these stations a greater distance onto the downdropped block--preferably several kilometers. However, the general configuration of the array is felt to be sound, and this sort of setup should provide excellent control in any future investigation.

As pertains to the location of the portable seismometers, there are at least two factors which should influence the choice of sites. One is that some method is needed to obtain accurate hypocenter locations, and the other applies to the basic problem under consideration -- to determine the focal mechanism. For the former, setups on the mountain block would probably be more valuable, since the vagaries of ray paths and velocities in the alluvium limit the usefulness of observations made here for location purposes. A good azimuthal coverage on the alluvium is necessary for observations of compressions and dilatations, however, particularly when it is considered that the initial motions observed from the instruments on Bell Flat were nearly always more distinct and clear-cut than those on the mountain block. As a starting point, it would probably be appropriate to emplace two of the portable instruments on the mountain block, one to the north and one to the south of the control net, and to emplace two on the alluvium in a similar manner. Since the plane of the fault is most likely a nodal plane, the orientation of the auxiliary plane (and thus the components of strike-slip and dip-slip) could then be determined by migrating the instruments to the north or south, in a line roughly parallel to the fault, until a nodal plane is crossed.

It is further felt that, if studies are to be continued at Slate Mountain, an area that should be of special interest is to the south of the present net. If it is possible to confirm the occurrence of reverse or left-lateral faulting here, a new area of speculation on the manner of faulting during the 1954 earthquake, and on tectonic faulting in general will be opened.

APPENDIX

Early Observations on Earthquake Focal Mechanisms

Since the early stages of instrumental seismology, it has been noted by various workers in the field that the initial motion of the earth's surface at the time of an earthquake is not necessarily in the same direction at different points around the epicenter; nor is the first motion recorded at one station from different earthquakes necessarily the same. In 1905, Omori pointed out that initial movement of the vertical component of earthquake waves recorded at seismograph stations was up (compressional) for earthquakes in one part of Japan, and down (dilatational) for earthquakes in another area. He assumed that the initial motion from any earthquake was of the same sense at all points around the epicenter, and attributed earthquakes where compressions were observed to subterranean explosions, or to the collapse of underground cavities where dilatations were observed.

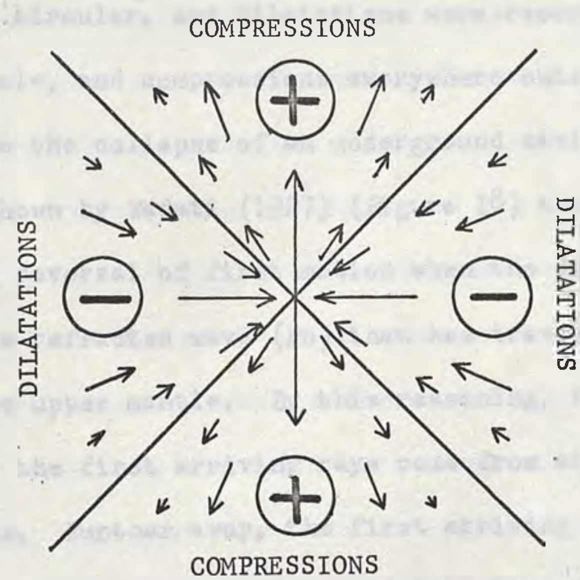


Figure 17. Shida's quadrantal distribution of compressions and dilatations (Milne)

Shida showed in 1909 that the movements due to an earthquake 350 kilometers southeast of Tokyo on January 1st, 1906, were recorded as compressions in some parts of Japan, and dilatations in others. The areas of compression and dilatation were separated by regions in which the initial amplitude of the first wave was too small to be seen. This led Shida to examine the distribution of patterns of compressions and dilatations from a large number of earthquakes; and as a result of his investigation, it appeared that the most usual type of pattern was one in which two nodal lines, on which the initial amplitude was zero, separated alternate regions of compression and dilatation. From these observations, Shida postulated that the force system responsible for the earthquakes was one of compression downward and inward toward the focus in the zones of surface dilatation, resulting in the zones of surface compression being forced apart (Figure 17). Shida also noticed another distribution, in which the nodal line was circular, and dilatations were recorded everywhere within the circle, and compressions everywhere outside. He attributed this pattern to the collapse of an underground cavity, but it was subsequently shown by Wadati (1927) (Figure 18) that this phenomenon was due to the reversal of first motion when the direct wave (Pg) is over-taken by a refracted wave (Pn) that has travelled with a higher velocity in the upper mantle. By this reasoning, for stations close to the source, the first arriving rays come from above the focus, and are dilatations. Further away, the first arriving rays are those that have been sent as compressions downward into the mantle, and have been brought back to the surface by refraction.

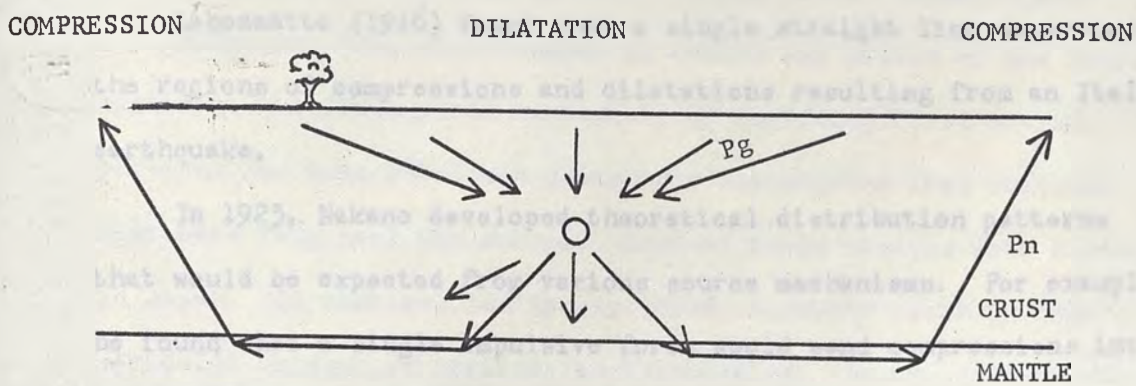


Figure 18. Wadati's explanation of Shida's Rockfall Hypothesis. The arrows indicate areas where the ground moved up or down.

In Russia, Galitzyn (1909) had also observed that motion at a recording station was sometimes compressional and sometimes dilatational. After perfecting a three-component set of seismographs that recorded horizontal as well as vertical motion, he found that the dilatations included a horizontal component toward the epicenter, and that the compressions were directed away from the epicenter. He also established that the surface particle motion was in a plane containing the great circle which passed through the epicenter and the recording station.

Gutenberg (1915), studying the Bavarian earthquake of November 16, 1911, noted a quadrant distribution of compressions and dilatations and, like Galitzyn, observed that the motion of all first arrivals was either toward or away from the epicenter. From this, he concluded that the first arriving wave must therefore be compressional in nature. Compressional waves will henceforth be referred to as P waves, and transverse, or shear waves, will be called S waves.

Labozzetta (1916) found that a single straight line separated the regions of compressions and dilatations resulting from an Italian earthquake.

In 1923, Nakano developed theoretical distribution patterns that would be expected from various source mechanisms. For example, he found that a single impulsive force would send compressions into one half-space, and dilatations into the other. A couple acting at the source would result in compressions and dilatations in alternate quarter spaces.

Further work led to the discovery that not all earthquakes produced such simple patterns of first motion. Tanahasi (1931), studying deep-focus earthquakes in Japan, found distribution patterns in the form of hyperbolas and ellipses. He thus concluded that, for these events, the nodal surfaces were conic sections, and postulated a mechanism in which the surface of separation between movements in opposite directions is a cone with its apex at the focus (Figure 19). According to this hypothesis, all motion inside the cone is compressional, and all motion outside is dilatational.

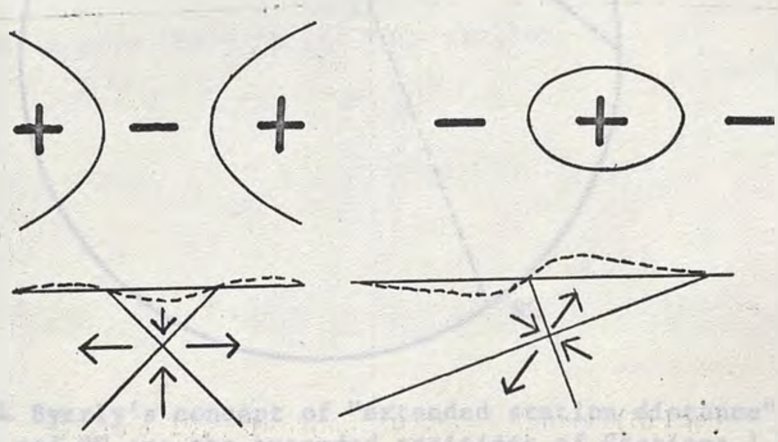


Figure 19. Tanahasi's Nodal Cones (Milne)

Expansion of a magma chamber in the direction of weakest confining pressure was postulated by Ishimoto (1932) as the causal agent.

Prior to 1926, all attempts to deduce the nature of the force system at the focus of an earthquake by analyzing first motion patterns had been performed using only seismograms from stations that were very near the source. Most of these studies were conducted in Japan. It remained for Byerly (1928) to apply readings from a worldwide network of stations to the problem. In the investigation of two large earthquakes -- the Chilean earthquake of 1922 and the Montana earthquake of 1925 -- Byerly found, for the first, a roughly hemispherical distribution of compressions and dilatations; and for the second, a quadrant distribution. In order to perform these studies, he introduced the concept of "extended station distance", in which a line tangent to a ray leaving the source is substituted for the ray

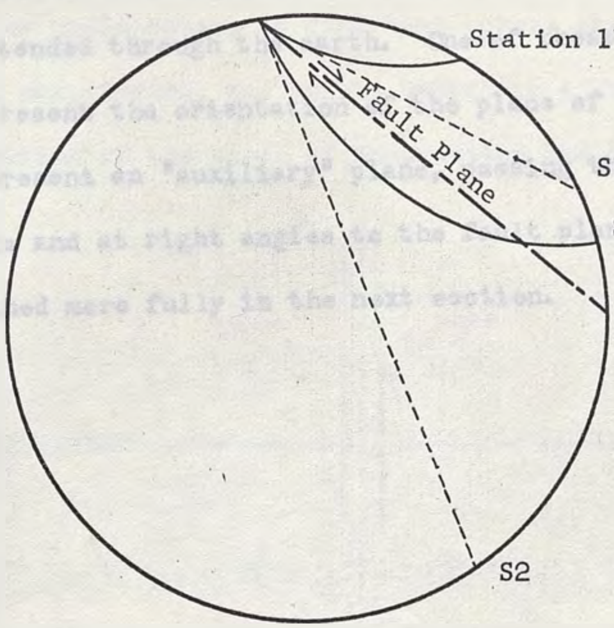


Figure 20. Byerly's concept of "extended station distance", where S1 and S2 are the extended positions of Stations 1 and 2

itself (Fig. 20). The station receiving this ray is then "extended" to the point on the globe where the tangent line intersects the surface. Various authors (cf., Jeffreys and Bullen, 1940) have published tables of epicentral distance vs. angle of emergence for the seismic ray, from which it is possible to obtain the orientation of the tangent line (for a seismic ray, the angle of emergence at a station is the same as the angle of incidence from a surface focus). If this were not done, refraction within the earth's interior would result in some observations being plotted on the wrong side of the nodal plane, as would the "unextended" observation at Station 2 in Figure 20.

The effect of the above procedure is to form a pattern of compressions and dilatations that would be observed on the surface of a sphere of uniform velocity throughout. By these means, Byerly attempted to divide the globe into areas in which all the observations were either compressions or dilatations, and then to separate these areas by two planes extended through the earth. One of these planes, he maintained, would represent the orientation of the plane of a fault, and the other would represent an "auxiliary" plane, passing through the focus of the earthquake and at right angles to the fault plane. This concept will be explained more fully in the next section.

Development of Modern Nodal Plane Theory

The San Francisco earthquake of April 18th, 1906, profoundly affected the thinking of seismologists all over the world. Here, the final effects of the forces generating the earthquake consisted of right-lateral strike-slip fractures over a 190-mile line from Point Arena southeastward, and Reid (1910) proposed his Theory of Elastic Rebound to explain the mechanism by which it was produced. This work, based on repeated geodetic surveys in the San Francisco region, suggested that strain had accumulated along the San Andreas Fault for perhaps the last 100 years, and had been released impulsively at the instant of the earthquake through the rebound of the Pacific side of the fault to the north. This proposal still largely influences the thinking of many of the world's leading seismologists.

Reid's model suggests that earthquakes must involve the sudden failure of the earth's crust under the action of a couple. If this is the case, we would expect to find that points ahead of the throw receive an initial compression, and points behind it a dilatation. It follows that separation of the areas of compression and dilatation should be

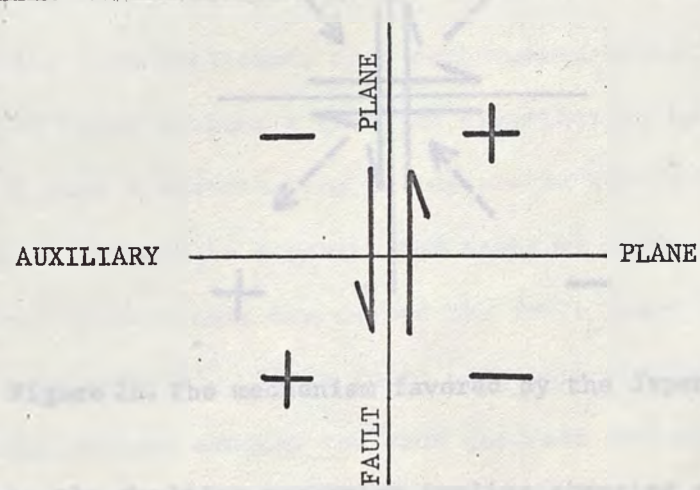


Figure21. The faulting mechanism

accomplished by the plane of the fault and by a plane at right angles to it (the auxiliary plane), both passing through the focus (Fig. 21).

The situation could not normally be expected to be this simple, since faults normally are not vertical, nor do they usually undergo strictly horizontal motion; but the concept of a pair of orthogonal planes -- the plane of the fault and an auxiliary plane at right angles -- should be completely general.

While this model has gained general acceptance from American seismologists (Byerly and Stauder, 1957) and seems to be the most satisfactory model for Russian earthquakes (Keylis-Borok, 1957), Japanese seismologists, largely owing to work performed by Honda, propose a different type of mechanism. The source mechanism favored by the Japanese is a pair of couples acting at right angles in a single plane (Honda, 1957). This is the equivalent of two forces in a line, directed toward the origin, and two others in the adjacent quadrants, directed outward (Fig. 22).

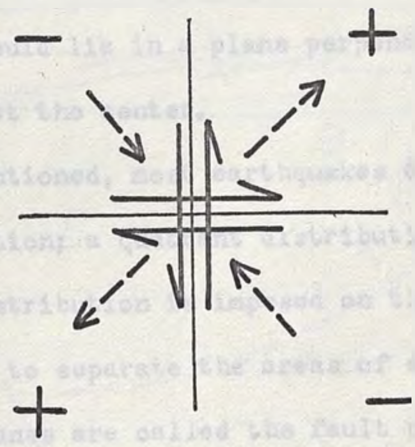


Figure 22. The mechanism favored by the Japanese

While the faulting mechanism implies shearing of two adjacent blocks without a change in their volume, the Japanese model is a purely deformational force system. Honda (1957) has named the faulting mechanism Model I, and the Japanese model, Model II. This terminology will be used throughout the remainder of this paper.

The Unit Focal Sphere

A useful device in visualizing the propagation of seismic waves from a point of disturbance is the unit focal sphere (Scheidegger, 1957). If, in theory, a small sphere surrounding the focus of an earthquake is isolated, and the character of the subsequent motion on its surface is inspected, it should be possible to deduce the nature of the force system at the center that would give rise to the observed displacement pattern. For instance, it should be clear that a simple force would send compressions into the hemisphere ahead of the direction of motion, and result in rarefactions in the hemisphere behind. Since there is no component at right angles to the axis along which the force is operating, a great circle would be observed on which there would be no motion. This great circle would lie in a plane perpendicular to, and passing through, the force at the center.

As has been mentioned, most earthquakes do not result in so simple a pattern of first motion; a quadrant distribution is more generally the rule. If such a distribution is imposed on the unit sphere, two nodal planes must be used to separate the areas of different first motion. As before, these planes are called the fault plane and the auxiliary plane (Byerly, 1938). It is found that both the Type I and Type II mechanisms produce exactly the same quadrant radiation pattern of P, and both satisfy the condition that compressions and dilatations are arranged in alternate quarter-spaces. The pattern produced by these mechanisms on the surface of the focal sphere has the following characteristics: (Honda, 1957)

1. Compressions may be separated from dilatations on the surface of the focal sphere by two planes intersecting at right angles, and oriented in such a manner that their line of intersection passes through the center of, and is perpendicular to the plane of the force system at the center. (This line is sometimes referred to as the Null Vector (Hodgson, 1957)). For the Type II source, the lines of force of both dipoles lie in one of the planes, while for the Type I source, the fault plane is in the line of force of the dipole, and the auxiliary plane is perpendicular to it.

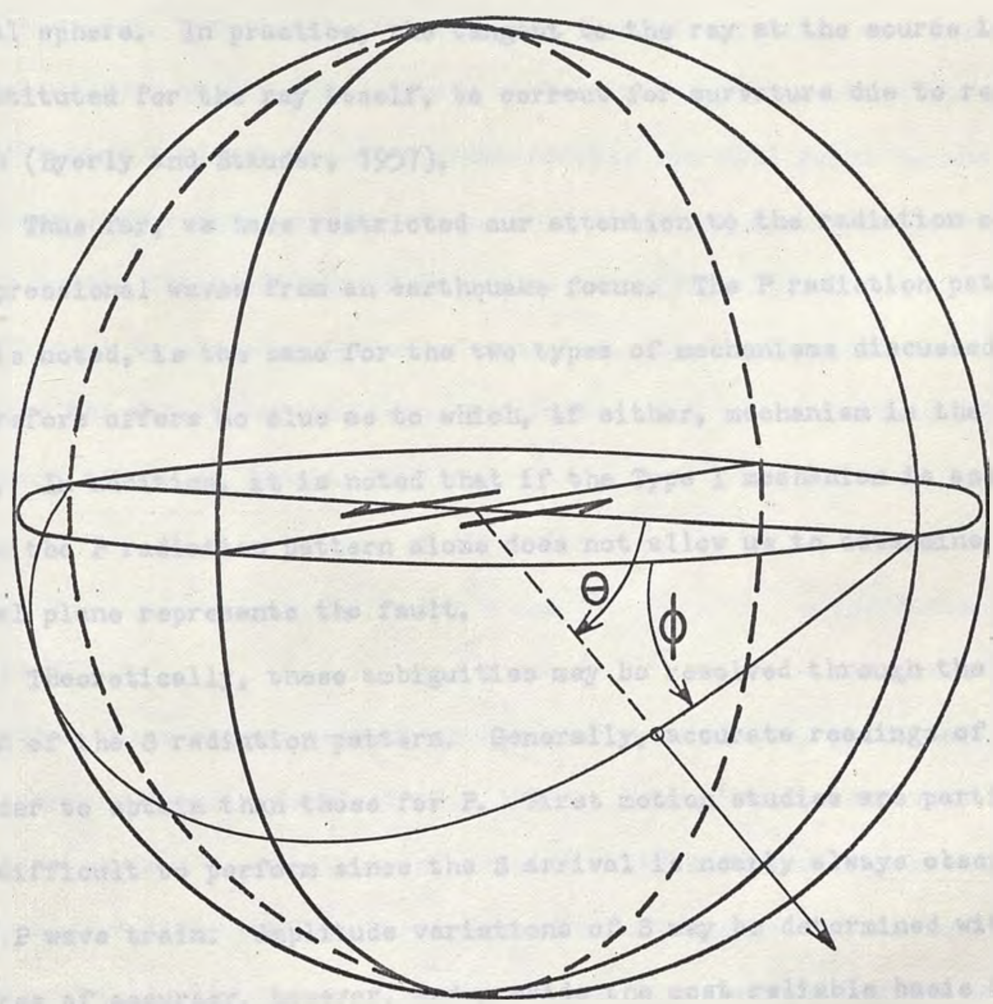


Figure 23. Spherical coordinate system used in defining P radiation pattern

2. The amplitude of P goes to zero on both nodal planes.

3. The maximum amplitude of P is attained in the plane of the force system, and in a direction midway between the two nodal planes.

4. Elsewhere over the surface of the focal sphere, the amplitude of P varies in proportion to $\sin 2\theta \cos \phi$. These are the angles of a spherical coordinate system so oriented that ϕ is the angle between the plane of the force system and the plane containing the ray, as the latter is rotated about a line lying in the plane of the force system and perpendicular to one of the nodal planes. Then θ is the polar angle between the line of rotation and the line containing the ray (Fig. 23).

In the discussion of P, it should be understood that the direction of vibration is always along a line passing through the center of the focal sphere. In practice, the tangent to the ray at the source is substituted for the ray itself, to correct for curvature due to refraction (Byerly and Stauder, 1957).

Thus far, we have restricted our attention to the radiation of compressional waves from an earthquake focus. The P radiation pattern, it is noted, is the same for the two types of mechanisms discussed and therefore offers no clue as to which, if either, mechanism is the correct one. In addition, it is noted that if the Type I mechanism is assumed, then the P radiation pattern alone does not allow us to determine which nodal plane represents the fault.

Theoretically, these ambiguities may be resolved through the inspection of the S radiation pattern. Generally, accurate readings of S are harder to obtain than those for P. First motion studies are particularly difficult to perform since the S arrival is nearly always obscured by the P wave train. Amplitude variations of S may be determined with some degree of accuracy, however, and provide the most reliable basis for resolution of the ambiguities (Ritsema, 1957; Honda, 1957).

In dealing with S, first note that the plane in which the direction

direction of motion at the source. In addition, for any directed force, the amplitude of S must go to zero on the line of action since there is no transverse component there. It therefore becomes apparent that the fault plane in the Type I mechanism may be distinguished from the auxiliary plane since the amplitude of S goes to zero there, while attaining a maximum on the auxiliary plane. Further, the direction of polarization on the focal sphere for the Type I mechanism will always lie on a great circle containing the points where the line of action of the dipole intersects the surface of the sphere (Fig. 24).

In contrast, amplitudes of S from the Type II mechanism are found to achieve a maximum on the focal sphere at both nodal planes while the direction of polarization need not lie on a great circle, but will point to one of four places on the focal sphere where lines bisecting the force system emerge. At these points the amplitude of S goes to zero (Fig. 25).

Referring to the same system of spherical coordinates that was used in describing the P radiation pattern, amplitudes of S on the surface of the unit sphere should be (Honda, 1957):

	θ direction	ϕ direction
Type I	$\cos^2\theta \cos\phi$	$-\cos\theta \cos\phi$
Type II	$\cos^2\theta \cos\phi$	$-\cos\theta \sin\phi$

Various other source mechanisms have been postulated, principally by Russian workers (Keylis-Borok et al., 1958). Some of these are very complex and involve various combinations of dipoles, simple forces, and rotations. However, observations of most earthquakes indicate motion at the source not unlike that of the two models discussed above, and the more complex models will not be discussed.

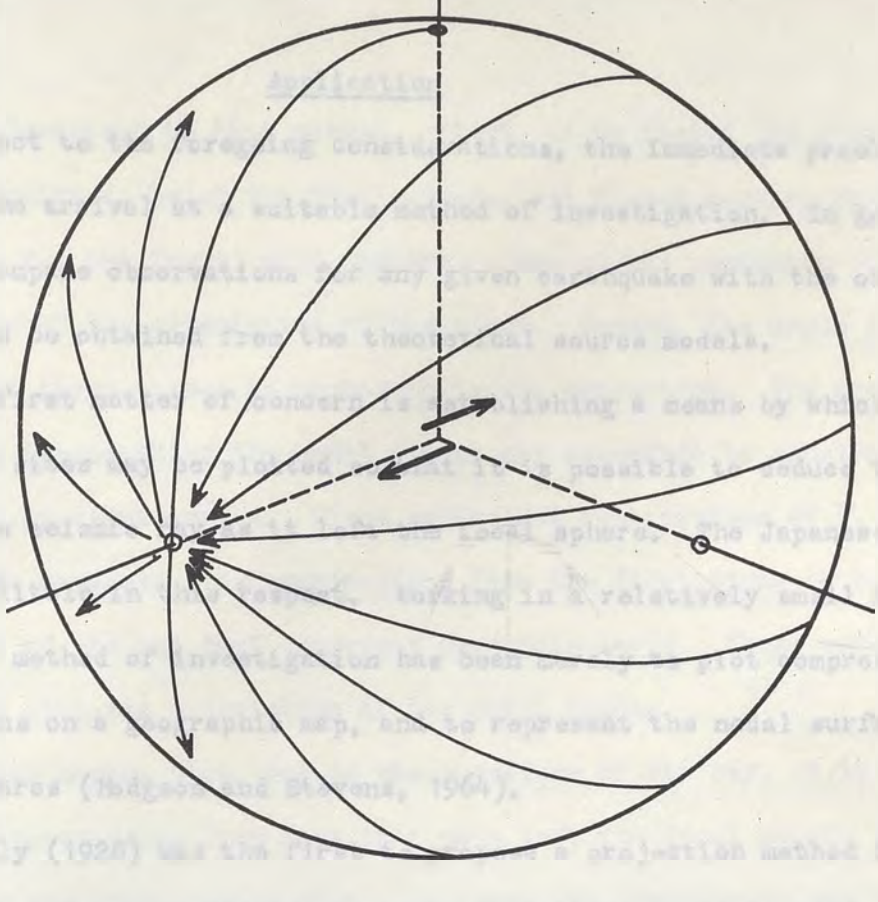


FIGURE 24. Directions of Polarization of S for the Type I Mechanism (schematic)

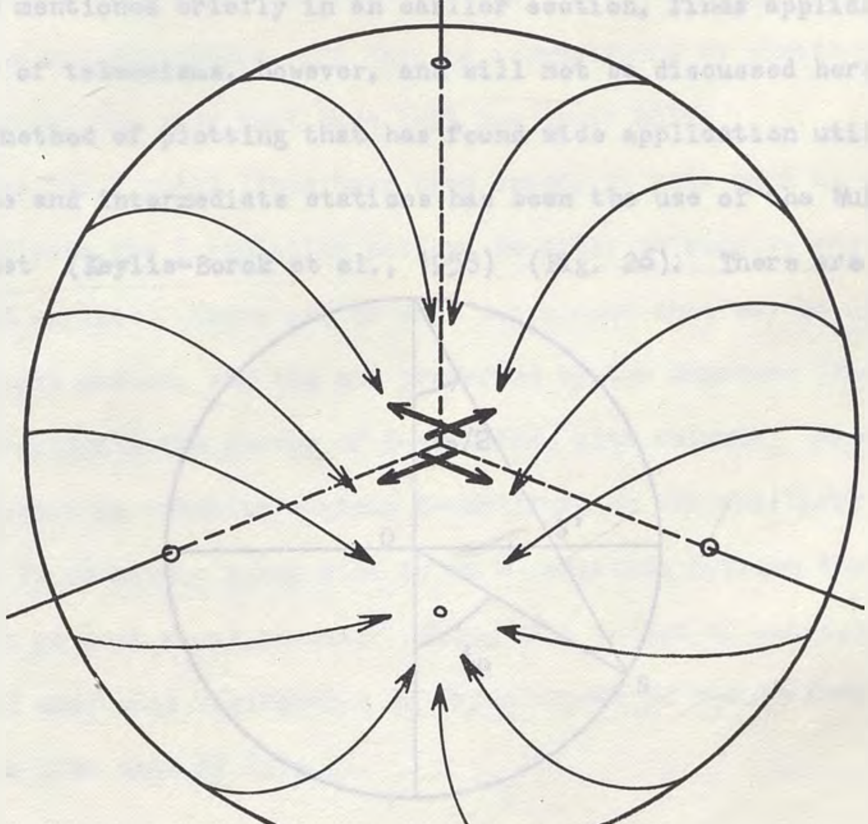


FIGURE 25. Directions of Polarization of S for the Type II Mechanism (schematic)

Application

Subject to the foregoing considerations, the immediate problem now becomes the arrival at a suitable method of investigation. In general, we wish to compare observations for any given earthquake with the observations that would be obtained from the theoretical source models.

The first matter of concern is establishing a means by which the various recording sites may be plotted so that it is possible to deduce the character of the seismic ray as it left the focal sphere. The Japanese have been troubled little in this respect. Working in a relatively small area, their principal method of investigation has been merely to plot compressions and dilatations on a geographic map, and to represent the nodal surfaces by two lines or arcs (Hodgson and Stevens, 1964).

Byerly (1928) was the first to propose a projection method by which observations from a worldwide network of stations could be used. His method, which was mentioned briefly in an earlier section, finds application only in the study of teleseisms, however, and will not be discussed here.

One method of plotting that has found wide application utilizing readings from close and intermediate stations has been the use of the Wulff stereographic net (Keylis-Borok et al., 1958) (Fig. 26). There are

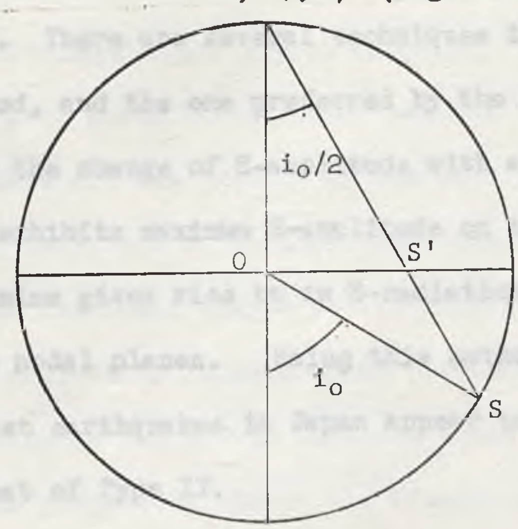


Figure 26. The Wulff projection. OS' is the distance from the origin at which the observations are plotted

several advantages to this method. First, if we regard the sphere of the projection as being the focal sphere, all planes passing through the center (e.g., the focus) will project as one of the meridians of the net, regardless of the orientation of the plane. Second, the angle of intersection of these planes is preserved in the projection. The projected meridians representing the nodal planes may therefore be constrained to intersect at right angles. Given sufficient observations of P, the problem is then to separate the compressions from the dilatations by two of the meridians of the net that intersect perpendicularly. These meridians will then give the orientation of the nodal planes.

It may happen that, due to the curvature of the ray, it is necessary to plot observations from rays that have left the focal sphere in both the upper and lower hemispheres. Although the hemispheres can be plotted separately, a more desirable procedure is to have all the observations plotted on one hemisphere, and this is accomplished by plotting backward extensions of the rays that have left the lower half.

After the P nodal lines have been drawn, it will then be necessary to investigate the S radiation pattern in order to resolve the ambiguities mentioned earlier. There are several techniques that may be used here. The simplest method, and the one preferred by the Japanese (Honda, 1957), is to investigate the change of S-amplitude with azimuth. Recall that the Type I mechanism exhibits maximum S-amplitude on the auxiliary plane, while the Type II mechanism gives rise to an S-radiation pattern that achieves a maximum on both nodal planes. Using this method of analysis, Honda has found that most earthquakes in Japan appear to result from a source mechanism like that of Type II.

On the whole, methods involving the direction of polarization of S seem to provide the most satisfactory means by which to select the model. The plane of polarization will maintain a constant attitude with respect to the ray along the entire path of travel but, since in most cases the ray is bent, it becomes necessary to project the plane back to its proper position with respect to the focal sphere.

Several approaches may be tried in applying the polarization of S to the focal sphere. Ritsema (1957) prefers to plot his observations directly on the Wulff net. To do this, he resolves the horizontal and vertical components of S at the recording station, projects the ray backward to the focal sphere (utilizing tables of angle of emergence versus distance) and projects a short line representing the direction of polarization onto the equatorial plane. When all the observations have been plotted, he then attempts to resolve the focal mechanism by comparing the S polarization pattern obtained with the patterns hypothesized for the theoretical models. Most of the earthquakes investigated by Ritsema appear to have resulted from the Type I mechanism.

Stauder (1960) determines the plane of polarization at the various stations by constructing particle motion diagrams. For teleseisms, this method appears to give quite satisfactory results. His findings indicate that some earthquakes are the product of one model, and some of the other. Stauder frequently makes use of another projection that is commonly used in conjunction with the focal sphere -- the central projection (Fig. 27). Here the plane of projection is most often situated on the pole of the top hemisphere, although the bottom hemisphere may also be used for distant observations. This projection offers the advantage of distinguishing between the S polarization patterns of the Type I and Type II mechanisms at a glance,

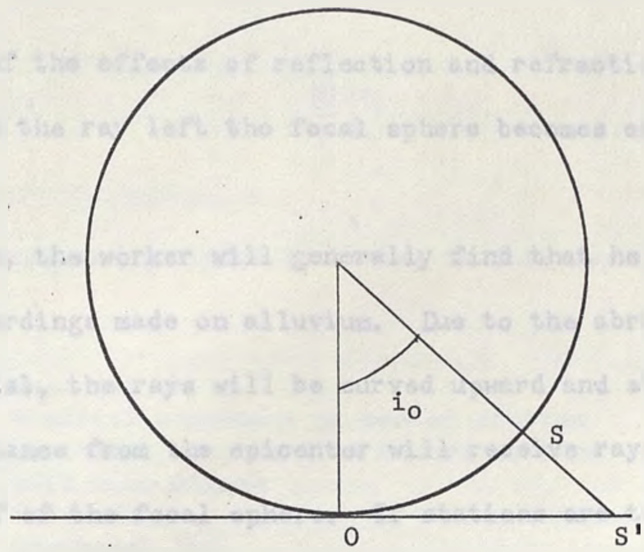


Figure 27. The Central projection. OS' is the distance from the origin at which the observations are plotted

since the great circle described by the lines of polarization of the Type I model project as straight lines, while the lines of polarization of the Type II model appear as hyperbolas. Although the nodal planes will also project as straight lines, the central projection does not permit constraining their projections to meet at right angles.

Special Problems related to Observations at Short Distances

In the study of focal mechanisms at teleseismic distances, one of the first problems to be encountered was the determination of the angles of incidence and emergence of the seismic ray. As the velocity of the near-surface layers varies, so did the angle of emergence. Subsequent to the publication of tables of angle of emergence versus various epicentral distances, however, (Jeffreys and Bullen, 1940) this problem was largely resolved.

Much more severe is the similar problem encountered by those who wish to study focal mechanisms of small earthquakes at very short distances. In this case, most, or all of the path will lie in an inhomogeneous medium, and, because of the effects of reflection and refraction, the vertical angle at which the ray left the focal sphere becomes extremely difficult to determine.

In Nevada, the worker will generally find that he must eventually resort to recordings made on alluvium. Due to the abrupt velocity jumps in this material, the rays will be curved upward and stations beyond a certain distance from the epicenter will receive rays that have left the lower half of the focal sphere. If stations are to be placed beyond this distance, it will be necessary to plot them accordingly. Further, lateral velocity variations between alluvium filled valleys and adjacent mountain ranges will cause waves to be refracted, as will the basement beneath the valleys.

Under these conditions, any study of focal mechanisms will also, of necessity, be a study of the geologic structure of a region, and into methods of precise hypocenter location.

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NOTE

On the seismograms included as Plates in this paper, the following details apply:

Trace 1: West leg
Trace 2: Vertical component at center station
Trace 3: East-West component at center station
Trace 4: WWVB time signal
Trace 5: North-South component at center station
Trace 6: Southeast leg
Trace 7: Northeast leg

Sense of motion on plates 1, 2, and 3 is such that an upward deflection of the trace implies upward movement of the ground on the vertical instruments, eastward motion of the ground on the East-West instrument, and northward motion of the ground on the North-South instrument.

However, on Plate 4, an upward deflection means ground motion downward, eastward, and southward.

Thus, in Table 1, a "C" under the column numbered, say, 6 means that the instrument on the southeast leg received an initial compression from that particular event. Similarly, "D" means dilatation, "E", east, etc.

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