UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

REVIEW OF EARTHQUAKE ACTIVITY AND CURRENT STATUS OF SEISMIC MONITORING IN THE REGION OF THE BRADLEY LAKE HYDROELECTRIC PROJECT, SOUTHERN KENAI PENINSULA, ALASKA: NOVEMBER 27, 1980 - NOVEMBER 30, 1981

by
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HIGHLIGHTS OF RECENT RESULTS

Over 900 earthquakes were located near the southern Kenai Peninsula during the period November 27, 1980 - November 30, 1981. Of these earthquakes, 127 were located at depths of 20 km or shallower and confirm the presence of active faults within the crust. Although many of the earthquakes occur close to the principal mapped faults and may indicate activity on portions of these faults, other as yet unmapped and possibly buried faults must be active to account for the observed distribution of shallow seismicity. The largest earthquake that occurred in the study area during this time had a coda-duration magnitude 4.8 (5.1m_b), and was located at 106 km depth beneath western Cook Inlet. Forty-two events had coda-duration magnitudes of 3 or larger, but all of these earthquakes were located at depths of 40 km or greater, in the Benioff zone beneath the southern Kenai Peninsula and Cook Inlet. The largest shallow earthquake within 25 km of Bradley Lake had a coda-duration magnitude of 2.1.

There is no strong correlation of the shallow seismicity with mapped fault traces. Focal mechanisms determined for selected shallow earthquakes near Bradley Lake are compatable with predominantly normal faulting controlled by east-west to southeast-northwest oriented tension.

A strong-motion accelerograph was installed near the main Bradley Lake high-gain seismic station, but to date has not been triggered by an earthquake.

INTRODUCTION

The Alaska District, Corps of Engineers plans to construct a hydroelectric facility on the southern Kenai Peninsula, Alaska. The project involves damming Bradley Lake, which is located in the Kenai Mountains at an elevation of 1,090 feet, and feeding the water through a tunnel to a power plant at sea level. In this region of tectonic interaction between the Pacific and North American plates (Figure 1), the potential for strong earthquakes needs to be addressed so that the hazards they could pose can be minimized. The most serious effect of earthquakes on man-made structures is structural damage due to strong shaking. Other potentially damaging aspects of earthquakes include surface faulting as well as shaking-induced effects such as liquefaction, landslides, differential settling, and seiches.

The Corps of Engineers has asked the U.S. Geological Survey, Office of Earthquake Studies (USGS-OES) to investigate the problem of seismic hazards in the Bradley Lake region. This entails collecting and analyzing earthquake data in the region of the proposed Bradley Lake Hydroelectric Project in order to develop a more detailed model for the tectonic framework. Particular emphasis is being placed on the distribution of shallow crustal earthquakes and their relationship to mapped or inferred faults.

The purpose of this report is to summarize the work completed to date, including the operation of the seismic stations and a review of the seismic data collected between November 27, 1980 (when the Bradley Lake network was installed) and November 30, 1981. Part of the data presented in this report was discussed in an earlier report (Lahr and Stephens, 1981) along with other available data from the USGS-OES network that has been operating in southern Alaska since 1971. The data presented in this report generally conform to the

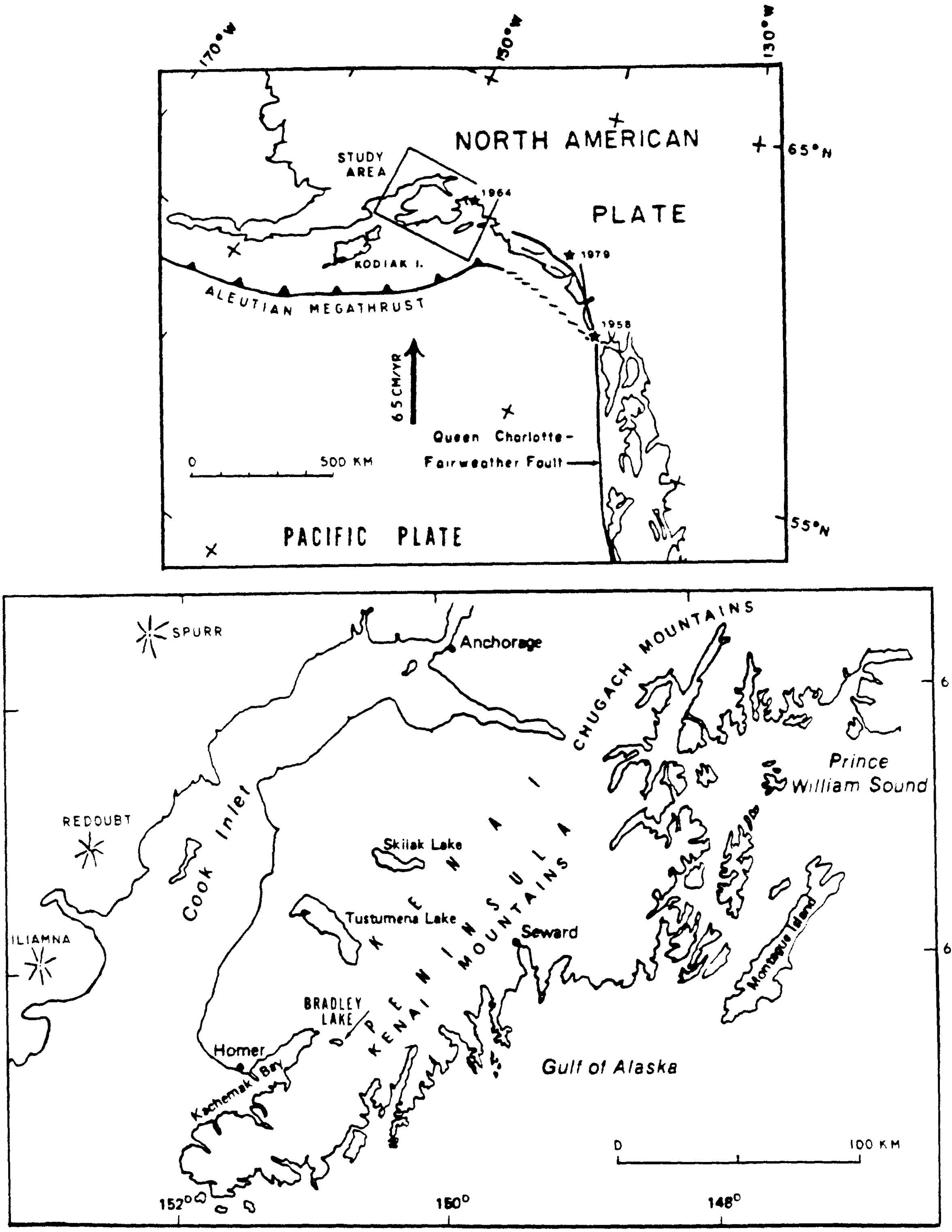


Figure 1. Upper- Current motion of Pacific plate with respect to North American plate. Projection is oblique Mercator using a pole at 54°N and 61°W. Rotation of the Pacific plate with respect to the North American plate about this pole is equivalent to vertical translation in this figure. Epicenters of the 1958, 1964, and 1979 earthquakes are shown.
Lower- Enlargement of the area outlined in upper figure, showing the setting of Bradley Lake. The locations of Spurr, Redoubt, and Iliamna volcanoes are indicated. Modified from Woodward-Clyde Consultants (1979).

essential features of the distribution of earthquake hypocenters and magnitudes described in the earlier report. The greater quantity of high-quality data now available allows us to make more reliable estimates of such parameters as the depth to the Benioff zone beneath Bradley Lake and the location of areas that are currently experiencing high rates of shallow seismicity. In addition, new data are presented about the style of faulting and current state of stress in the crust as inferred from focal mechanisms determined from P-wave first-motions.

SEISMOTECTONIC FRAMEWORK : CURRENT STATE OF KNOWLEDGE

The Bradley Lake region is located in the tectonic zone of interaction between the North American plate and the relatively northwestward-moving Pacific plate (Figure 1). The average rate of convergence near the southern Kenai Peninsula over the past 3 m.y. is 6.5 cm/yr (Minster and Jordan, 1978). Direct evidence for continued convergent motion comes from studies of recent large earthquakes along portions of the Pacific-North American plate boundary adjacent to the Gulf of Alaska. For example, the 1964 Alaska earthquake resulted from dip slip motion of about 12 m (Hastie and Savage, 1970) on the portion of the Aleutian megathrust extending from Prince William Sound to southern Kodiak Island and dipping northwestward beneath the continent.

The seismicity associated with the processes of convergent plate motion in Alaska may generally be divided into five spatially distinct groups:

1. Earthquakes which occur on the gently dipping Aleutian megathrust (the interface zone between the Pacific and North American Plates);
2. Earthquakes which occur in the wedge of crust above the active megathrust zone;

3. Earthquakes which occur within that portion of the Pacific plate which has been thrust beneath Alaska (Benioff zone events);
4. Earthquakes within the Pacific plate seaward of the Aleutian megathrust;
5. Shallow earthquakes near the active volcanoes.

The Bradley Lake region is most directly affected by the first three types of events.

INSTRUMENTATION

During most of the past year the high-gain seismic stations at the five Bradley Lake sites (Figure 2) operated satisfactorily. Several of the stations were not operating for several weeks between late April and early July 1981, as a result of unexpected environmental problems. An unusual ice problem and flooding almost destroyed the main Bradley Lake site (BRLK). The ice snapped the coaxial cables inside of the antenna masts and the high water discharged the batteries. The instrumentation was moved to the top of a small knoll to provide for better drainage. To increase reliability, the radio repeater for BRNW, BRNE, and BRSE was separated from the local three-component seismograph. This involved installing another antenna/mast as well as battery culvert. In addition, all mast guys were anchored to the rocks using a rock drill and concrete anchors.

BRSE and BRSW were in good condition. At BRNW the batteries drowned; new batteries were installed on a raised base. At BRNE the lid had blown off the culvert and was lost in 2 feet of snow. The electronics were undamaged and a new lid was put on the culvert.

On a later visit an SMA1 accelerograph was installed at the main Bradley

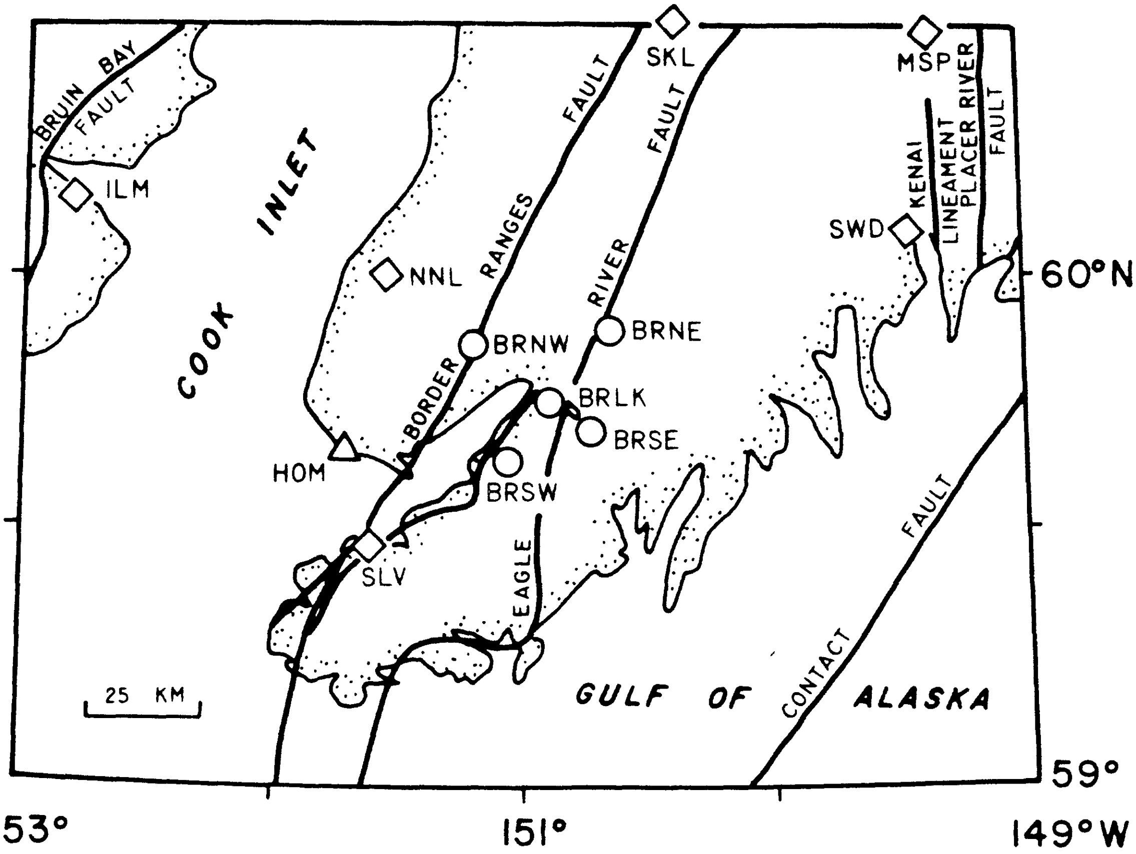


Figure 2 Map of the study area in the Bradley Lake region. Symbols represent seismograph stations funded by the U.S. Geological Survey (diamonds), the Corps of Engineers (circles), and the University of Alaska (triangles). Heavy solid lines indicate principle faults, after Beikman (1980), Plafker (1969), Tysdal and Case (1979), and Plafker and others (1977). Location of Bradley Lake is indicated by small oval next to station BRLK near center of map.

Lake site. Our standard free-field installation was used except that a new charge regulator circuit was added to trickle charge the SMA1 batteries from the high-capacity air cell batteries used to power the high-gain seismograph. Thus the need to change the SMA1 batteries has been reduced from every year to every 5 years.

At Diamond Ridge the RF-2 receiver was retuned and a pre-amplifier installed. An A1VCO was also installed at the local Homer station, HOM (Figure 2), operated by the University of Alaska, so that the data could be recorded on the USGS Develocorder films in Palmer.

DATA PROCESSING TECHNIQUES

The data recorded from USGS-OES seismic stations in the Bradley Lake region are mailed weekly from Palmer, Alaska, to Menlo Park, California, where they are processed using the following multi-step routine:

1. Preliminary scanning: The paper records of BRLK and BRSW are scanned to identify and note times of seismic events within the Bradley Lake network and the surrounding area.
2. Final scanning: The events noted in preliminary scanning are found on the Develocorder film record and any event with a P- to S-phase time interval of less than or equal to 10 seconds at one of the Bradley Lake stations is noted for subsequent timing.
3. Timing: For each of the identified events that has been recorded on the 16-mm films at four or more stations in the Bradley Lake region the following data are read from each station: P- and S-phase arrival times; direction of first motion of the P wave; duration of signal in excess of 1 centimeter threshold amplitude; and period and amplitude

of maximum recorded signal.

4. Initial computer processing: The data read from the films are batch processed by computer using the program HYPOELLIPSE (Lahr, 1980) to obtain the origin time, hypocenter, magnitude, and first-motion plot for each earthquake.
5. Review of initial computer results: Each hypocentral solution is checked for large traveltime residuals and for a poor spatial distribution of stations. Arrival times that produce large residuals are re-read. For shocks with a poor azimuthal distribution of stations, readings from additional stations are sought.
6. Final computer processing: The data for those events with poor hypocentral solutions are rerun with corrections and the new solutions are checked once again for large residuals that might be due to remaining errors.

ANALYSIS OF HYPOCENTER QUALITY

Two types of errors enter into the determination of hypocenters: systematic errors limiting the accuracy and random errors limiting the precision. Systematic errors arise principally from incorrect modeling of the seismic velocity within the earth. Random errors result from effects such as random timing errors, and their effect on each earthquake is estimated through the use of standard statistical techniques.

The magnitude of the systematic errors can be greatly reduced by close spacing of seismographic stations within the area of interest, as the hypocentral solution in this situation is much less sensitive to the velocity model assumed for the earth. For this reason, the earthquakes located in the

Bradley Lake region since the installation of the additional five stations in late 1980 are expected to have smaller systematic offsets than those located earlier with the less dense regional network.

For each earthquake the lengths and orientations of the principal axes of the joint confidence ellipsoid are calculated. The one-standard-deviation confidence ellipsoid describes the region of space within which one is 68 percent confident that the hypocenter lies, assuming that the only source of error is the estimated random reading error. The size and orientation of the ellipsoid is a function of the station geometry. For earthquakes within the network, the lengths of the ellipsoid axes are generally on the order of 2 to 3 km.

To fully evaluate the quality of a hypocenter, both the size and orientation of the confidence ellipsoid, the root mean square (RMS) residual for the solution, and the station geometry must be considered.

RESULTS

The epicenters of 907 earthquakes that occurred between November 27, 1980, and November 30, 1981, and were located near the southern Kenai Peninsula are shown in Figure 3. Most of these events occurred within the northwestward-dipping Benioff zone that underlies the southern Kenai Peninsula and Cook Inlet (Figure 4). The largest earthquake that occurred during this time period was an event of coda-duration magnitude 4.8 ($5.1 m_b$) which was located at a depth of 106 km near the northwest part of the study area near Iliamna volcano. Forty-two earthquakes had coda-duration magnitudes of 3 or larger (Table 1 and Figure 5), but all of these events had computed depths of 40 km or more which would place them in the Benioff zone. Eight of the largest earthquakes were reported in the Preliminary Determination of Epicenters as

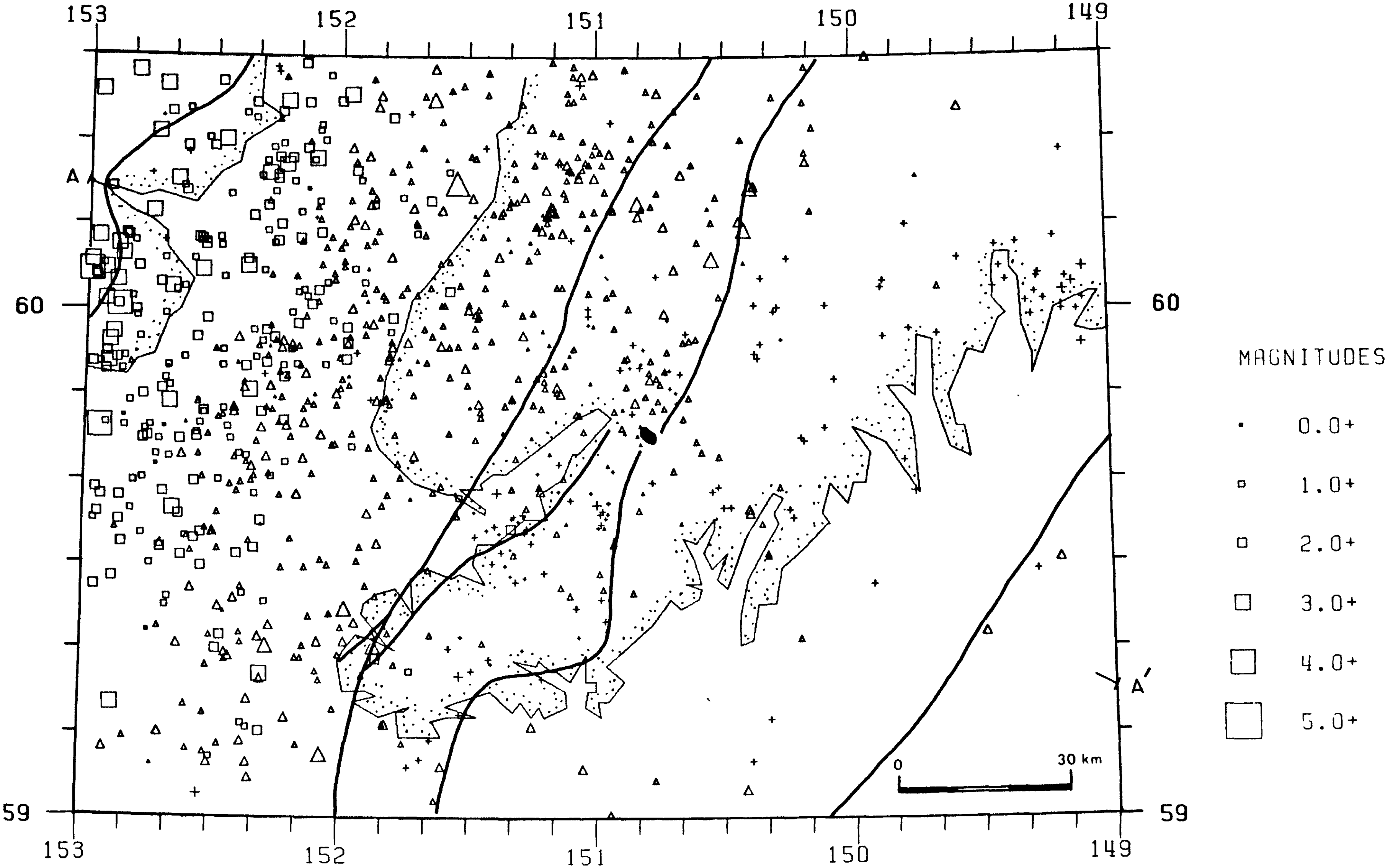


Figure 3 Map of epicenters of 907 earthquakes located near southern Kenai Peninsula between November 27, 1980, and November 30, 1981. Plotting symbol size is proportional to magnitude, as indicated, and symbol type corresponds to depth as follows: cross, <30 km; triangle, 30-69 km; square ≥70 km. Heavy solid lines correspond to mapped fault traces identified in Figure 2. Locations of Bradley Lake is indicated by small solid oval at center of figure.

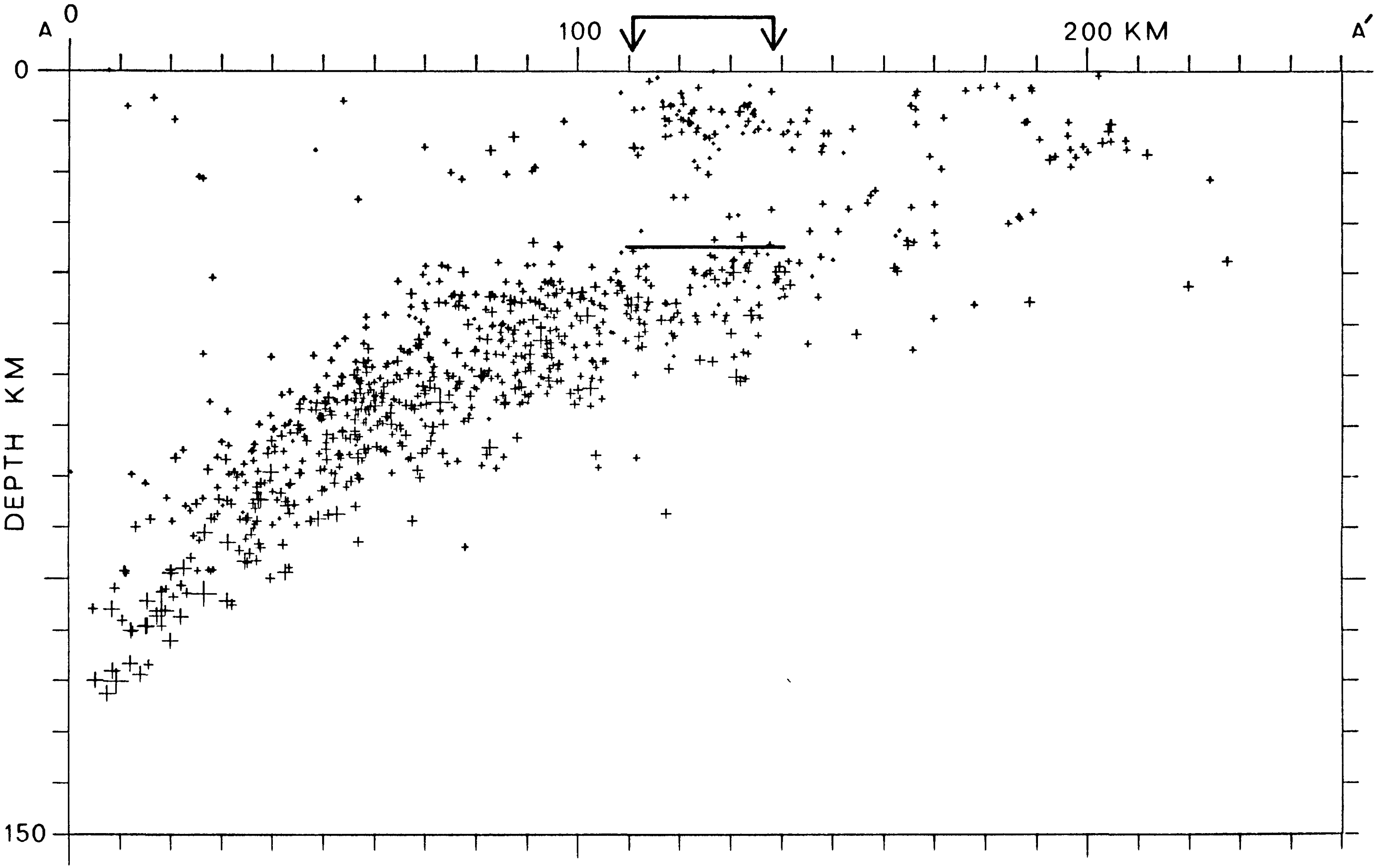


Figure 4 Hypocenters of Figure 3 projected onto vertical plane along A-A'. Plotting symbol is proportional to magnitude as indicated in Figure 3. Extent of Bradley Lake network is shown at top of figure. Northwestward dipping zone of seismicity below 35 km depth is the Benioff zone, which is inferred to lie within subducted Pacific plate. Solid line at 35 km depth below Bradley Lake network indicates top of Benioff zone.

TABLE 1

EARTHQUAKES OF CODA-DURATION MAGNITUDE 3 AND LARGER NEAR SOUTHERN KENAI PENINSULA
NOVEMBER 27, 1980 - NOVEMBER 30, 1981

1980		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	MB	NP	NS	GAP DEG	D3 KM	RMS SEC	ERH KM	ERZ KM	Q
NOV	27	15	51	54.6	60	6.5	152	51.6	118.7	3.3		18	5	85	83	0.59	3.1	2.8	B
	28	17	44	4.2	60	17.1	152	13.3	84.5	3.6	4.6	28	5	55	56	0.46	1.1	2.8	B
DEC	11	22	11	0.7	60	2.8	152	39.9	91.1	3.8		24	3	74	76	0.38	1.5	3.5	B
					FELT III AT KENAI AND SOLDOTNA														
	29	17	2	34.8	60	4.7	152	55.6	116.6	3.0		24	9	73	78	0.69	1.3	1.8	A
1981																			
JAN	7	0	18	42.6	60	8.5	152	57.4	122.6	3.3		8	2	209	126	0.20	3.8	2.6	B
	23	17	39	42.2	59	57.2	152	53.6	112.0	3.6		24	5	59	74	0.50	1.4	3.2	B
	26	18	24	54.5	60	9.5	150	25.0	48.1	3.2	4.0	35	8	99	51	0.54	1.0	2.6	B
FEB	23	13	3	8.8	60	14.5	150	23.6	60.2	3.8	4.8	32	1	95	55	0.48	1.4	2.8	B
					FELT IV AT KENAI, HOMER, MOOSE PASS, AND SEWARD														
MAR	6	6	44	33.8	60	5.2	152	22.0	79.1	3.1	4.6	25	7	55	72	0.31	1.3	2.0	A
APR	22	6	31	48.3	60	21.0	152	43.9	118.1	3.7		25	3	81	93	0.28	1.8	3.8	B
	24	7	52	55.5	59	20.3	151	51.9	48.4	3.4	4.0	23	6	134	85	0.38	1.8	3.3	B
					FELT AT HOMER														
	24	21	29	45.7	60	28.3	152	49.0	127.4	3.2	4.0	22	8	67	89	0.39	1.6	3.3	B
MAY	15	14	7	26.1	60	6.1	150	32.6	39.8	3.0		23	6	113	61	0.55	1.6	4.2	B
	17	8	51	9.7	60	20.1	152	27.7	97.8	3.0		20	5	79	108	0.48	1.8	3.4	B
	21	20	29	34.3	59	46.1	152	56.5	102.9	4.1	4.6	20	1	142	95	0.30	2.9	4.3	B
					FELT ON KENAI PENINSULA AND AT ANCHORAGE														
	27	5	18	36.8	60	1.2	152	55.5	109.4	3.0		19	6	135	91	0.44	2.5	2.8	B
	28	19	9	23.7	60	11.6	152	44.8	104.4	3.6	4.1	22	8	76	82	0.62	1.7	2.2	A
	30	12	44	55.1	59	56.3	152	54.4	98.8	3.1		23	11	83	76	0.34	1.2	1.6	A
JUL	13	18	27	3.1	59	24.7	151	58.6	53.1	3.1		25	5	116	66	0.38	1.7	2.0	A
					FELT III AT HOMER AND SELDOVIA														
	21	3	17	22.8	59	17.0	152	18.1	74.2	3.5	4.5	28	7	121	96	0.24	1.5	3.1	B
AUG	1	1	42	18.1	60	0.5	152	52.4	106.3	4.8	5.1	28	2	113	78	0.39	1.8	4.1	B
					FELT IV IN ANCHORAGE-HOMER AREA														
	5	10	21	53.6	59	36.6	152	39.1	88.3	3.7		24	6	83	64	0.34	1.5	2.8	B
	7	11	31	18.3	60	25.9	152	57.5	130.9	3.0		27	4	74	97	0.34	1.7	4.1	B
	11	21	27	51.7	59	50.5	152	21.1	87.3	3.3		26	8	71	60	0.36	1.4	2.2	A
	26	9	16	11.8	59	20.4	152	16.8	60.2	3.0		25	7	114	84	0.34	1.6	3.2	B
SEP	7	9	57	13.7	60	17.9	152	6.0	98.7	3.4		29	10	59	53	0.52	1.2	2.3	A
	9	18	0	4.3	60	24.6	152	13.1	104.3	3.6		30	8	55	66	0.44	1.2	2.5	B
	23	10	45	11.4	60	7.6	152	52.8	110.0	3.2		26	15	73	82	0.52	1.4	2.1	A
OCT	3	12	3	6.1	59	13.4	152	52.7	76.3	3.2		24	8	106	97	0.34	1.6	4.0	B
	11	4	28	45.6	60	3.4	152	53.0	109.2	3.1		26	10	67	82	0.59	1.8	1.8	A
	13	23	12	58.7	60	5.6	152	59.1	106.0	3.0		26	12	72	76	0.32	1.3	2.1	A
	14	11	3	22.8	60	25.5	151	58.1	85.6	3.8		27	7	63	57	0.47	1.2	2.3	A
	15	21	14	28.7	59	49.2	152	40.1	84.7	3.2		27	8	75	84	0.47	1.4	1.9	A
	16	18	21	32.8	59	7.5	152	3.9	62.5	3.1		26	13	136	94	0.35	1.4	3.5	B
	18	12	36	49.6	60	24.9	151	38.2	66.0	3.1		31	9	54	46	0.63	1.1	2.3	A
	19	1	46	19.1	60	16.2	152	17.4	96.6	3.9		30	3	57	61	0.44	1.4	3.5	B
NOV	1	9	57	26.3	60	15.4	152	38.9	107.2	3.2		29	8	77	79	0.54	1.2	2.4	A
	3	4	3	15.9	60	4.7	152	32.6	92.8	3.7		31	7	64	69	0.50	1.2	1.8	A
	13	18	10	31.1	60	12.6	150	50.3	46.2	3.4		27	3	78	45	0.82	1.4	2.7	B
	16	23	49	50.1	60	4.5	152	59.2	120.1	4.5	4.5	32	2	69	64	0.39	1.4	2.3	A
					FELT II AT HOMER														
	17	11	28	42.6	60	15.0	151	32.7	65.2	4.3	4.7	35	2	54	57	0.48	1.1	2.7	B
					FELT IV AT KENAI, HOMER, NINILCHIK, SOLDOTNA, CLAM GULCH, COOPER LANDING, TYONEK, STERLING, KASILOF, AND GIRDWOOD; ALSO FELT III AT ANCHORAGE, AND II AT PALMER														
	23	3	32	31.1	59	53.8	152	54.6	107.4	3.0		32	9	73	73	0.55	1.3	2.0	A

ORIGIN TIME: UNIVERSAL TIME (UT). TO CONVERT TO ALASKA STANDARD TIME SUBTRACT 10 HR.
MAG: CODA-DURATION MAGNITUDE
MB: BODY WAVE MAGNITUDE LISTED IN THE PRELIMINARY DETERMINATION OF EPICENTERS
NP: NUMBER OF P-WAVE ARRIVALS USED IN LOCATING THE EARTHQUAKE
NS: NUMBER OF S-WAVE ARRIVALS USED IN LOCATING THE EARTHQUAKE
GAP: LARGEST AZIMUTHAL SEPARATION IN DEGREES BETWEEN STATIONS
D3: EPICENTRAL DISTANCE, IN KILOMETERS TO THE THIRD CLOSEST STATION
RMS: ROOT-MEAN-SQUARE IN SECONDS OF TRAVELTIME RESIDUALS
ERH: LARGEST HORIZONTAL DEVIATION FROM THE HYPOCENTER WITHIN THE ONE-STANDARD-DEVIATION CONFIDENCE ELLIPSOID. THIS QUANTITY IS A MEASURE OF THE EPICENTRAL PRECISION.
ERZ: LARGEST VERTICAL DEVIATION FROM THE HYPOCENTER WITHIN THE ONE-STANDARD-DEVIATION CONFIDENCE ELLIPSOID. THIS QUANTITY IS A MEASURE OF THE DEPTH PRECISION.
Q: QUALITY OF THE HYPOCENTER. THIS INDEX IS A MEASURE OF THE PRECISION OF THE HYPOCENTER AND IS CALCULATED FROM ERH AND ERZ AS FOLLOWS:

Q	ERH	ERZ
A	≤ 2.5	≤ 2.5
B	≤ 5.0	≤ 5.0
C	≤10.0	≤10.0
D	>10.0	>10.0

POOR DETERMINATIONS OF THE PARAMTERES MAY RESULT FROM RANDOM ERRORS PRESENT IN THE PHASE DATA, OR FROM SYSTEMATIC ERRORS INTRODUCED EITHER BY THE VELOCITY MODELS USED OR BY THE RELATIVE POSITIONS OF THE TRUE HYPOCENTER AND THE STATIONS USED IN THE SOLUTION. ONE SHOULD BE PARTICULARLY CAUTIOUS USING SOLUTIONS THAT HAVE GAP > 180 DEGREES, NP < 5, NS = 0, D3 > 75 KM, RMS > 0.75, ERH > 5 KM, OR ERZ > 10 KM. SOLUTIONS WITH A AND B QUALITY ARE GENERALLY MORE RELIABLE, BUT THIS DOES NOT GUARANTEE THAT THE ACCURACY OF THE SOLUTIONS IS WITHIN THE LIMITS IMPLIED BY ERH AND ERZ.

FELT REPORTS ARE TAKEN FROM THE PRELIMINARY DETERMINATION OF EPICENTERS. A COPY OF INTENSITY SCALE CURRENTLY IN USE BY NEIS IS LISTED IN THE APPENDIX.

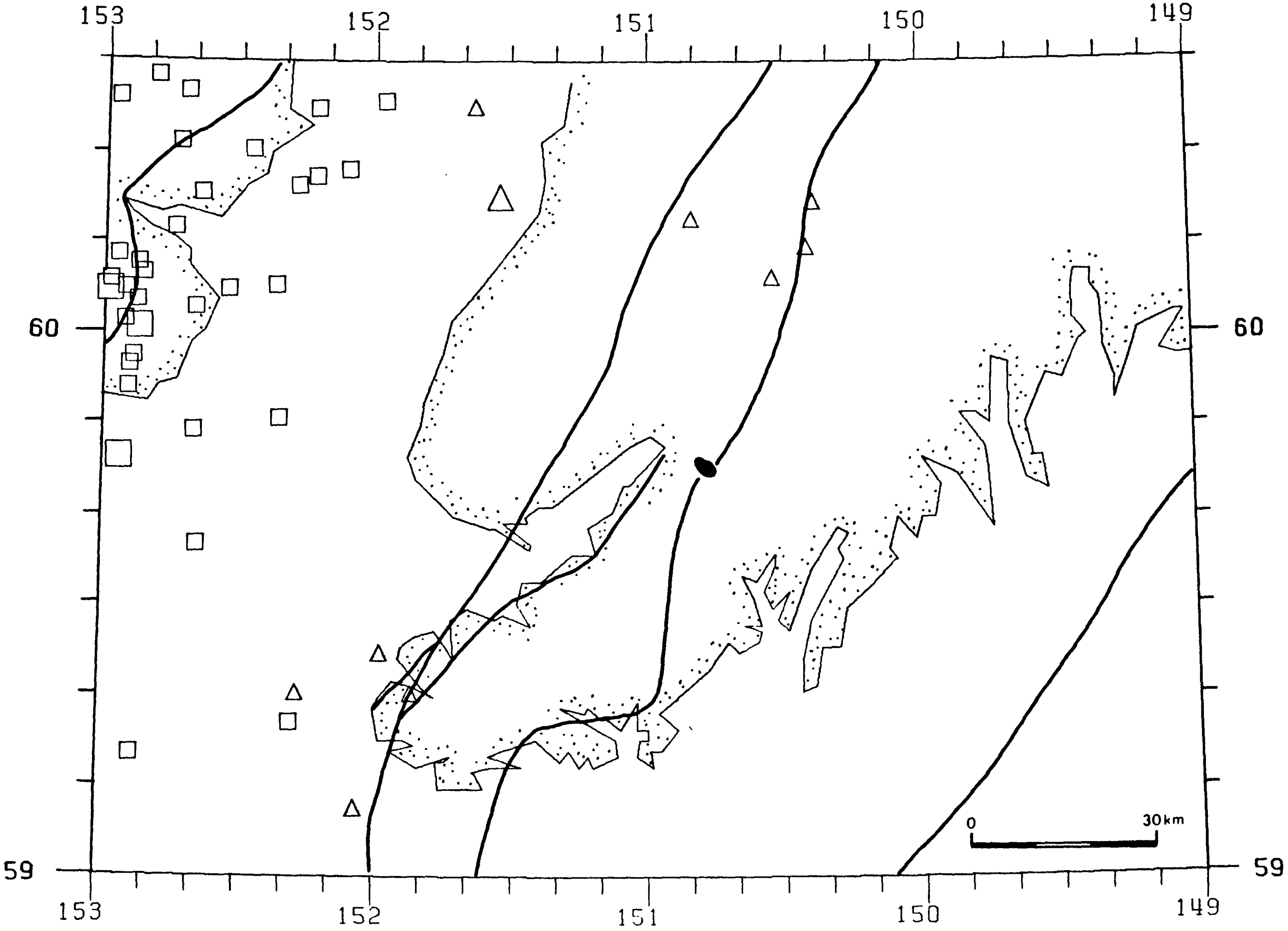


Figure 5 Map of epicenters for 42 earthquakes from Figure 3 with coda-duration magnitude 3 or larger. Hypocenter parameters of these events are listed in Table 1. Note that shallowest event occurred at 40 km depth. Plotting symbols are described in Figure 3. Heavy solid lines correspond to mapped fault traces identified in Figure 2. Location of Bradley Lake is indicated by solid oval at center of map.

being felt with maximum intensities ranging from about II to IV (Table 1 and Appendix) in the Kenai-Anchorage area.

Other features of the seismicity that were noted in an earlier report (Lahr and Stephens, 1981) and which can be observed in the data presented here are that the Benioff zone seismicity dies out near Bradley Lake (near 115 km along the section in Figure 4), that the shallow crustal activity is concentrated east of Cook Inlet, and that few events were located along the Aleutian megathrust.

Benioff zone earthquakes are generally assumed to occur within a subducted plate and near its upper surface. At shallow depths the upper limit of the Benioff zone activity will be near and possibly coincide with the zone of thrust contact between the plates. Thus the maximum depth to the thrust zone beneath Bradley Lake is 35 ± 5 km based on the abrupt increase in the rate of activity at this depth (Figure 4).

During the time period of this study, five earthquakes that occurred beneath the Bradley Lake station array were located at depths between 20 and 30 km. The nature of this intermediate-depth seismic activity is uncertain; it may indicate that some faults in the upper crust extend down into the lower crust, or alternatively it may be associated with the zone of thrust contact between the two converging plates. Further work, including additional data, is needed to help resolve this question.

PATTERN OF SHALLOW EARTHQUAKES

Shallow (depth less than 20 km) earthquakes (Figure 6) occur within the crust and confirm the presence of active faults within the crust. Of the located shallow earthquakes, the smallest had coda-duration magnitudes of 0.3, and the two largest had coda-duration magnitudes of 2.8. The largest shallow

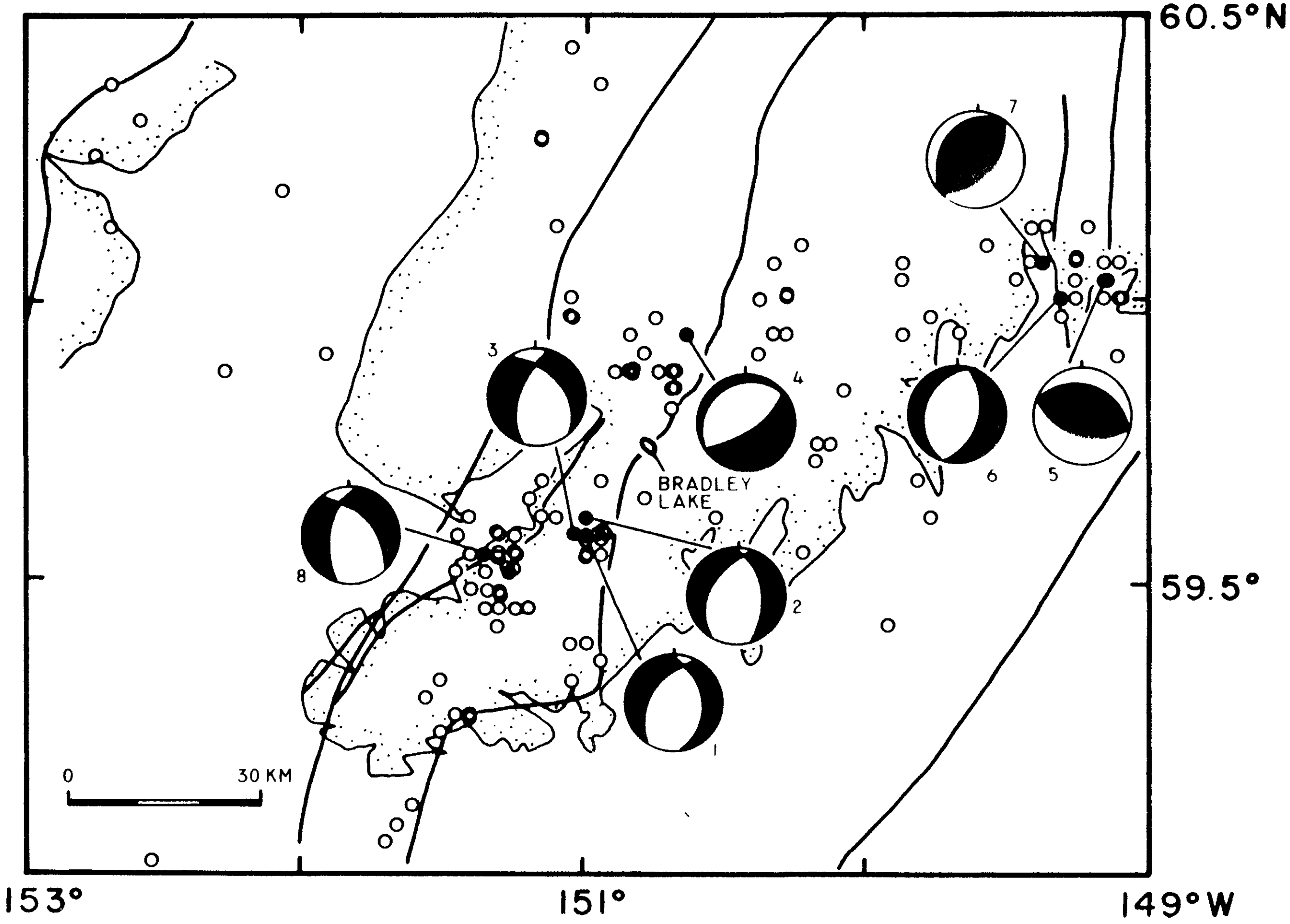


Figure 6 Map of epicenters of 127 shallow (depth <20km) earthquakes that occurred near the southern Kenai Peninsula between November 27, 1980, and November 30, 1981. Small solid circles indicate selected events for which focal mechanisms from Figures 7A and 7B are shown. Event numbers correspond to those in Figure 7 and Table 2. Focal mechanisms are lower hemisphere projections with compressional quadrants shaded. Heavy solid lines correspond to mapped fault traces identified in Figure 2.

TABLE 2

SELECTED SHALLOW EARTHQUAKES FOR WHICH FOCAL MECHANISMS HAVE BEEN DETERMINED

	ORIGIN TIME, UT						LAT., N		LONG., W		DEPTH	CODA
NUMBER	YR	MO	DY	HR	MN	SEC	DEG	MIN	DEG	MIN	KM	MAG
1	81	02	08	11	43	35.9	59	37.20	151	0.83	7.1	2.0
2	81	02	17	00	26	32.7	59	37.39	151	0.77	7.0	2.3
3	81	06	10	13	40	15.5	59	36.97	151	4.56	8.1	2.0
4	81	10	22	04	15	14.7	59	56.79	150	38.75	5.5	1.6
5	81	02	02	04	38	37.4	60	2.03	149	9.4	13.4	2.4
6	81	05	29	04	10	48.6	60	1.33	149	18.58	15.6	2.1
7	81	09	04	16	20	02.6	60	3.80	149	22.30	10.3	1.9
8	81	11	24	14	40	04.5	59	34.47	151	21.35	7.7	2.7

earthquake that occurred within 25 km epicentral distance from Bradley Lake was an event of coda-duration magnitude 2.1.

Most of the crustal activity occurred beneath the Kenai Peninsula and southeast of the Border Ranges fault. It should be noted, however, that the magnitude detection threshold for locating events is not uniform across the study area, which partially accounts for the apparent concentration of seismicity near the Bradley Lake stations. In general there is not a strong correlation of the earthquakes with the traces of the mapped faults, but the epicenters do tend to cluster spatially. Some of the more prominent clusters are: one that straddles the portion of an unnamed fault that runs along the south of Kachemak Bay; two that occur a few kilometers west of the Eagle River fault, about 15 km north and 20 km south of Bradley Lake; a more diffuse cluster that occurs east of the Eagle River fault about 30 km northeast of Bradley Lake; and one near the southern end of the Placer River fault and Kenai lineament. It is interesting to note that numerous earthquakes are located only a few kilometers west of the Eagle River fault from about 15 km northeast of Bradley Lake to the point where the fault is truncated by the lower map boundary. This seismicity pattern follows a major deviation of the fault along its length. One possible explanation for this pattern is that the earthquakes are occurring along the down-dip extension of the Eagle River fault. Whether or not this correlation is significant will be investigated further as additional data become available.

As discussed previously by Lahr and Stephens (1981), the current pattern of seismicity may be strongly influenced by the stress redistribution following the 1964 earthquake, and this pattern may change slowly over tens of years as stresses build up prior to another large earthquake.

FOCAL MECHANISMS

Preliminary focal mechanisms were determined from P-wave first motions of selected, well-recorded shallow earthquakes throughout the southern Kenai Peninsula (Figures 6, 7A, and 7B). Considering the generally poor coverage of the focal sphere for many of the events, there is a reasonable consistency in the type of faulting indicated by the mechanisms. The five events near the center of Figure 6 (events 1-4 and 8) all indicate or are consistent with predominantly normal faulting. For three of these events (2, 4, and 8) the strike of at least one of the nodal planes is reasonably well constrained to be oriented between NNE-SSW and NE-SW, subparallel to the trend of nearby mapped fault traces. The tension axes of these three mechanisms are oriented either east-west or southeast-northwest. This orientation of stresses is contrary to what might be expected in a zone of northwest-directed plate convergence and indeed is suggested by the regional geology. However, some theoretical studies (for example, Melosh and Fleitout, 1982; Bischke, 1974) suggest that portions of the overriding plate adjacent to a subduction zone may be in tension during the early part of the seismic cycle following a large earthquake (in this case the 1964 earthquake), and that these zones change to compression prior to the next large earthquake.

The three mechanisms (5, 6, 7) in the northeast part of Figure 6 suggest that the local stress pattern in this area may be very complicated. One event (6) indicates normal faulting, while the other two are thrust mechanisms. The difference between mechanisms 5 and 7 is supported by both events having several stations reporting in common, but with opposite polarities. Further work is needed to resolve these complexities.

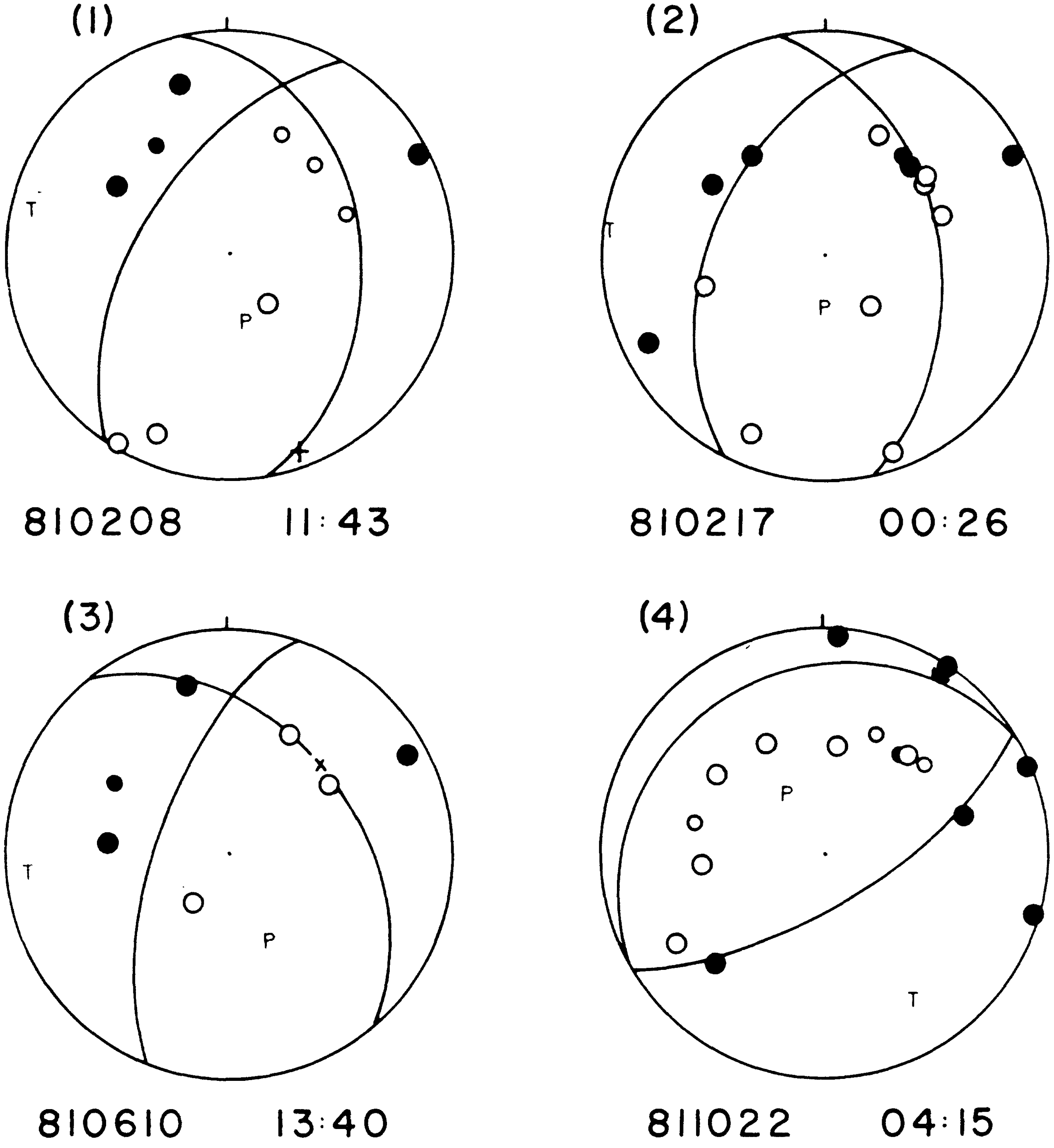
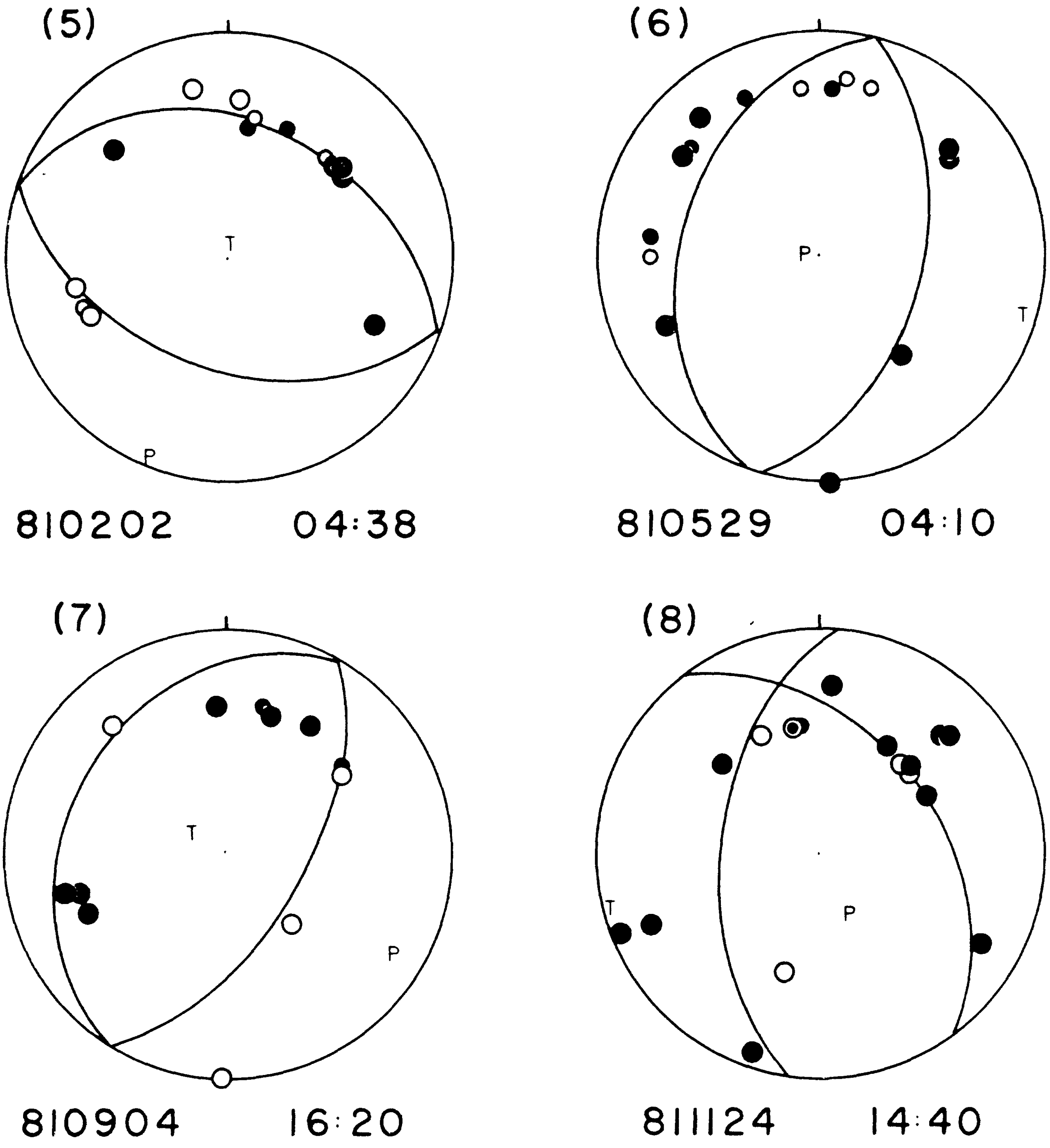


Figure 7A P-wave first-motion plots for selected shallow (depth <20km) earthquakes that occurred near the southern Kenai Peninsula. Compressions and dilatations are indicated by solid and open symbols, respectively, and larger symbol size corresponds to more reliable readings. Nodal compressions and dilatations are indicated by '+' and '-' signs. An 'x' indicates two or more readings of opposite polarity at the same point. The axes of maximum and least compressive stress are represented by the symbols P and T. Symbols are plotted on equal-area projections of the lower hemisphere.



(5) 810202 04:38

(6) 810529 04:10

(7) 810904 16:20

(8) 811124 14:40

Figure 7B Figure description same as for Figure 7A.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The operation of the Bradley Lake network has proved highly successful to date. High-quality hypocenter and P-wave first-motion data, particularly for earthquakes in the crust and shallow part of the Benioff zone, are helping to refine our understanding of the tectonic processes active in the Bradley Lake region. Earthquake activity below Bradley Lake indicates that the maximum depth to the megathrust zone between the Pacific and overriding North American plates is 35 ± 5 km. If the megathrust is at 35 km depth, then the events located at depths between 20 and 30 km may indicate that some faults in the upper crust extend down into the lower crust. Alternatively, the zone of megathrust interaction may be shallower than 35 km and involve a complex zone of splay faulting. The well-located shallow earthquakes confirm the presence of active faults in the upper 10-15 km of the crust. The pattern of crustal activity revealed by currently available data is insufficient to determine whether or not the previously mapped faults are active, although there is a suggestion of seismicity closely paralleling 100 km of the Eagle River fault. Focal mechanisms determined for selected shallow crustal events with 35 km of Bradley Lake are compatable with normal faulting in response to east-west to southeast-northwest tension. Additional data and relocation of current data with relative location techniques may help clarify the nature of the shallow earthquakes.

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APPENDIX: INTENSITY SCALE USED BY NEIS

MODIFIED MERCALLI INTENSITY SCALE OF 1931

Adapted from Sieberg's Mercalli-Cancani scale, modified and condensed.

I. Not felt - or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway--doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practically all outdoors by many or most: outdoors direction estimated. Awakened many, or most. Frightened few--slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes, glassware, to some extent. Cracked windows--in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors, shutters, abruptly. Pendulum clocks stopped, started or ran fast, or slow. Moved small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees, bushes, shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees, bushes, shaken slightly to moderately. Liquid set in strong motion. Small bells rang--church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knick-knacks, books, pictures. Overturned furniture in many instances. Moved furnishings of moderately heavy kind.

VII. Frightened all--general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows, furniture to some extent. shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general--alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly--branches, trunks, broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls. Cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) structures built especially to withstand earthquakes: Threw out of plumb some wood-frame houses built especially to withstand earthquakes; great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changed level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipe lines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipe lines buried in earth completely out of service.

XII. Damage total--practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.