MARC L. SBAR
MUAWIA BARAZANGI
JAMES DORMAN
CHRISTOPHER H. SCHOLZ
Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964
ROBERT B. SMITH *Department of Geological and Geophysical Sciences, University of Utah, Salt Lake City, Utah 84112*

Tectonics of the Intermountain Seismic Belt, Western United States: Microearthquake Seismicity and Composite Fault Plane Solutions

ABSTRACT

During the summer of 1969, six portable seismographs were operated at 82 sites along the Intermountain Seismic Belt from southwestern Utah to northwestern Montana. This survey followed a well-known seismic belt along the eastern physiographic boundary of the Basin and Range province, and within the middle and northern Rocky Mountains. In general, the 120 microearthquakes located in this study follow the same spatial trend as the macroseismic earthquakes reported by the NOS (formerly USCGS). Most of the microearthquakes clustered in time and space along well-known fault zones on which late Tertiary or younger movements have occurred. All of the accurately located hypocenters occurred between the surface and a 20 km depth. Composite fault plane solutions along the Hurricane and Sevier fault zones (southwestern Utah), Tushar and Sevier fault zones (Marysvale area, Utah), and Wasatch and East Cache fault zones in central and northern Utah indicate vertical-motion on steeply dipping fault planes. These motions may be indicative of differential movements between the Basin and Range province and the Colorado Plateau-Rocky Mountains. Composite fault plane solutions (CFPS) in the Caribou Mountains, southeastern Idaho, and Flathead Lake area, northwestern Montana, show normal faulting on less steeply dipping planes and have west-northwest trending extensional axes. Swarm activity was also observed in the above two regions. Between the above two areas of uplift and extension lies a region of complicated geology and seismicity.

INTRODUCTION

During the summer of 1969 the authors undertook a field investigation of the seismicity and tectonics of the Intermountain Seismic Belt. In Utah, this region forms the boundary between the Colorado Plateau on the east and the Basin and Range province on the west, and north of Utah it lies within the middle and northern Rocky Mountains (Fig. 1). Tectonically, this belt forms the eastern boundary of a region of low upper mantle P-wave velocity (Archambeau and others, 1969; Julian, 1970; Prodehl, 1970) and high heat flow (Roy and others, 1968; Blackwell, 1969; Roy and others, 1971) that extends beneath the Basin and Range province and the Rocky Mountain Trench. The eastern part of the Basin and Range province has been the site of extensive igneous activity and a zone of major block faulting from mid-Tertiary to the present (Eardley, 1962; Hamblin, 1963; Hamilton and Meyers, 1966; Armstrong and others, 1969).

The Intermountain Seismic Belt is marked by relatively high seismicity (Cook and Smith, 1967; Barazangi and Dorman, 1969) of both the tectonic and swarm type (Sykes, 1970). Molnar and Oliver (1969) showed that the high-frequency Sn phase is highly attenuated across the Basin and Range province, a property that is also characteristic of mid-oceanic ridges and the regions behind most island arcs.

Geological Society of America Bulletin, v. 83, p. 13–28, 10 figs., January 1972

A wealth of geological and geophysical data is available for the Intermountain Seismic Belt, yet unlike many of the tectonically active oceanic areas of the earth, the relation of this region to global tectonics is not well understood. We believe that through the use of microearthquake techniques as applied by Ward and others (1969), Sbar and others (1970), and Seeber and others (1970), additional information regarding the current movements in the Intermountain Seismic Belt can be obtained, leading to a better understanding of the origin and development of this area. We present new microearthquake data in the form of located events and composite fault plane solutions. The fault motions determined in this study are those of differential motion on a near vertical plane and west-northwest extension. The possible interrelation of the adjacent tectonic provinces with the Intermountain Seismic Belt is examined.

In the body of the paper the method of analysis is only mentioned briefly, since it is discussed in detail by the authors listed below. Each area is then treated separately in sequence from north to south.

METHOD OF ANALYSIS

The methods employed in this study both for the location of microearthquakes and the determination of the composite fault plane solutions have been described by Seeber and others (1970) and Sbar and others (1970). The instrumentation is discussed by Boucher and Fitch (1969) and Ward and others (1969). The instruments were generally operated at a magnification of 3×10^6 to 6×10^6 at 25 Hz. Second marks were superimposed on the records to provide a timing accuracy of $\pm$ 0.1 sec. Clock corrections using WWV were made daily. This study used six portable instruments with site spacings from 10 km to 30 km depending on the local physical conditions. The locations were determined graphically using the method described by Seeber and others (1970). A check on the accuracy of hypocenter determinations was made using quarry blasts from the Bingham Canyon Copper Mine in northern Utah. The hypocenter of a blast that was recorded on all six stations was located within 2 km of the mine. This was taken as the uncertainty of location under favorable circumstances.

The Jeffreys-Bullen (J-B) velocity structure for the crust was used in all of the hypocentral locations since, in most of the specific areas surveyed, refraction profiles were not available. In those areas where refraction data were available (Berg and others, 1960; Prodehl, 1970) the difference in location using the different models was found to be less than the graphical intersection error in determining the location, due to the small hypocentral distances as well as the similarity in velocity structure of the models. Each hypocentral location was given a quality factor indicated by the different sized symbols in the figures. The largest symbol indicates a possible error in location of about 2 km. The intermediate size symbol represents an error of about 5 km and the small symbol an error of about 10 km. No attempt was made to locate events at distances greater than about 60 km from the network.

Most of the time six stations were operating simultaneously in an area. When stations were recording in more than one area (Fig. 2) two or

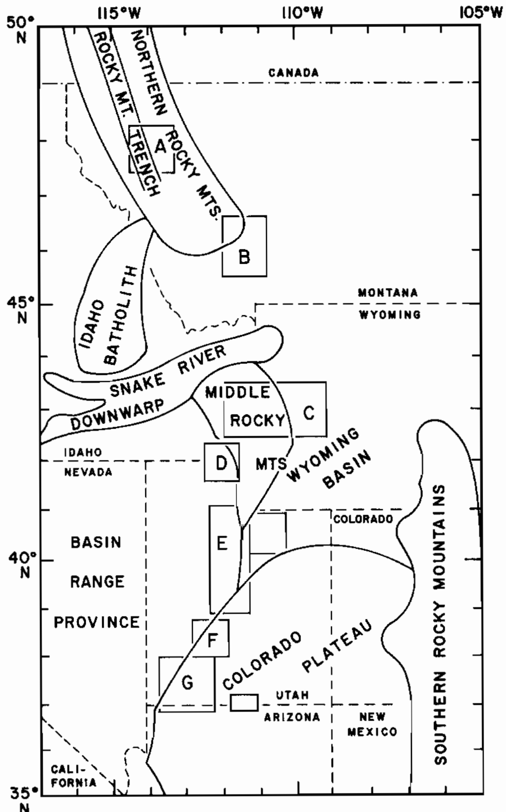

Figure 1. Map of Intermountain Seismic Belt showing tectonic provinces and regions surveyed (boxes): (A) Flathead Lake, (B) Three Forks, (C) Caribou Mountains, (D) Cache Valley, (E) Central Utah, (F) Marysvale, (G) Sevier-Hurricane, (H) Uinta Mountain, and (I) Lake Powell.

four stations would be recording simultaneously in each area. Part of the time (see figures) one of the six vertical geophones was replaced by a horizontal geophone in order to better detect the S-wave arrival.

The first motions of the P-wave for each microearthquake were read with the aid of a low-power microscope. These were then plotted on the upper hemisphere of an equal area projection about the hypocenter. Since the angle of emergence from the focal sphere is sensitive to the crustal structure, and in particular to the velocity gradient, it is important to select an accurate structure. In most of the areas surveyed, seismic refraction information was not available. Because of this, several structures (J-B, Berg and others, 1960; Prodehl, 1970) were compared using a three-dimensional ray tracing program described by Jacob (1970). It was found that the variation of the angle of emergence with crustal model was greatest for foci with shallower depths. The velocity structure of Prodehl (1970) is the best available in most cases, and was used where applicable. At greater epicentral distances, some of the rays emerged from the lower hemisphere of the focal sphere. These were projected onto the upper hemisphere. All of the focal plots determined from the microearthquakes in each area were superimposed to form a composite fault plane solution (CFPS), since the data from any single microearthquake were insufficient to determine the nodal planes of the fault plane solution (FPS). Only one of the two nodal planes of the CFPS can be the fault plane, which cannot be determined uniquely from the CFPS. Hence the fault plane is usually chosen to agree with the general strike and sense of motion of faults mapped at the surface. Magnitudes were not individually determined

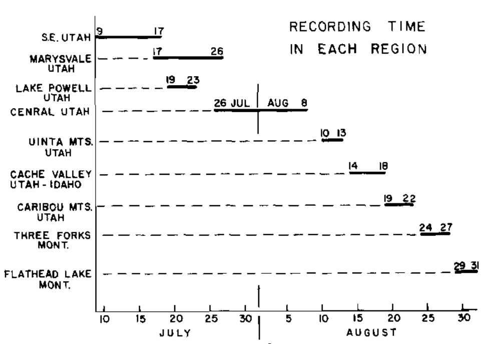

Figure 2. Graph indicating the days of recording in each of the areas.

for these microearthquakes, but the magnitude range of the events recorded was approximately −1 to 2½.

PRESENTATION OF DATA AND DISCUSSION OF INDIVIDUAL AREAS

Flathead Lake Area, Northwestern Montana

The primary geologic feature in this area is the southern extension of the Rocky Mountain Trench (Fig. 1A). The origin of this feature in Montana is described by Mudge (1970). The major tectonic movement was uplift during the Cretaceous and early Tertiary (Laramide orogeny) and gravity sliding to the east during the early Tertiary, forming the Disturbed Belt of thrust faults in western Montana (Mudge, 1970). Block faulting was initiated after the sliding and, based on the current seismic activity (Figs. 3 and 10), is still continuing. The block faulting occurred at the head of the gravity slides resulting in the formation of the Rocky Mountain Trench (Mudge, 1970) which in the area of investigation, is bounded by the east by the Mission Fault (Fig. 3).

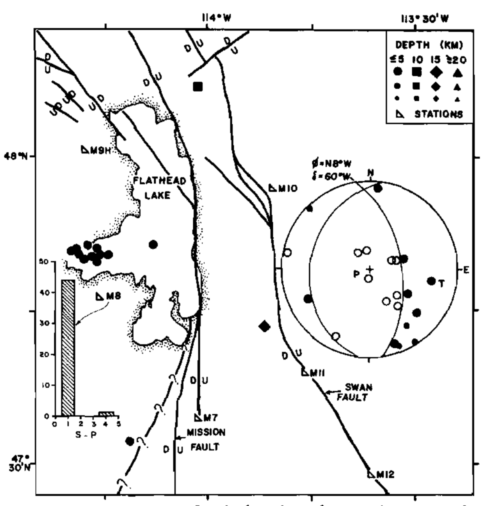

Figure 3. Map of Flathead Lake region, northwestern Montana (Fig. 1A). Geology from Mudge (1970). Solid symbols represent microearthquakes. Large microearthquake symbol indicates an error in hypocenter location of ± 2 km, intermediate symbol ± 5 km, small symbol, ± 10 km. The focal plot is an equal area projection of the upper hemisphere. Solid circles are compressions. Open circles are dilatations. Smaller circles are less reliable first motions. Stations with an H have a horizontal geophone and no vertical.

The cluster of microearthquakes shown beneath the western part of Flathead Lake is part of a swarm of earthquakes which started in April 1969 and appears to have continued with diminished activity at least until March 1970. Of the 31 events listed by the NOS (National Ocean Survey, formerly U.S. Coast and Geodetic Survey) in this region, only ten occurred from January 1962 to April 1969. The other 21 events occurred in one year from April 1969 to March 1970.

In this paper we define a microearthquake swarm as a series of events of nearly the same size separated in time by hours or even minutes and localized in space. The depths of the microearthquakes in the swarm ranged from near-surface to three km. The scatter in the east-west direction probably reflects the better north-south control in the station distribution. A histogram showing the number of microearthquakes recorded versus S-P times is shown for station M8. This histogram illustrates the unusually high activity of the swarm as compared with the region as a whole. The other microearthquakes were located near enough to known recently active faults to suggest that they may be associated with these faults. A question exists as to whether or not these faults flatten at depth. Our data cannot clarify this problem, although we can demonstrate that faulting extends to at least a 15-km depth as indicated by the deepest hypocenter in this area. Bally and others (1966) show seismic reflection data which implies that similar faults in the southern Canadian Rocky Mountains do flatten at a depth of no greater than 8 km.

No microearthquakes were located in the Disturbed Belt to the east of the area shown in Figure 3. The NOS plot of epicenters (Fig. 10) also indicates a lack of activity in this region. This historic seismic activity correlates with the region of uplift postulated by Mudge (1970).

The composite fault plane solution (CFPS) shown in Figure 3 is an equal area projection of the upper hemisphere. It shows normal faulting with west-northwest extension, and the nodal planes are well determined. In this particular case, changes in the angles of emergence of the points, which would change their radial distance from the center of the plot, would only change the dip angles of the nodal planes, but not the mechanism itself. For the CFPS, the cluster of microearthquakes in the swarm was treated as a single point, since nine of the ten largest events had the same first motions at the various stations and the azimuth at each station was essentially the same for all events. The fault plane striking N. 8° W. correlates well with the regional strike of the faults shown in Figure 3, and the sense of motion is the same as that on both the Swan and Mission faults. The dip is westerly as shown by Mudge (1970) for these faults. It should be emphasized that the fault planes of each of the microearthquakes may differ from that of the CFPS shown in Figure 3, and that the well-determined nodal planes indicated may be a coincidence. However, the correlation of the fault plane with known structural geology and the favorable comparison with teleseismic fault plane solutions, in the cases of Cache Valley and Marysvale (Smith and Sbar, in prep.), argue strongly for the validity of this technique in sampling the regional trends.

Three Forks Area, Southwestern Montana

The Three Forks area is at the southern terminus of the Disturbed Belt of western Montana (Figs. 1B and 4). This area also seems to be one of transition from generally north to west-northwest-trending structures to one of east-trending features. The geology is complex and various hypotheses have been presented for its origin. Robinson (1961) summarized these ideas and presented a more coherent though still incomplete picture of the region, which is used in a comparison with our data. The most recently active faults in the area (late Miocene and Pliocene) are the high-angle faults along the Bridger Range (Fig. 4). The thrust faults in the center are believed to be of Laramide age and the age of the Willow Creek Fault is unsure, but Robinson (1961) suggested that the Willow Creek fault was active in the Precambrian and during the Laramide orogeny. These older faults may provide weak zones on which the current stress is being relieved.

Microearthquakes were located near both the east- and north-trending older faults and no evidence of swarm activity was observed. The deepest event recorded was 15 km. The nodal planes determined from the CFPS have nearly the same strike as the two sets of faults above. Whether the orientation of the nodal planes represents a system of faults throughout the region with the same orientation, or is merely fortuitous we cannot determine. However, microearthquakes occurring on faults of different types and strikes would not be expected

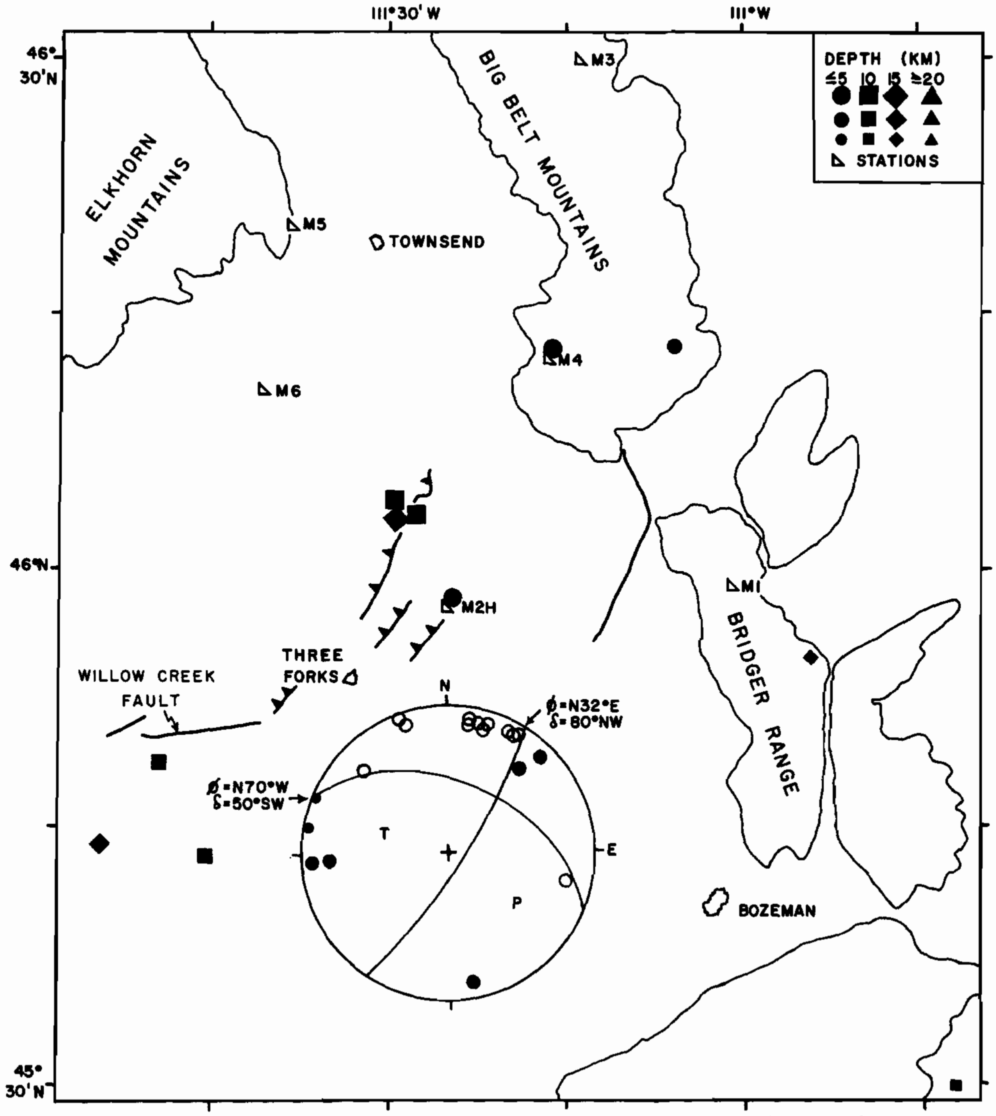

Figure 4. Map of Three Forks area, southwestern Montana (Fig. 1B). Fault locations from Robinson (1961). See Figure 3 for explanation of symbols. The teeth are on the upper plate of the thrust faults.

to have the same nodal planes, though they may have the same tension and compression axes. We are not sure of the meaning of this solution at this time. It is included only because further research may explain it. For the above reasons, it is not included in Figure 10.

Caribou Mountains, Southeastern Idaho

The structure in the Caribou Mountains (Figs. 1C and 5) is dominated by two major types of deformation, thrust faulting of Laramide age and more recent block faulting (Armstrong and Oriel, 1965). The strike of the thrusts is generally north with thrusting to the east. No metamorphism, major fault breccia or mylonites have been found to be associated with these thrusts. During the Eocene the deformation changed to one of block faulting which has continued to the present, with three phases distinguishable. The latest of these phases has a strike that is north to northwest and is generally parallel to the present moun-

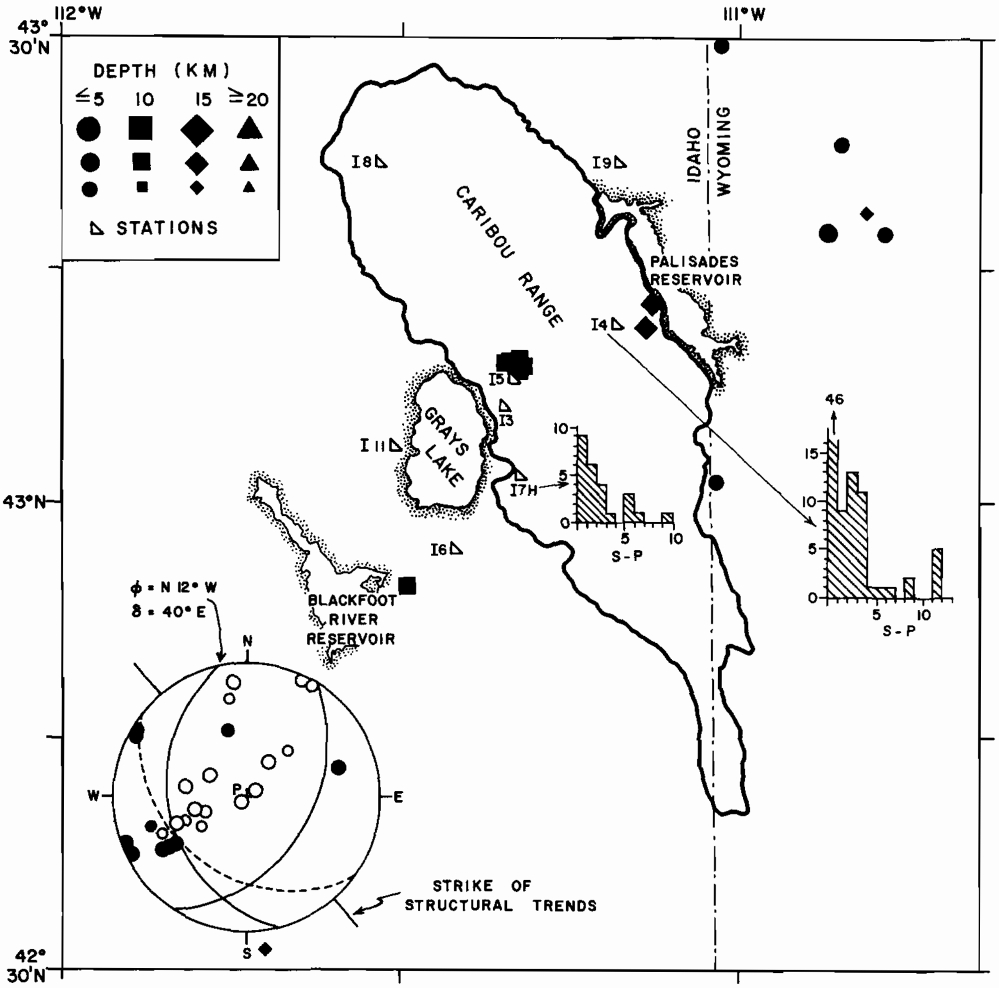

Figure 5. Map of Caribou Mountains region, southeastern Idaho (Fig. 1C). Structural trends from Geologic Map of Idaho (Ross and Forrester, 1959). See Figure 3 for explanation of symbols.

tain fronts with vertical motion dominant. Figure 5 shows the microearthquakes located during the four days of recording in that area. Only six of the stations shown were occupied at any one time. The activity in the area was scattered with the exception of three "hot spots" near stations I7, I4, and I5, where swarm type of activity was observed (*see* histograms near I4 and I7). Two of these three spots of swarm activity were also described in a report by Westphal and Lange (1966). In 1964, they recorded no activity near station I4, but significant activity near I5. Of the 56 earthquakes that they located, none were east of the Palisades Reservoir even though they had the capability to detect events there. Most of the activity which they located occurred between Grays Lake and the Palisades Reservoir. However, in our study moderate microearthquake activity was observed to the east of the reservoir. The spatial difference in the activity recorded by Westphal and Lange (1966) and our study emphasizes the sporadic nature of the seismicity. Of the microearthquakes recorded at station I4, most had S-P times less than or equal to one sec (see histogram, Fig. 5). At one extreme these events could be near the surface and about seven km from the station, or at the other, near the station and about seven km deep. In either case they would be considered very shallow microearthquakes. It is interesting that numerous microearthquakes were recorded close to the Palisades Reservoir. Possibly some of them may be associated with the reservoir loading. In this study we were unable to determine the relationship between the loading and seismicity. However, since this is a seismically active area, attention should be directed to the possibility of a causal relation between the seismicity and the reservoir loading. The cluster of five events near I5 occurred within one hour and the depth was well determined at 12 km from station I5. The events recorded at I7 had a wide range of S-P times, but many are considered members of swarms, since they were clustered in time and in groups with the same S-P times and other similar characteristics.

The other microearthquakes were scattered over a large area and seven were located off the map area. Since the more distant events would have to be larger to be recorded, this suggests that a large area of high seismicity exists in the Caribou Mountains region. The NOS epicenter locations shown in Figure 10 support this point.

The CFPS in this region shows predominant normal faulting with a northwest-trending extensional axis and fault plane striking N. 12° W. The dashed line indicates the limits for possible orientations of the fault plane. The strike of the structural trends is also plotted on the equal area projection. The strike of the fault plane correlates well with the strike of the most recent block faults described by Armstrong and Oriel (1965).

Cache Valley, Northern Utah

The Cache Valley region forms the northern part of the eastern boundary of the Basin and Range province with the Middle Rocky Mountains to the east (Fig. 1D). The valley is bounded on the east by the East Cache fault (Fig. 6). The western side is comprised of low hills which are bounded on the west by the Wasatch Fault (Fig. 6). Both of these faults are steeply dipping and have the west side downthrown (Eardley, 1962). It is quite possible that they form steplike faults on the east side of a large graben. All of the other faults shown in Figure 6 are also high angle faults.

Cache Valley and the surrounding area have been the site of several destructive earthquakes throughout the last 100 yrs (Cook and Smith, 1967). As a result, one might expect the earthquake activity to be relatively high. However, both the teleseismic activity in Figure 10 and the microearthquake activity in Figure 6 would be considered moderate for the Intermountain Seismic Belt. The population distribution may have had a strong influence on the destructiveness of the above earthquakes. The microearthquakes recorded were very shallow (≤ 5 km) and were observed to cluster in small groups of two to three events.

The fault plane striking N. 22° W. that was determined from the CFPS has a strike similar to that of the Wasatch and East Cache fault zones although the strike of the fault plane is not well-determined. The fault plane solution (FPS) found by Smith and Sbar (in prep.) for an earthquake in Cache Valley has the same sense of motion, but the strike is N. 10° E. If the one dilatation at the lower end of the plane in our CFPS were removed, it could rotate to about N. 15° E. The fault plane is steeply dipping and the CFPS indicates the same sense of motion as on the Wasatch and East Cache faults.

Central Utah

The Central Utah area separates the Basin and Range province from the Colorado Plateau (Fig. 1E). The dominant feature in this area is the Wasatch fault zone and its impressive scarp. The fault zone terminates south of Utah Lake (Fig. 7; Cook and Berg, 1961; Stokes, 1963). In the southern part of this region near the town of Gunnison the name Thousand Lake fault zone is applied to a series of faults along the Wasatch monocline (Cook and Smith, 1967). The Wasatch fault as mentioned above is steeply dipping with the west side down. The sense of motion on the Long Ridge fault (Fig. 7), however, is questionable on the geologic map of Cook and Berg (1961).

The microearthquake activity in the region is extremely low compared to the teleseismic activity shown in Figure 10, both in the northern and southern parts of Figure 7. Of the microearthquakes that were located, the four between the Long Ridge fault and the Wasatch fault zone occurred within a time span of 6.5 hrs, suggestive of a small swarm since no major shock occurred.

It is interesting that a topographic feature as impressive as the Wasatch fault zone should have such low seismic activity. Indeed, among recent macroseismic events a prominent gap exists in the central part of this region (Fig. 10E). The recording time in the central Utah area was the longest in the study (Fig. 2), and some of the instruments near the Wasatch fault zone were operated at their maximum

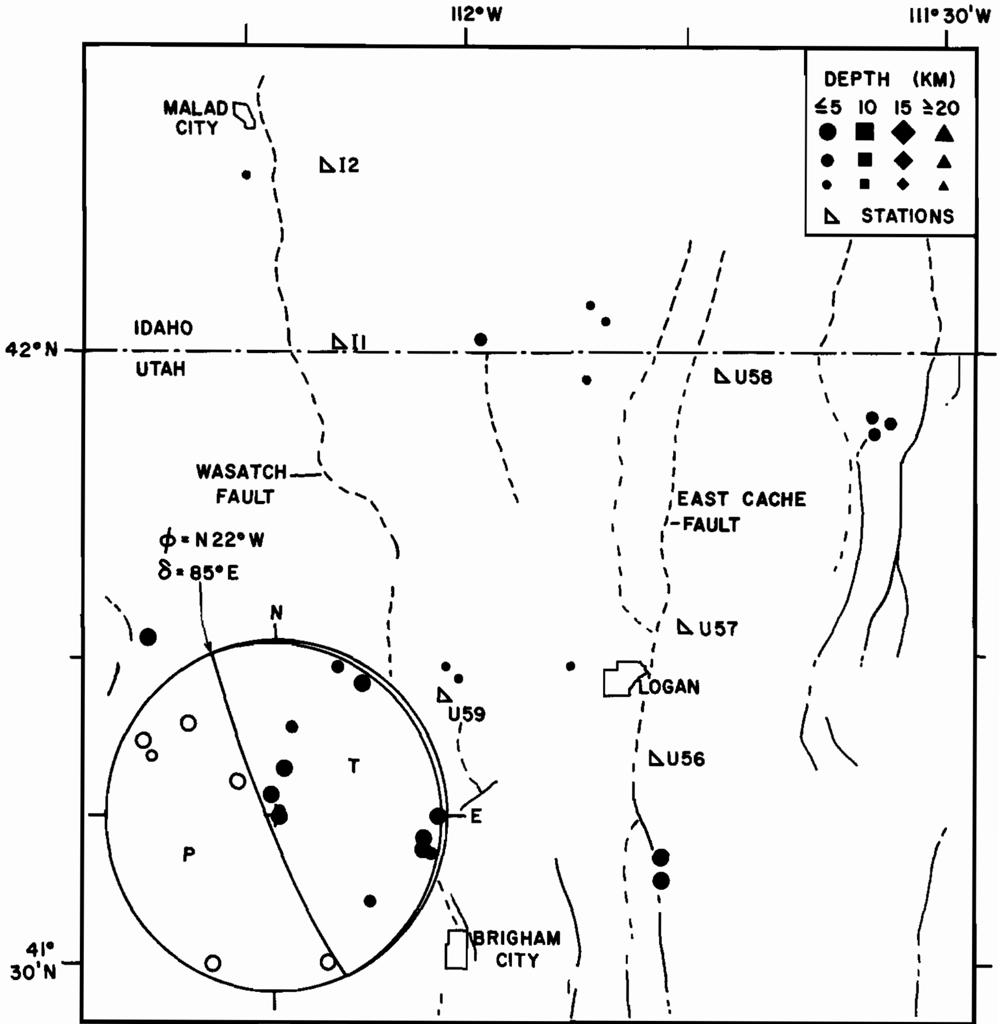

Figure 6. Map of Cache Valley region, northern Utah and southeastern Idaho (Fig. 1D). Geology from Stokes (1963) and Geologic Map of Idaho. See Figure 3 for explanation of symbols.

gain of 2.5×10^7 at 25 Hz. In addition, the listing of Cook and Smith (1967) shows only minor activity south of Salt Lake City since 1850. Therefore, the seismicity gap south of Salt Lake City is well established. A gap such as this is indicative of the uneven character of the seismicity in the Intermountain Seismic Belt.

The loading of some artificial lakes is known to have had major effects on the local seismic regime. The natural filling and dessication of Lake Bonneville, which at its maximum stage contained about as much water as Lake Michigan does today, imposed transient loads perhaps 100 times as great as any artificial reservoir filled in recent decades. The time scale of Broecker and Kaufman (1965) places several such cycles within the last 20,000 yrs, the highest (Bonneville) shore line having been cut about 12,000 yrs ago. Crittenden's (1963) bathymetric map shows that the water load occupied the basin, or tectonically downthrown block, adjacent to presently quiet segments of the Wasatch fault. The load would, therefore, tend to accelerate tectonic faulting during periods of rising water and to retard tectonic faulting during periods of receding water. In addition, variations in fluid pressure at the fault plane may have influenced fault slippage. The long-term tectonic regime may have been modified by the short-term oscillations of lake levels. However, the data available appear to be insufficient to determine whether these transient effects persist to the present, and whether the central Utah quiet zone is related to recent isostatic adjustments.

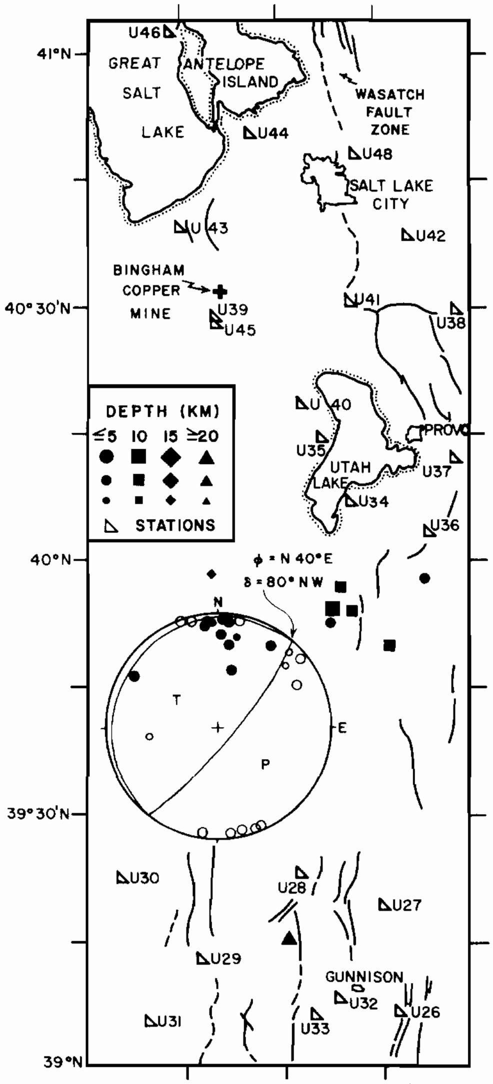

Figure 7. Map of central Utah (Fig. 1E). Geology from Stokes (1963). See Figure 3 for explanation of symbols.

All of the well-located microearthquakes located in Figure 7 were used in the CFPS. The nodal plane that is dipping nearly horizontal is well determined by the points on the equal-area projection. Since the two nodal planes must be orthogonal, the pole of the above plane and the data points fixed the position of the second nodal plane. The fault plane chosen was this second nodal plane. The sense of motion shown here does not agree with that of the Wasatch fault zone. However, most of the microearthquakes located in this study are west of the Wasatch fault zone and may be associated with the west side of the graben defined by the gravity study of Cook and Berg (1961). The two microearthquakes to the east could have the opposite sense of motion as that shown in the CFPS on a fault plane about N. 10° W. and still fit this solution. Because of this problem, we believe that this CFPS is weak, but favors motion on a steeply dipping plane with the east side down.

Marysvale, Southwestern Utah

The Marysvale area (Fig. 8) is geologically *unusual among the regions so far mentioned.* It is a region of extensive volcanic activity from the early to late Tertiary, which has resulted in extensive uranium mineralization (Kerr and others, 1957). This region is on the eastern margin of the Basin and Range province (Fig. 1F) and is dissected by two major fault zones. The Sevier fault zone is prominent here and extends into southern Utah. The Tushar Fault zone forms the west side of a graben bounded by these faults. The fault zones here trend northwest, in contrast to the usual northeast trend of major fault zones in the southern third of Utah (Stokes, 1963). The junction of these trends near Marysvale was the center of the volcanic episodes (Kerr and others, 1957).

The Cache Valley and Marysvale areas were the two most seismically active areas monitored in Utah during this investigation. Most of the activity at Marysvale was found to lie on the west side of the graben. A wide range of depths from near surface to 20 km was observed for these hypocenters. Even though this is an area of late Tertiary volcanism, no evidence of swarm activity was observed. The histogram of the number of microearthquakes versus S-P time for station U22 in Figure 8 indicates the higher activity recorded there as opposed to other instrument locations; however, the na-

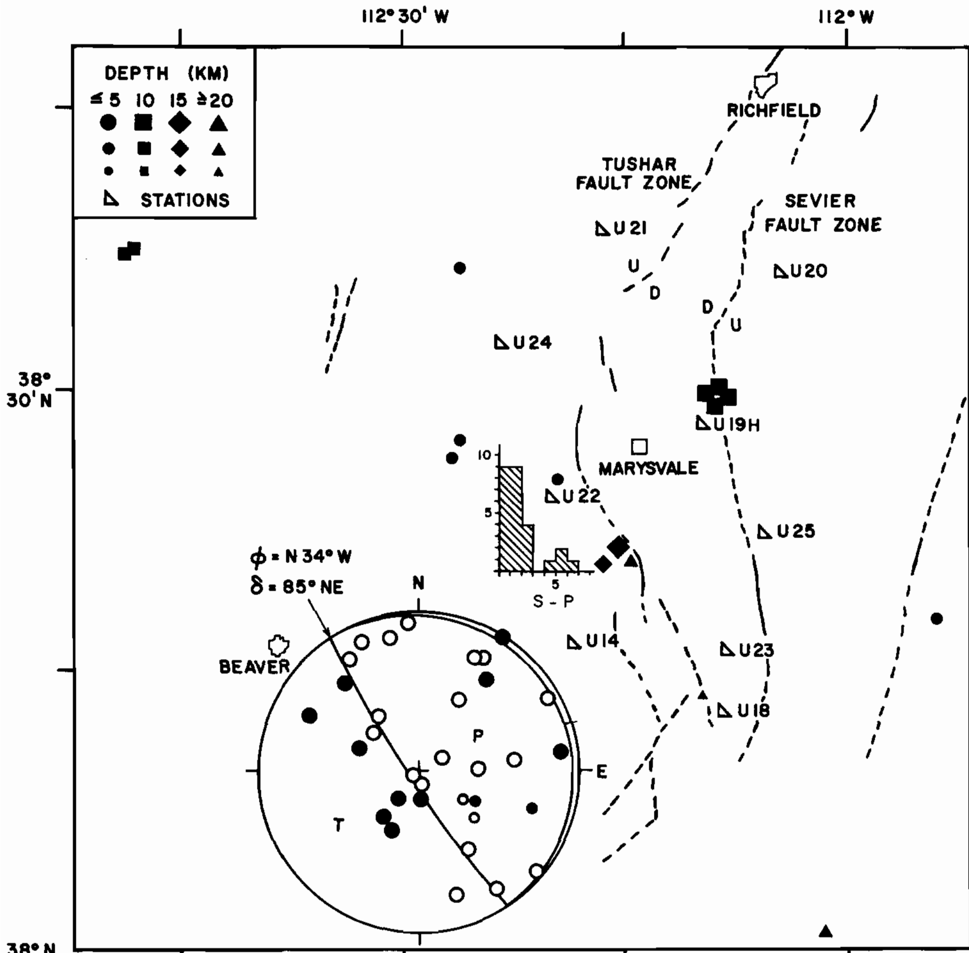

Figure 8. Map of Marysvale region, southcentral Utah (Fig. 1F). Geology from Stokes (1963). See Figure 3 for explanation of symbols. Station U19 was used as a horizontal part of the time.

ture of those events was not swarm type. Also, the four shocks near U19 were not a swarm, but a main shock and three aftershocks.

The CFPS shown in Figure 8 has a steeply dipping fault plane with a strike similar to that of the northwest-trending faults and a sense of motion the same as the Tushar fault zone. It is evident that a few of the events do not satisfy this solution, since they show the opposite first motion as that expected. This is reasonable, since the two major fault zones in this area have opposite motion. However, the four micro-earthquakes near U19 in Figure 8 had first motions consistent with the CFPS even though they occurred on the Sevier fault zone, which has the opposite sense of motion. This CFPS is quite similar to a teleseismic FPS determined by Smith and Sbar (in prep.) for a magnitude 5.8 earthquake in this area that occurred in October 1967. The strike of this FPS is about 20° from that of the CFPS determined in this study, but the sense of motion is the same. The high activity at Marysvale may be aftershock activity from the 1967 earthquake or symptomatic of high regional activity.

Hurricane and Sevier Fault Zones, Southwestern Utah

The geology of southwestern Utah is dominated by two major northeast-trending fault zones (Fig. 9). Both are high-angle faults with the west side downthrown (Stokes, 1963;

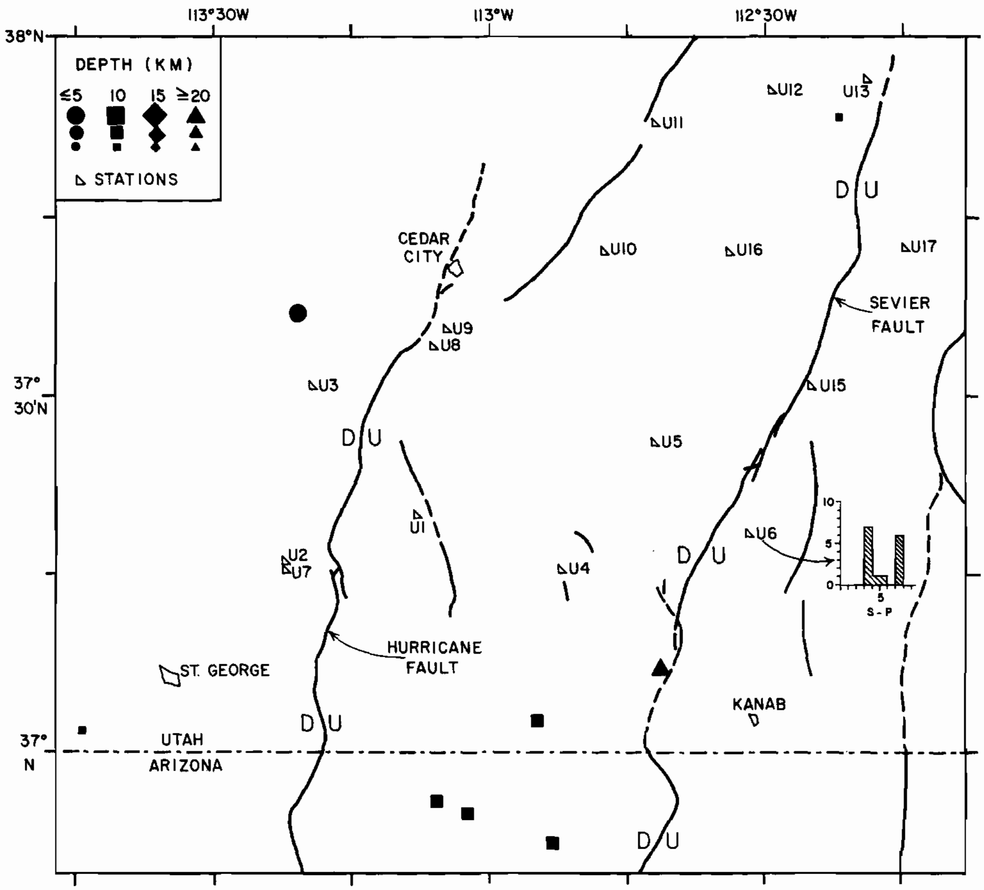

Figure 9. Map of Sevier-Hurricane fault zone region of southwestern Utah. Geology from Stokes (1963) and Moore and others (1960). See Figure 3 for explanation of symbols.

King, 1969). In addition, both faults have a significant topographic expression. The Hurricane fault is believed to have experienced an episode of major movement as late as Quaternary (Gardner, 1941), and volcanic activity has occurred less than 1,000 yrs ago (Hamblin, 1963). Numerous smaller faults with a northwest trend are also found in this area. Only a few of these are shown in Figure 9.

The microearthquake activity in this region was observed to be very low. Most of the events located were in the south-central portion of the figure and not obviously related to any of the faults shown. A number of microearthquakes was recorded at station U6. This was one of the most sensitive stations in this area. Interestingly, no events were recorded with S-P times less than three sec. The events with S-P times near three sec have a character similar to the microearthquake on the Sevier fault south of U6, which has an S-P time of 3.8 sec at that station. These events may be from the same area. The location of most of the other microearthquakes recorded at U6 cannot be determined. These events did not appear to be swarm type, since they did not cluster in time. The depths of the microearthquakes plotted in Figure 9 ranged from 5 to 20 km. A focal mechanism was not able to be determined for this region.

Lake Powell and Uinta Mountains, Utah

Microearthquake instruments were operated in these two areas for specific reasons. Lake Powell (Fig. 10I) is a reservoir in southern Utah that is currently being filled by the Colorado River. Recording was done to determine if any microearthquake activity would be associated with the filling of this reservoir. In the few days of recording around the lake, no activity was observed. A seismometer has been operated at the Lake Powell dam site since 1960 by the NOS at a lower sensitivity than those used in this study. Through 1970 no local earthquakes have been recorded near the dam (Mickey, 1970).

The Uinta Mountains (Fig. 10H) are an anomalous structural feature in that they have an east-west trend. This range is bounded by east-trending faults on both the north and south.

Historically, this area has had very low seismic activity (Cook and Smith, 1967; Fig. 10). We recorded for four days near the southern boundary fault of the Uinta Mountains and observed no microearthquakes. This is consistent with the historic results.

We deliberately surveyed an inactive area to check the hypothesis that microearthquakes most probably would not be found in a region that is macroseismically inactive. After evaluating microearthquake data from various sources in different regions, Boucher and Fitch (1969) stated that "there is a high probability that a given day's recording will yield a frequency of events that is well within an order of magnitude of the mean" for that area. The results of Ward and Bjornsson (1971) in Iceland substantiate this statement. It seems reasonable to assume that the higher the general seismicity the more representative the sample.

In this survey the activity within a region seemed to be sporadic with microearthquakes clustering in space and time. However, the relative activity of the various regions compares favorably with that listed by the NOS and plotted in Figure 10.

EVALUATION OF RESULTS AND GEOLOGICAL IMPLICATIONS

Some general observations can be made about the nature of the seismic activity in the Intermountain Seismic Belt. Of the microearthquakes that were located with an accuracy of 5 km or better, none had a depth greater than 20 km. Most of the events had depths of 15 km or less—well above the transition zone from crust to mantle at 29 to 36 km indicated by Prodehl (1970) for the Basin and Range province. If the ideas of Scholz and others (1969) for the San Andreas system in California can be applied to this region, we can define a zone of stick-slip motion from near the surface to about 15 km with a gradual change to aseismic slip below 15 km.

A characteristic feature of the seismicity of the Intermountain Seismic Belt is its sporadic nature. This can be seen by the change, with time, in the locus of activity in a region and also in the initiation and termination of swarms. Flathead Lake (Fig. 3) and the Caribou Mountains (Fig. 5) are the regions of highest swarm activity. In Iceland, Ward and Bjornsson (1971) have observed a general association of swarms with geothermal areas in zones of fissure systems. These swarms were at depths from 2 km to 6 km and occurred in zones with radii less than 5 km. They postulated that the swarms may be caused by the weakening effect of the water in the geothermal areas on the crust. Mogi (1963) related swarms to heterogeneity or nonuniform stress in the focal region. Sykes (1970) presented several hy-

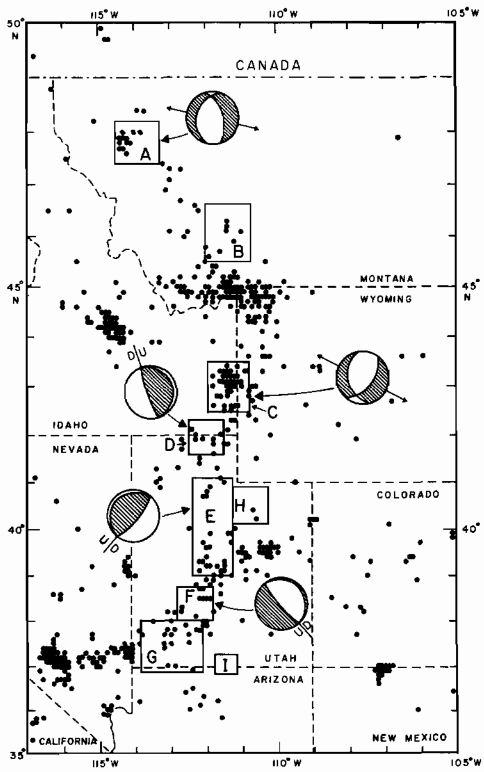

Figure 10. Map of Intermountain Seismic Belt showing NOS epicenters (1961–1969), areas surveyed, and composite fault plane solutions for these areas. The shaded area in the fault plane solution represents the compressional quadrant.

potheses that related swarm activity to processes, such as that described above, that can be found in volcanic areas. These hypotheses are that swarms are a result of concentrated stress, heterogeneous materials and structures, and (or) localized sources of high fluid pressure. However, he did not believe that the data available were adequate to distinguish among these three hypotheses. In line with the above ideas, an attempt was made to correlate the presence of the observed microearthquake swarms with Quaternary volcanics. No correlation could be found. However, the possibility still exists that these swarms are associated with buried plutonic activity. This is supported to some extent by the high heat flow observed in this region (Roy and others, 1968; Blackwell, 1969).

If the seismic activity observed in this microearthquake study is compared with that previously recorded in the NOS listing or in earlier listings (Cook and Smith, 1967), considerable variation can be seen. The southern part of the central Utah map (Fig. 10E) is an area of high activity and yet only one earthquake was recorded there in the course of this study (Fig. 7). More than half of the activity recorded at Flathead Lake from 1961 to 1969 listed by the NOS (Fig. 10) occurred from April 1969 to February 1970. The high microearthquake activity also recorded there is probably a reflection of this recent activity. According to a listing by Cook and Smith (1967), the activity in the vicinity of the Hurricane fault should be higher than that on the Sevier fault. Our investigation and the NOS listing show slightly higher activity on the Sevier fault. In the Caribou Mountain area (Fig. 5) a distinct change in the locus of activity was observed in the comparison of our locations with those of Westphal and Lange (1966). New activity was located east of the Palisades Reservoir and near station I4. The rate of activity was also observed to vary on a daily basis in most of the areas. The above examples indicate that the activity in the Intermountain Seismic Belt is sporadic and may vary considerably with time.

The CFPS determined in this study were found to correlate well with the observed structural geology in most cases. It is significant that most of the microearthquakes in a given region should satisfy the same CFPS since they occur on separate but similar faults that are kilometers apart, and the magnitude of the events range from -1 to 2.5. If a relation between fault length and magnitude can be extrapolated to small earthquakes (Wyss and Brune, 1968), the area ruptured by these microearthquakes would then range from a few square meters to about a half a square kilometer. The observation that the fault planes are well determined in most of the CFPS's imply that most of the microearthquakes express a regional pattern of movement or stress even though they are on faults separated by a few tens of kilometers. An inspection of the various CFPS demonstrates that in the better examples (Flathead Lake, Fig. 3; Marysvale, Fig. 8), a number of data points would have to be eliminated to change the strike and dip of the slip plane by a few degrees. In other cases, the elimination of only one data point can change the solution by as much as 35° (for example, Cache Valley, Fig. 6). Because the CFPS correlate quite well with the observed geology, it is reasonable to assume that they represent an average fault plane orientation and direction of slip for the different regions surveyed at the time of the survey.

Figure 10 presents the CFPS determined in this study superimposed on a seismicity map of the Intermountain Seismic Belt. Based on these mechanisms, we can divide the Intermountain Seismic Belt into two regions of different tectonic character with the boundary between the Caribou Mountains, Idaho (Fig. 10C), and Cache Valley, Utah (Fig. 10D). The CFPS at Flathead Lake (Fig. 10A) and the Caribou Mountains indicate normal faulting with the extensional axes striking west-northwest and approximately horizontal. Both of the above regions have high swarm activity. This amount of swarm activity was not observed elsewhere in the Intermountain Seismic Belt during this study.

Mudge (1970) has investigated the geology and evolution of northwestern Montana. He postulated that this area has developed as a result of uplift which was initiated in the late Jurassic. This uplift caused the thrusting to the east as well as normal faulting at the head of the thrusts. Armstrong and Oriel (1965) have described normal faulting as the latest stage of faulting in the Caribou Mountain area.

Between the above two areas of uplift and extension lies a region of complicated geology and seismicity, which includes the Hebgen Lake and the Yellowstone areas. Our results at

Three Forks indicated primarily strike-slip motion with a west-northwest trend. The FPS found for the 1959 Hebgen Lake earthquake (magnitude 7.1) also has a west-northwest strike; however, it is a dip-slip fault, with a dip of 54° SW., and the southwest side downthrown. Because of the difference in these mechanisms, the connection between the two zones of extension is obscure. A detailed microearthquake investigation in the area of Hebgen Lake and Yellowstone Park would help to clarify this problem. The above results do not necessarily imply rifting as in oceanic ridges, but indicate that west-northwest-trending extension is occurring in this region. Gumper and Scholz (1971) have observed a similar pattern on the western boundary of the Basin and Range province.

Farther to the south the three CFPS determined in Utah (Fig. 10) indicate differential motion on steeply dipping faults. In northern Utah a detailed gravity survey (Cook and Berg, 1961) showed evidence of a series of grabens about 100 km wide with a steplike series of faults on each side. The seismic zone shown in Figure 10 is also about 100 km wide and the CFPS may indicate, by their sense of motion, which side of the graben was moving during the time of the microearthquake survey. The graben and the seismic zone define the transition zone between the Basin and Range province and the Colorado Plateau.

The features of the Intermountain Seismic Belt in Utah can be explained as the boundary between two lithospheric plates of different characteristics. In a model taken from Archambeau and others (1969), the Basin and Range province is a region with a thin crust (25 to 30 km), and an upper mantle with a low P-wave velocity which extends to 150 to 200 km in depth. To the east the Colorado Plateau has a thicker crust (50 km) and a higher upper mantle P-wave velocity. The crust and uppermost mantle form a "lid" about 100 km thick over a lower P-wave velocity zone that extends to about 200 km. The differences between these two tectonic provinces thus extend to about 100 km in depth. Differential vertical motion between these two "plates" presumably results in the observed seismicity. This concept is discussed in more detail in Scholz and others (1971).

Since, in general, the motions resulting from the CFPS are in agreement with those observed to have occurred over the past 15 m.y., it is reasonable to assume that those tectonic forces that have generated the Intermountain Seismic Belt block faulting have continued in some fashion to the present.

CONCLUSIONS

The results of this study indicate that the Intermountain Seismic Belt can be divided into two regions of differing tectonics. In both of these regions, the well-located microearthquakes were found to occur between the surface and 20 km in depth, and to cluster both in space and time. The northern region extends from the Caribou Mountains in southeastern Idaho to Flathead Lake in northwestern Montana. This area is dominated by west-northwest extension with normal faulting and swarm activity observed at the Caribou Mountains and Flathead Lake. No significant swarm activity was detected elsewhere. However, the tectonic connection between these two areas of uplift and extension is still obscure.

An important feature of the composite fault plane solutions in the southern region (Utah) is that the inferred fault planes tend to be nearly vertical, with the relative movements also vertical. The above fault plane solutions as well as the spatial distribution of the earthquakes in Utah can be explained by the interaction of two distinctly different crustal and upper mantle tectonic provinces, the Colorado Plateau to the east with the Basin and Range province to the west.

ACKNOWLEDGMENTS

The authors would like to thank Frank Gumper for providing the results of his research prior to publication. Kenneth King of the NOS, formerly USCGS, kindly arranged for the loan of a field vehicle from his office in Las Vegas. Critical review of the manuscript by Professors Bryan Isacks and Jack Oliver is gratefully acknowledged. We also benefitted from many stimulating discussions with Professor Isacks. We wish to thank Raymond Price and Robert Wesson for their helpful suggestions and criticism. Klaus Jacob kindly provided us with a copy of his ray-tracing program.

The funding for this project was provided by the National Science Foundation grants GA 11150 and GA 1537 as well as the American Chemical Society Petroleum Research Fund grant 756-A2.

REFERENCES CITED

Archambeau, C. F., Flinn, E. A., and Lambert, D. G., 1969, Fine structure of the Upper Mantle: Jour. Geophys. Research, v. 74, p. 5825–5865.

Armstrong, F. C., and Oriel, S. S., 1965, Tectonic development of Idaho-Wyoming thrust belt: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 1847–1866.

Armstrong, R. L., Ekren, E. B., McKee, E. H., and Noble, D. C., 1969, Space-time relations of Cenozoic silicic volcanism in the Great Basin of the western United States: Am. Jour. Sci., v. 267, p. 478–490.

Bally, A. W., Gordy, P. L., and Stewart, G. A., 1966, Structure, seismic data, and orogenic evolution of the southern Canadian Rocky Mountains: Bull. Canadian Petroleum Geology, v. 14, p. 337–381.

Barazangi, M., and Dorman, J., 1969, World seismicity maps compiled from ESSA, Coast and Geodetic Survey, epicenter data, 1961–1967: Seismol. Soc. America Bull., v. 59, p. 369–380.

Berg, J. W., Jr., Cook, K. L., Narans, H. D., Jr., and Dolan, W. M., 1960, Seismic investigation of crustal structure in the eastern part of the Basin and Range province: Seismol. Soc. America Bull., v. 50, p. 511–535.

Blackwell, D. D., 1969, Heat flow determinations in the northwestern United States: Jour. Geophys. Research, v. 74, p. 992–1007.

Boucher, G., and Fitch, T., 1969, Microearthquake seismicity on the Denali fault: Jour. Geophys. Research, v. 74, p. 6638–6648.

Broecker, W. S., and Kaufman, A., 1965, Radiocarbon chronology of Lake Lahontan and Lake Bonneville II, Great Basin: Geol. Soc. America Bull., v. 76, p. 537–566.

Cook, K. L., and Berg, J. W., Jr., 1961, Regional gravity survey along the central and southern Wasatch front, Utah: U.S. Geol. Survey Prof. Paper 316-E, 89 p.

Cook, K. L., and Smith, R. B., 1967, Seismicity in Utah, 1850 through June 1965: Seismol. Soc. America Bull., v. 57, p. 689–718.

Crittenden, M. D., Jr., 1963, Effective viscosity of the earth derived from isostatic loading of Pleistocene Lake Bonneville: Jour. Geophys. Research, v. 68, no. 19, p. 5517–5530.

Eardley, A. J., 1962, Structural geology of North America (2d ed.): New York, Harper and Row, 743 p.

Gardner, L. S., 1941, The Hurricane fault in southwestern Utah and northwestern Arizona: Am. Jour. Sci., v. 239, p. 241–260.

Gumper, F., and Scholz, C., 1971, Microseismicity and tectonics of the Nevada Seismic Zone: Seismol. Soc. America Bull., v. 61, no. 5.

Hamblin, W. K., 1963, Late Cenozoic basalts of the St. George Basin, Utah, *in* Heylmum, E. B., ed., Guidebook to the geology of southwest Utah: Intermt. Assoc. Petroleum Geologists, v. 12, p. 84–89.

Hamilton, W., and Myers, W. B., 1966, Cenozoic tectonics of the western United States: Rev. Geophysics, v. 4, p. 509–549.

Jacob, K. H., 1970, Three dimensional seismic ray tracing in a lateral heterogeneous spherical earth: Jour. Geophys. Research, v. 75, p. 6675–6689.

Julian, B., 1970, Variations in upper mantle structure beneath North America [Ph.D. thesis]: Pasadena, California Institute of Technology, 208 p.

Kerr, P. F., Brophy, G. P., Dahl, H. M., Green, J., and Woolard, L. E., 1957, Marysvale, Utah, uranium area: Geol. Soc. America Spec. Paper 64, 212 p.

King, P. B., 1969, Tectonic map of North America: U.S. Geol. Survey, scale 1:5,000,000.

Mickey, W. V., 1970, Earthquakes and dams: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 2, no. 7, p. 622.

Mogi, K., 1963, Some discussions on aftershocks, foreshocks, and earthquake swarms—the fracture of a semi-infinite body caused by an inner stress origin and its relation to the earthquake phenomena, 3: Tokyo Univ. Earthquake Research Inst. Bull., v. 41, p. 615–658.

Molnar, P., and Oliver, J., 1969, Lateral variations of attenuation in the upper mantle and discontinuities in the lithosphere: Jour. Geophys. Research, v. 74, p. 2648–2682.

Moore, R. T., Wilson, E. D., and O'Haire, R. T., 1960, Geologic map of Coconino County, Arizona: Arizona Bur. Mines Bull. 170 p.

Mudge, M. R., 1970, Origin of the disturbed belt in northwestern Montana: Geol. Soc. America Bull., v. 81, p. 377–392.

Prodehl, C., 1970, Seismic refraction study of crustal structure in the western United States: Geol. Soc. America Bull., v. 81, p. 2629–2646.

Robinson, G. P., 1961, Origin and development of the Three Forks Basin, Montana: Geol. Soc. America Bull., v. 72, p. 1003–1014.

Ross, C. P., and Forrester, J. D., 1959, Geologic map of the state of Idaho (reprint): U.S. Geol. Survey and Idaho Bur. Mines and Geology, scale 1:500,000.

Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, R., 1968, Heat flow in the United States: Jour. Geophys. Research, v. 73, p. 5207–5221.

Roy, R. F., Blackwell, D. D., and Decker, E. R., 1971, Continental heat flow, *in* Symposium of the nature of the solid earth, in honor of Professor F. Birch: New York, McGraw Hill Book Company (in press).

Sbar, M. L., Rynn, J.M.W., Gumper, F. J., and

Lahr, J. C., 1970, An earthquake sequence and focal mechanism solution, Lake Hopatcong, northern New Jersey: Seismol. Soc. America Bull., v. 60, p. 1231–1243.

Scholz, C. H., Wyss, M., and Smith, W. S., 1969, Seismic and aseismic slip on the San Andreas fault: Jour. Geophys. Research, v. 74, p. 2049–2069.

Scholz, C. H., Barazangi, M., and Sbar, M. L., 1971, Late Cenozoic evolution of the Great Basin, western United States as an ensialic inter-arc basin: Geol. Soc. America Bull., v. 82, p. 2979–2990.

Seeber, L., Barazangi, M., and Nowroozi, A., 1970, Microearthquake seismicity and tectonics of coastal northern California: Seismol. Soc. America Bull., v. 60, p. 1669–1699.

Stokes, W. L., ed., 1963, Geologic map of Utah: Utah State Land Board, scale 1:250,000.

Sykes, L. R., 1970, Earthquake swarms and sea-floor spreading: Jour. Geophys. Research, v. 75, p. 6598–6611.

Ward, P. L., Palmason, G., and Drake, C., 1969, Microearthquake survey and the Mid-Atlantic Ridge in Iceland: Jour. Geophys. Research, v. 74, p. 665–684.

Ward, P. L., and Bjornsson, S., 1971, Microearthquakes, swarms, and the geothermal areas: Jour. Geophys. Research, v. 76, p. 3953–3982.

Westphal, W. H., and Lange, A. L., 1966, Local seismic monitoring: Stanford Research Inst. Tech. Rept., 242 p.

Wyss, M. and Brune, J. N., 1968, Seismic moment, stress and source dimensions for earthquakes in the California-Nevada region: Jour. Geophys. Research, v. 73, p. 4681–4694.

Manuscript Received by the Society March 1, 1971

Revised Manuscript Received July 9, 1971

Lamont-Doherty Geological Observatory Contribution No. 1704

PRINTED IN U.S.A.