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

by

John C. Lahr and Christopher D. Stephens

Submitted to:
Department of the Army
Alaska District, Corps of Engineers
Post Office Box 7002
Anchorage, Alaska 99510

Open-File Report 81-736

Menlo Park, California

1981

CONTENTS

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 important 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: establishing a network of five seismic stations around Bradley Lake in October 1980 to augment the previously existing USGS-OES network on the Kenai Peninsula; developing appropriate techniques for processing the data from the Bradley Lake region; reviewing the available USGS-OES seismic data, including one month during which the Bradley Lake network was operating; and clarifying the problems that will be addressed as more data is collected.

GENERAL NATURE AND SCOPE OF STUDY

The available seismic history for the region of the Bradley Lake Hydroelectric Project will be augmented with a more accurate and complete set of earthquake locations derived from the expanded network of seismograph stations now operating on the southern Kenai Peninsula. Specific objectives of the work to be undertaken for the Corps of Engineers include:

1.) Using data from the local seismograph network, derive locations and magnitudes for earthquakes within the region of the Project.

2.) Assess the relationship, if any, between the shallow earthquakes and mapped faults.

3.) Derive a more accurate estimate of the depth and configuration of the principal thrust fault zone which is activated by great earthquakes such as occurred in 1964.

4.) Prepare focal mechanism solutions to aid in interpreting the tectonic processes active in the region.

5.) Compile and evaluate frequency versus magnitude relationships for seismic activity within and adjacent to the study area.

METHODS AND RATIONALE OF SEISMIC DATA COLLECTION AND ANALYSIS

Installation of the Bradley Lake network

The U.S. Geological Survey has been engaged in a program of telemetered seismic recording in the region including Bradley Lake since 1971. The locations and installation dates of seismic stations are summarized in Figure 2.

The rationale for increasing the station density in the Bradley Lake region is twofold:

1.) To decrease the magnitude threshold for locatable events so that a large number of earthquakes can be located in just a few years time.

2.) To increase the accuracy of the earthquake locations so that the Benioff zone events can be clearly differentiated from the shallow crustal events and so that the possible correlation of earthquakes with mapped or inferred faults in the region can be tested.

During October 1980, an array of five seismic stations was installed around Bradley Lake. BRLK, the station nearest the lake, has three components (vertical, north-south, and east-west). Three of the four outlying vertical component stations are radioed to BRLK where the signals are combined and telemetered to the White Alice microwave facility above Homer. The fifth station, BRSW, is radioed directly to the microwave facility.

At the microwave facility the seven signals are filtered and multiplexed by equipment installed for this network. Since late November 1980 the multiplexed signal has been transmitted on to the NOAA Alaska Tsunami Warning Center in Palmer for recording on magnetic tape and film. Two of the stations are also recorded on a paper monitor record. At the time of this report (mid-February 1981) all of the Bradley Lake stations are working well, although occasional radio interference has yet to be eliminated.

Data processing techniques

The data recorded from USGS-OES seismic stations in the Bradley Lake region is mailed weekly from Palmer, Alaska, to Menlo Park, California, where it is 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 interval 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 one centimeter threshold amplitude; and period and amplitude of maximum recorded signal.

4. Initial computer processing: The data read from the films is 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 travel-time 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 more for large residuals that might be due to remaining errors.

Analysis of hypocentral 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 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. Although the ellipsoid is a function of the station geometry, it is not very sensitive to the station geometry for earthquakes within the network.

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.

SCIENTIFIC RESULTS AND DISCUSSION

Seismo-tectonic 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. The 1958 earthquake on the Fairweather fault was accompanied by right lateral strike-slip motion of as much as 6.5 m (Tocher, 1960). 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 1979 St. Elias earthquake involved low-angle north-northwest oriented thrusting of about 2 m (Hasegawa and others, 1980; Stephens and others, 1980c).

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 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.

Review of currently available USGS seismic data

Figure 3 presents a summary of the magnitude and time of occurrence of the earthquakes included in this report. Each event is shown as a point at the corresponding time and magnitude position.

For the time period January 1972 through December 1980, 986 earthquakes have been routinely processed and located by the USGS-OES in the Bradley Lake region (Lahr and others, 1974; Fogleman and others, 1978; Stephens and others, 1979; Stephens and others, 1980a, 1980b; and unpublished data). Included are 90 earthquakes occurring since the beginning of the operation of the Bradley Lake network on 27 November 1980 that are smaller than those routinely processed in the past.

In Figure 3 the time intervals in which data have not been processed are quite apparent. These gaps have resulted primarily from vacancies on our staff of data analysts which at times have been hard to fill. This situation is made more difficult by the extensive training period required before a new data analyst is able to make a positive contribution to the data processing.

The minimum magnitude threshold of located events varies considerably with time. This has been a function of our criteria for selecting which events to locate and does not reflect any temporal change in earthquake activity.

Seismicity patterns

The epicentral distribution of events is displayed in Figure 4. Earthquakes from all depths are included so crustal events are not distinguished from the deeper Benioff zone seismicity. Note that the approximately one-month sample of events located since the Bradley Lake network was installed has made a substantial contribution to the total number of earthquakes available for the southern Kenai Peninsula region, as compared with an aggregate of 5.9 years of completed data processing shown in the upper portion of Figure 4.

In order to show the depth relationship of the earthquakes in Figure 4, the events are also shown in cross section (Figures 5 and 6). An interpretation of these cross sections in terms of geology and the underthrusting Pacific plate is shown in Figure 7. The northwest-dipping slab of hypocenters that extends to more than 100 km depth, termed the Benioff zone, is assumed to lie within the upper 20 km of the Pacific plate. These events fix the position and depth of the Pacific plate northwest of Bradley Lake. The Pacific plate is assumed to have an approximately constant dip between Bradley Lake and the Aleutian trench where the megathrust outcrops (Figure 1). These assumptions place the upper surface of the Pacific plate, and therefore the Aleutian megathrust, at a distance of 29 km from Bradley Lake using the older data (Figure 7, upper) and at a distance of 35 km based on earthquakes located with the Bradley Lake network (Figure 6, lower). This distance is important in terms of estimating the ground motion at Bradley Lake from large earthquakes on the Aleutian megathrust. The 35-km estimate is probably more accurate because of the improved network coverage, but further refinement will be possible as:

1) more data is collected, and

2) an improved velocity model is determined specifically for this region.

It is notable that the Benioff zone activity dies out near Bradley Lake, that crustal activity is concentrated seaward of Cook Inlet, and that there is not a concentration of events along the Aleutian megathrust. The estimated landward limit of the 1964 rupture of the Aleutian megathrust (Hastie and Savage, 1970) is noted in Figure 7, lower. The current pattern of seismicity may be strongly affected by the stress redistribution in 1964, and this pattern may change slowly over tens of years as stresses build prior to another large earthquake. The possibility of long-term cyclic changes in seismicity will be addressed in future work, as they could invalidate conclusions based on a short period of observations.

Relationship of shallow earthquakes to mapped faults

Several major faults have been mapped in the Bradley Lake region (Figures 2 and 7). Shallow earthquakes do occur in the region, but there is no unequivocal geologic or historical seismic evidence for recent activity on any of these faults (see, for example, Woodward-Clyde Consultants, 1980, p. 17-22.). One explanation for the lack of recognized ground displacement on the major faults is that the deformation associated with the shallow seismicity may be broadly distributed on numerous unrecognized (and possibly buried) faults. An alternate explanation for the lack of observed displacements on the major faults is that movement may not be consistently in the same direction, so that the cumulative displacement of many earthquakes is not very great. One of the objectives of continued seismic monitoring in the region will be to infer the distribution and type of active faults from the observed seismicity.

Shallow crustal earthquakes can be distinguished easily from Benioff zone events northwest of Bradley Lake where the Benioff zone begins to dip steeply into the mantle (Figure 5, upper). As the Benioff zone approaches crustal depths beneath Bradley Lake the resolution between the zone of shallow crustal activity and deeper events becomes less distinct. A clear vertical separation between these two zones is apparent, however, in the distribution of hypocenters determined using the Bradley Lake seismic stations (Figure 5, lower), thus emphasizing how critical these stations are for resolving the regional seismo-tectonic structure. East and southeast of Bradley Lake nearly all of the seismic activity is confined to shallow depths, but it is not clear whether the earthquakes are occurring within the overlying wedge of continental material, at the thrust contact between the two plates, or within the Pacific plate. Based on both of the cross sections in Figure 5, earthquakes shallower than 20 km almost certainly occur within the crust. In order to investigate the relationship of crustal activity to mapped faults, only the events that occurred in this depth range are considered. Epicenters of the shallow events are shown in Figures 8 through 11.

The distribution of shallow activity can best be described as diffuse with a general northeast-southwest trend evident in Figure 11, lower. Although the epicenters are not aligned with the mapped surface faults, over half of the events in each data set are located within 10 km of a fault trace. Considering the uncertainty in the hypocenter locations and the probable non-vertical dip of the faults, it is possible that many of the earthquakes are occurring on downdip extensions of the mapped faults. The improved accuracy and greater number of hypocenter locations provided by the Bradley Lake stations are expected to help resolve this question as more earthquakes are located.

Many shallow earthquakes were located away from the mapped faults. Epicenters of some of these events are in the Kenai Lowlands west of the Border Ranges fault (Figure 8, upper). The Tertiary sediments of this area are deformed by northeast-southwest trending folds and faulted anticlinal structures that still may be growing in response to a regional northwest-directed tectonic compression (Kirschner and Lyon, 1973; Tysdal, 1976). Some or all of the shallow earthquakes located in this area may be associated with these structures.

The nature of the shallow earthquakes occurring east of the Eagle River fault is not clear. The most prominent feature in the distribution of these events is the high rate of activity near the southern end of the Kenai lineament and the Placer River fault (Figure 8, upper). This cluster of activity is located within an area where a number of observations suggesting crustal faulting were made following the 1964 Prince William Sound earthquake. The area lies at the southwest corner of an abrupt discontinuity in the distribution of aftershock activity from the 1964 earthquake noted by Page (1969). Plafker (1969) attributed observed ground breakage along the Kenai lineament and dislocations deduced from triangulation measurements after the 1964 earthquake either to crustal warping or to left-lateral movement on a buried north-south trending fault.

The largest of all the shallow earthquakes that occurred since 1972 in the Bradley Lake region was a magnitude 5.0 event on February 5, 1976 located near the southern end of the Kenai lineament. This earthquake did not have a significant aftershock sequence, an observation that would be consistent with a subcrustal origin for the event (Page, 1968). A more detailed study of this area is planned in order to determine whether the seismic activity is occurring primarily within or below the crust.

Magnitude distribution and recurrence rates

The data processed by the USGS-OES since 1972 includes six events of magnitude 5 and larger, the largest having a magnitude of 5.3. The OES-determined magnitudes for these events are generally within a few tenths of a unit of the body-wave magnitudes (m_b) reported in the U.S.G.S. Preliminary Determination of Epicenters (PDE) notices. A review of the PDE data, which is probably complete for events of magnitude 5 and larger since 1972, indicates that no events in this magnitude range occurred in the time periods for which the regional network data has not yet been completed. Five of the six largest events that occurred between 1972 and 1981 were located at subcrustal depths; four occurred beneath Iliamna volcano at depths ranging from about 90 to 160 km, and one occurred within the Benioff zone beneath the Kenai Lowlands at a depth of about 50 km. The only shallow magnitude 5 event is the one discussed in the previous section that occurred near the southern end of the Kenai lineament, about 90 km east-northeast of Bradley Lake.

As mentioned earlier, a sharp contrast in the rate of seismic activity above and below a depth of about 20 km is clearly evident in the upper cross section in Figure 5. Because this contrast probably reflects a difference in the mechanical or tectonic processes that control earthquake occurrence, the frequency-magnitude distributions of the two depth ranges are considered separately (Figure 12). For magnitudes above the threshold where the data set is complete, the frequency-magnitude distribution is described by the Gutenberg-Richter relationship $\log N(M) = A - bM$ where $N(M)$ is the number of events of magnitude M or greater and A and b are constants. Although the rate of occurrence of the deeper events is considerably higher than in the overlying wedge of continental material, the b-value for both data sets is not significantly different from 1.0, a value commonly obtained for earthquakes throughout the world. The implied return time for earthquakes of magnitude 5 and larger is one year for events below 20-km depth, and is 35 years for shallower events.

Care must be taken in extrapolating magnitude recurrence data either in time or to larger magnitudes. For example, large temporal fluctuations in seismicity rate are known to occur, so the long-term average rate of activity may be significantly different from what has been observed over a relatively short interval of time. Other complications arise in deciding whether or not to include earthquakes of different tectonic origin in the same data sample. In addition, the recurrence relationship for earthquakes in a given region may not be linear over the magnitude range from microearthquakes (magnitudes less than about 3) to the largest events possible. Obviously a breakdown will occur when the largest events are not contained entirely within the region under consideration. In considering the return time of the largest earthquakes it is necessary to take a broader view in both space and time, and although the microearthquake data collected from the Bradley Lake array alone is not expected to resolve this problem, the various estimates of the return rate of large earthquakes will be reviewed and discussed in future reports.

RECOMMENDATIONS FOR FUTURE WORK

A program for detailed seismic monitoring of the Bradley Lake region has been developed and is now operating extremely well. The data analyzed to date and discussed in this report demonstrate the utility of operating this array, both in terms of increasing the rate at which earthquake data are collected and improving the accuracy of the data. The principal goals of this work are:

1) Study the shallow seismicity in detail and determine what, if any, relationship exists between the earthquakes and the mapped faults and lineaments.

2) Determine more accurately the configuration of the Aleutian megathrust zone and the closest distance from Bradley Lake to the zone.

3) Utilize both the pattern of seismicity and the results of focal mechanism determinations to develop an improved tectonic model for the region.

4) Determine an appropriate frequency-magnitude recurrence relationship for the principal faults and nearby tectonic zones, with particular emphasis on those earthquakes which could pose a hazard to the hydroelectric project.

5) Investigate the problem of long-term temporal and spacial variations in the seismicity and estimate the effect that such variations might have on the conclusions drawn from a relatively short interval of time.

Continued operation of the Bradley Lake network through fiscal year 1984 is strongly recommended in order to record and analyze a sufficient number of shallow earthquakes to address these goals.

The possibility of installing a strong-motion instrument at the Bradley Lake site was discussed last year. This type of instrumentation operates only during the relatively infrequent large earthquakes that produce ground accelerations greater than 0.01 g, so a short interval of operation would not be cost effective. The strong motion instruments now being operated by the USGS-OES at Seldovia, Homer and Seward are in jeopardy of removal due to the termination of a NOAA-supported seismic monitoring program in fiscal year 1982. We recommend that the Corps of Engineers, rather than installing additional strong motion instruments, fund the continued maintenance of these three stations. We further recommend operating the strong motion stations for at least 10 years, independent of decisions about when to terminate the high-gain network.

ACKNOWLEDGEMENTS

The seismic data used in the preparation of this report was collected and compiled through the efforts of many individuals within the U. S. Geological Survey and other organizations over many years. We gratefully acknowledge their contributions. John Rogers installed the seismic stations of the Bradley Lake array. Kent Fogleman and Janet Melnick processed most of the initial seismic data collect from these stations. Robert Page, Sam Stewart, and Christopher Rojan critically reviewed this report and offered many helpful suggestions.

This study was funded by the Department of the Army, Alaska District Corps of Engineers.

REFERENCES

Beikman, H. M., compiler, 1980, Geologic map of Alaska: U.S. Geological Survey, scale 1:2,500,000.

Fisher, M. A. and Magoon, L. B., 1978, Geologic Framework of Lower Cook Inlet, Alaska, The American Association of Petroleum Geologists Bulletin, v. 62, no. 3, p. 373-402.

Fogleman, K. A., Stephens, Christopher, Lahr, J. C., Helton, Suzanne, and Allan, Maryann, 1978, Catalog of earthquakes in southern Alaska, October-December 1977, U. S. Geological Survey Open-File Report 78-1097, 28 p.

Hasegawa, H. S., Lahr, J. C., and Stephens, C. D., 1980, Fault parameters of the St. Elias , Alaska, earthquake of February 28, 1979, Bulletin of the Seismological Society of America, v. 70, no. 5, p. 1657-1660.

Hastie, L. M. and Savage, J. C., 1970, A dislocation model for the 1964 Alaska earthquake, Bulletin of the Seismological Socity of America, v. 60, no. 4, p. 1389-1392.

Kirschner, C. E., and Lyon, C. A., 1973, Stratigraphic and tectonic development of Cook Inlet petroleum province, in M. G. Pitcher, ed., Arctic Geology: American Association of Petroleum Geologists Memoir 19, p. 396-407.

Lahr, J. C., 1980, HYPOELLIPSE/MULTICS, A computer program for determining local earthquake hypocentral parameters, magnitude, and first motion pattern, U. S. Geological Survey Open-File Report 80-59, 59 p.

Lahr, J. C., Page, R. A., and Thomas, J. A., 1974, Catalog of earthquakes in south central Alaska, April-June 1972, U. S. Geological Survey Open-File Report, 35 p.

Minster, J. B. and Jordon, T. H., 1978, Present-day plate motions, Journal of Geophysical Research, v. 83, no. B11, p. 5331-5354.

Page, R. A., 1968, Focal depths of aftershocks, Journal of Geophysical Research, v. 73, no. 12, p. 3897-3903.

Page, R. A., 1969, Aftershocks and microaftershocks of the great Alaska earthquake of 1964, Bulletin of the Seismological Society of America, v. 59, no. 3, p. 1131-1168.

Plafker, George, 1969, Tectonic of the March 27, 1964 Alaska earthquake, U. S. Geological Survey Professional Paper, 543-I, 74 p.

Plafker, George, Jones, D. L., and Pessegno, E. A., Jr., 1977, A Cretaceous accretionary flysch and melange terrane along the Gulf of Alaska margin, _in_ The U.S. Geological Survey in Alaska: Accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B41-B42.

Stephens, C. D., Lahr, J. C., Fogleman, K. A., Allan, M. A., and Helton, S. M., 1979, Catalog of earthquakes in southern Alaska, January-March 1978, U. S. Geological Survey Open-File Report 79-718, 31 p.

Stephens, C. D., Fogleman, K. A., Lahr, J. C., Helton, S. M., Cancilla, R. S., Tam, Roy, and Freiberg, J. A., 1980a, Catalog of earthquakes in southern Alaska, January-March 1980, U. S. Geological Survey Open-File Report 80-1253, 55 p.

Stephens, C. D., Lahr, J. C., Fogleman, K. A., Helton, S. M., Cancilla, R. S. Tam, Roy, and Baldonado, K. A., 1980b, Catalog of earthquakes in southern Alaska, October-December 1979, U. S. Geological Survey Open-File Report 80-2002, 53 p.

Stephens, C. D., Lahr, J. C., Fogleman, K. A., and Horner, R. B., 1980c, The St. Elias, Alaska, earthquake of February 28, 1979: Regional recording of aftershocks and short-term, pre-earthquake seismicity, Bulletin of the Seismological Society of America, v. 70, no. 5, p. 1607-1633.

Tocher, Don, 1960, The Alaska earthquake of July 10, 1958: Movement on the Fairweather fault and field investigations of southern epicentral region, Bulletin of the Seismological Society of America, v. 50, no. 2, p. 267-292.

Tysdal, R. G., 1976, A preliminary evaluation of selected earthquake-related geologic hazards in the Kenai lowland, Alaska, U. S. Geological Survey Open-File Report 76-270, 30 p.

Tysdal, R. G. and Case, J. E., 1979, Geologic map of the Seward and Blying Sound quadrangles, Alaska: U.S. Geological Survey Map I-1150, scale 1:250,000.

Woodward-Clyde Consultants, 1979, Reconnaissance geology Bradley Lake Hydroelectric project: Submitted to Department of the Army, Alaska District, Corps of Engineers, Anchorage, Alaska, 1979.

Woodward-Clyde Consultants, 1980, Seismic study Bradley Lake Hydoelectric Project, submitted to U. S. Department of the Army, Corp of Engineers, 39 p.

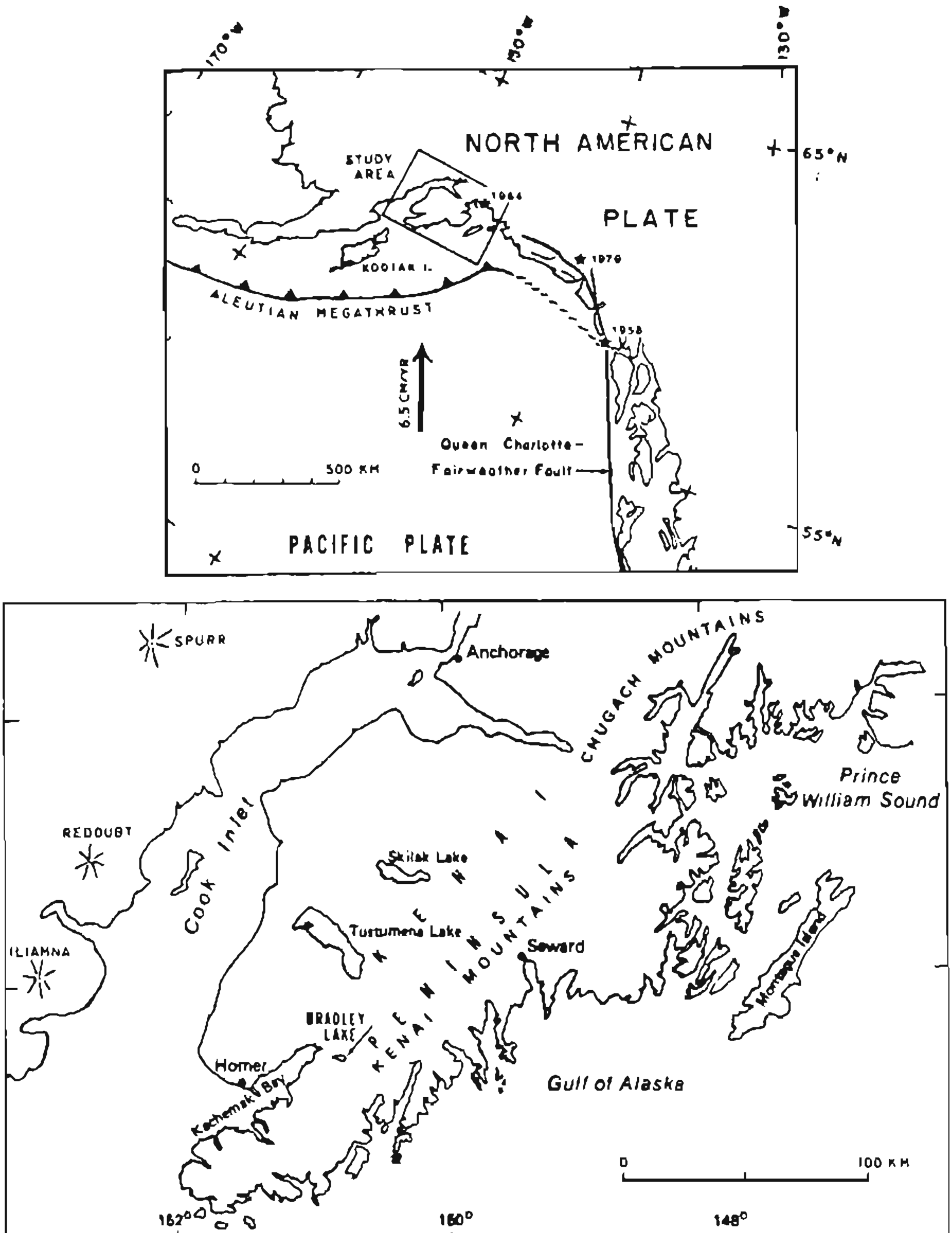


Figure 1. Upper- Current motion of Pacific plate with respect to North American plate. Projection is oblique Mercator using a pole at 54°N and 61°W. Rotation of the Pacific plate with respect to the North American plate about this pole is equivalent to vertical translation in this figure. Epicenters 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).

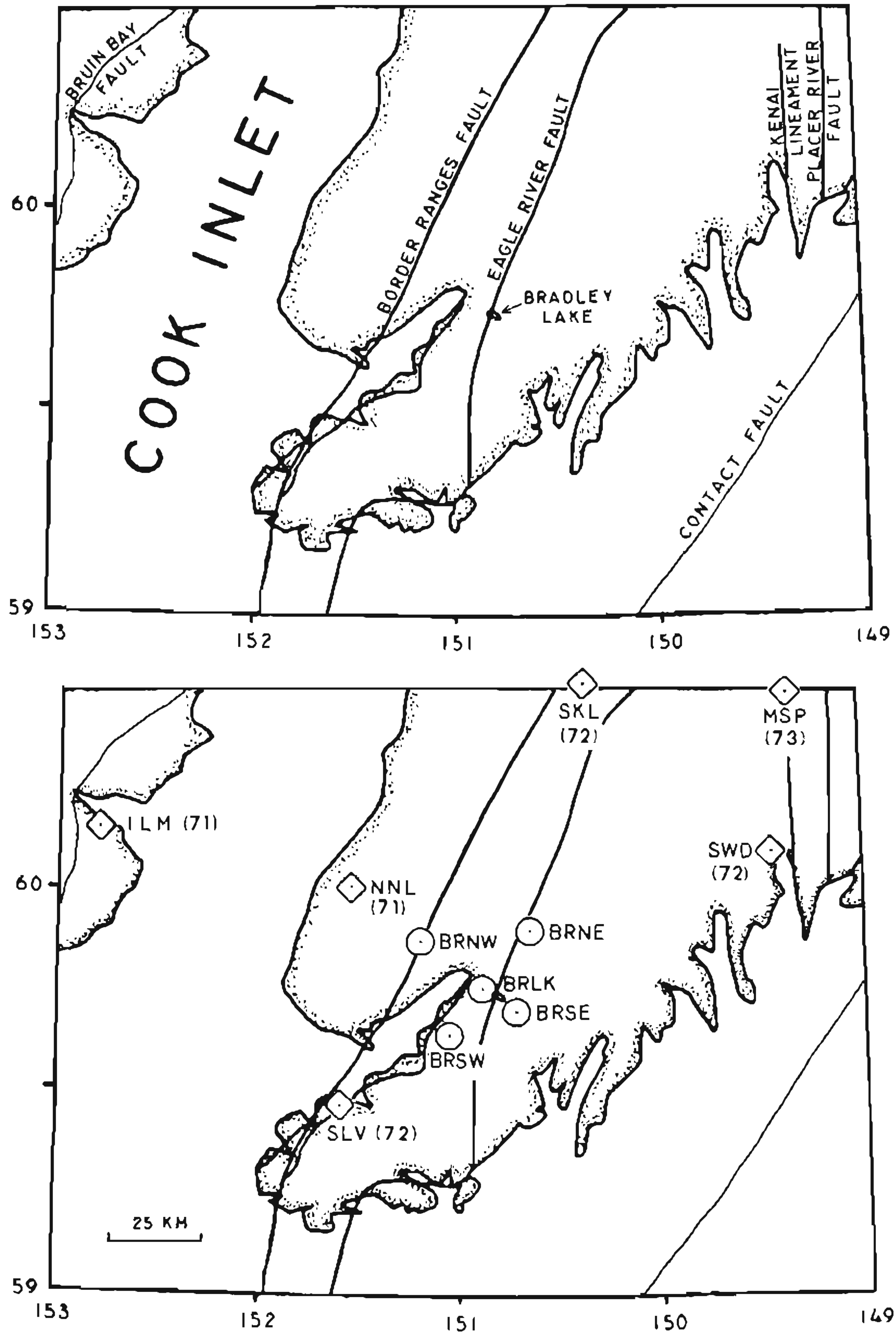


Figure 2. Map of Bradly Lake region. Upper- Principal faults, after Beikman (1980), Plafker (1969), Tysdal and Case (1979), and Plafker and others (1977). Lower- Seismograph stations funded by the U. S. Geological Survey (diamonds) and the Corps of Engineers (circles). Numbers in parentheses next to station codes are last two digits of the year that the station was installed. All of the Bradley Lake stations (four letter codes) were installed in 1980.

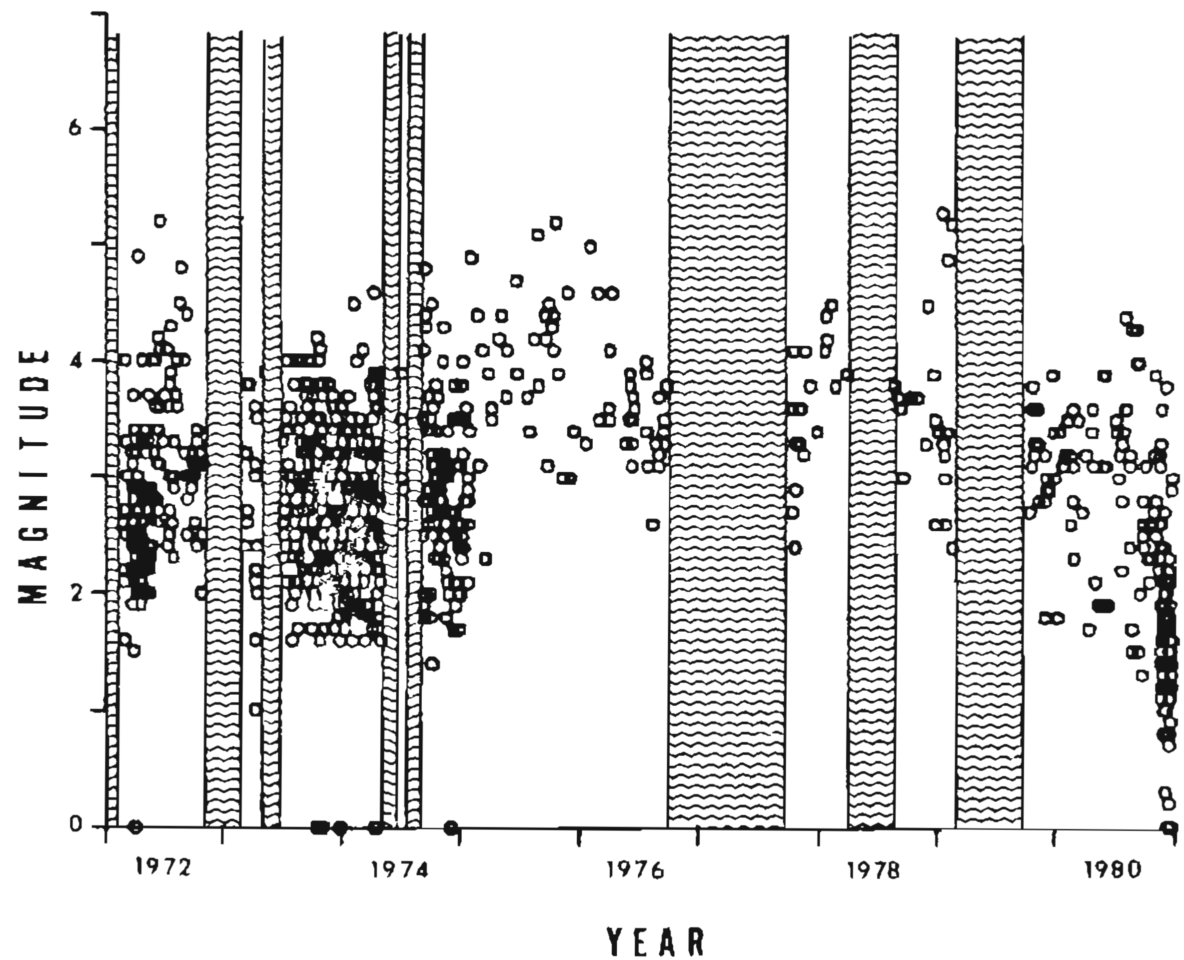


Figure 3. Magnitude-time processing history for earthquakes within the region mapped in Figure 2. Gaps in data analysis are indicated by wave pattern (see text).

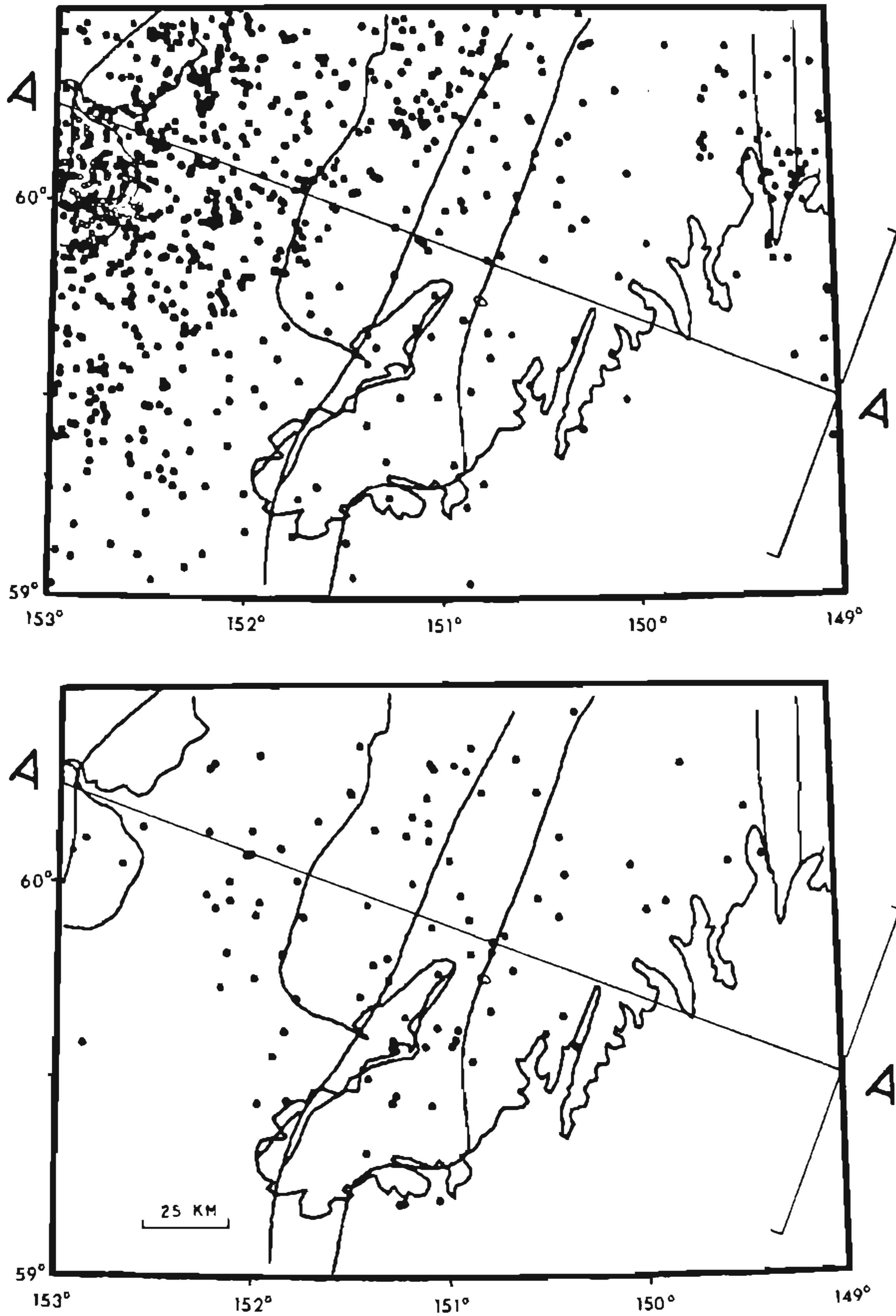


Figure 4. Seismicity in the Bradley Lake region.
Upper- February 24, 1972 through November 26, 1980, 887 events plotted.
Lower- November 27, 1980 through December 31, 1980, 99 events plotted.

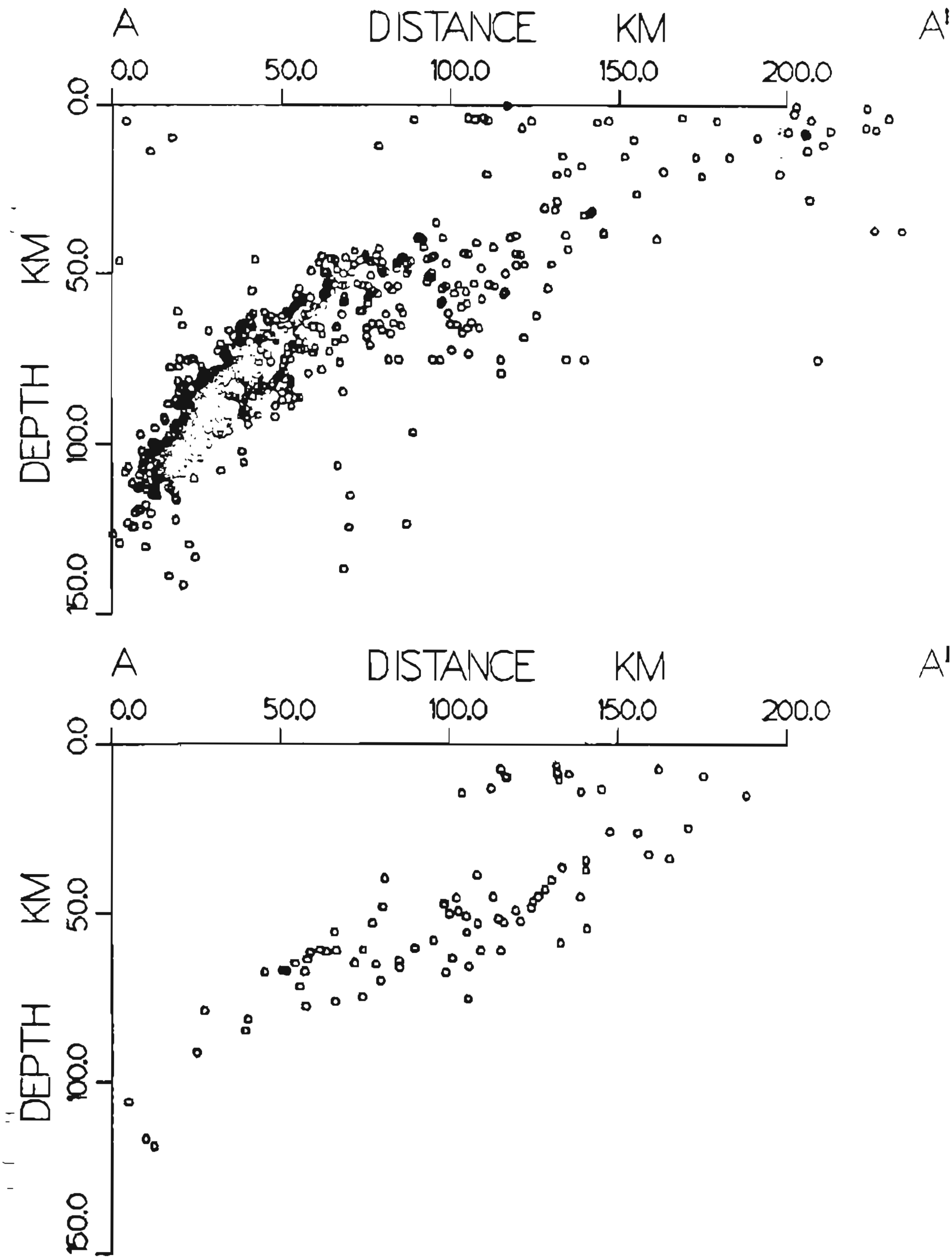


Figure 5. Vertical cross sections of the earthquake data within 50 km of the plane A-A' noted in Figure 4. The location of Bradley Lake (BL) is indicated by an arrow. The time intervals of upper and lower plots are the same as for Figure 4.

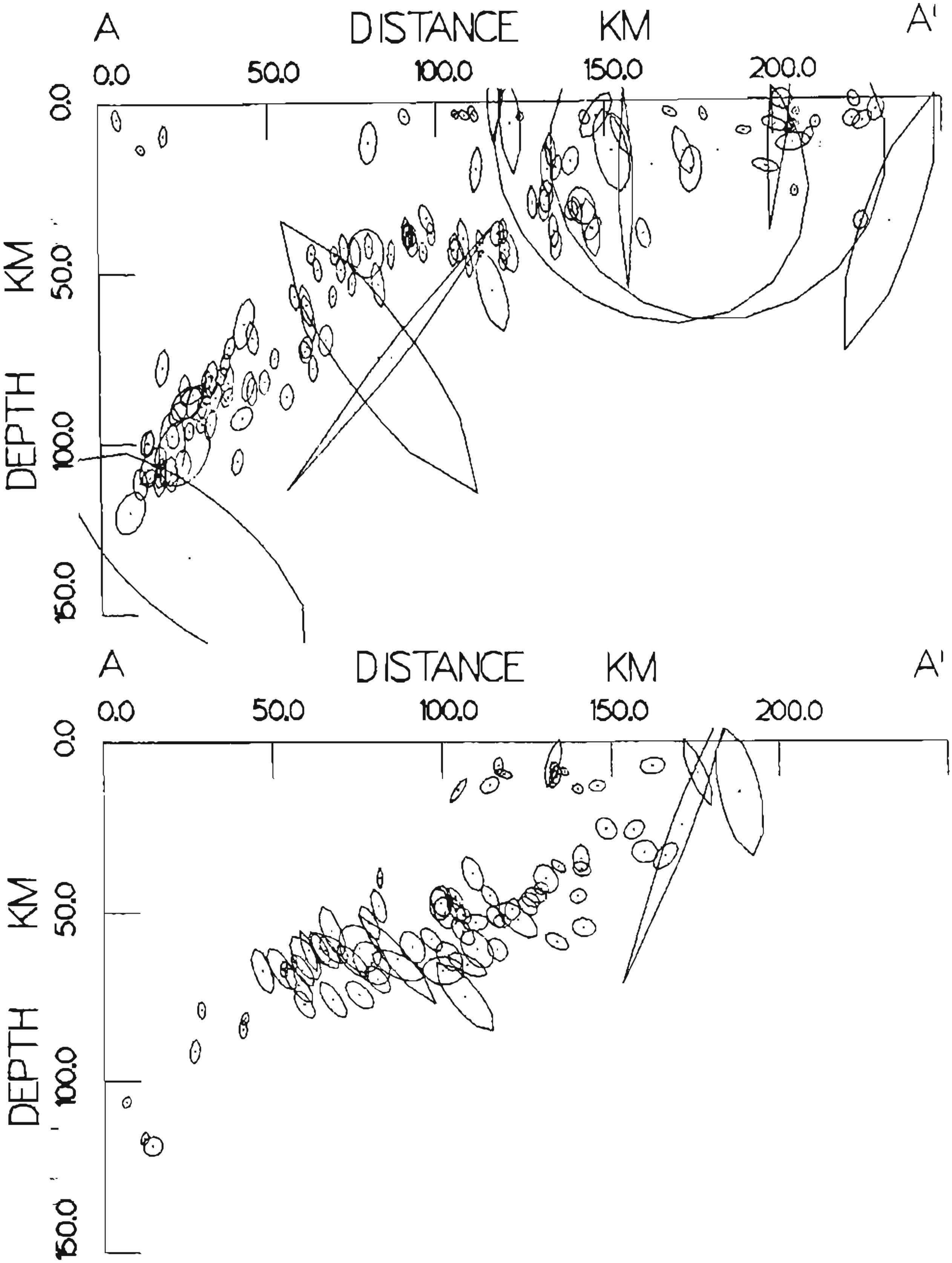


Figure 6. Vertical cross sections as plotted in Figure 5, with projected one-standard-deviation confidence error ellipsoids. Upper- To reduce the density of error ellipsoids for deeper events, only every ninth event below 45 km is included.

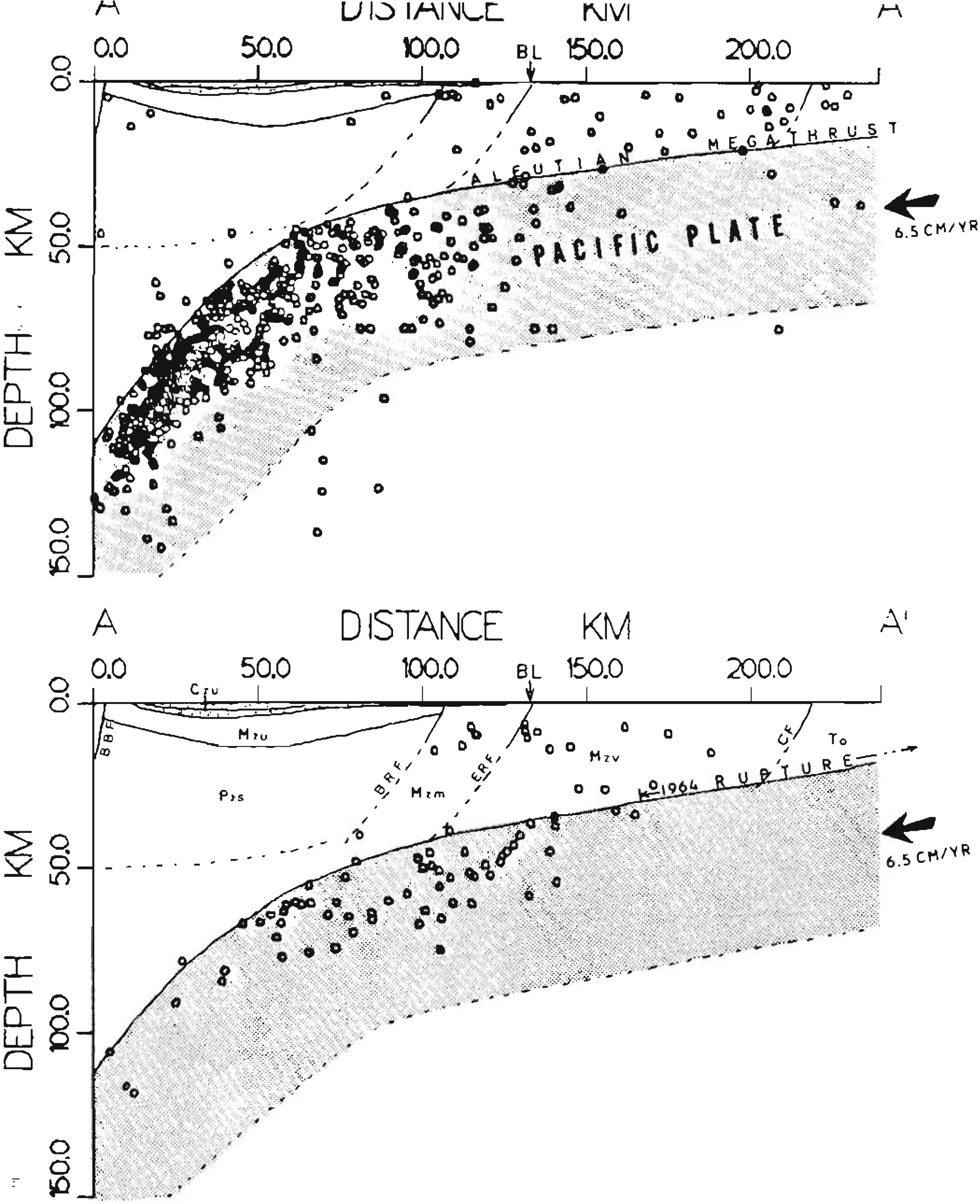


Figure 7. The seismic data from Figure 5 with geology and tectonic interpretation superimposed. BBF - Bruin Bay fault, BRF - Border Ranges fault, ERF - Eagle River fault, CF - Contact fault, Czu - undifferentiated Cenozoic, Mzu - undifferentiated Mesozoic, Pzs - Paleozoic metamorphics, Mzm - Cretaceous melange, Mzv - upper Cretaceous flysch, To - Lower Tertiary flysch. Geology from Plafker and others (1977) and Fisher and Magoon (1978).

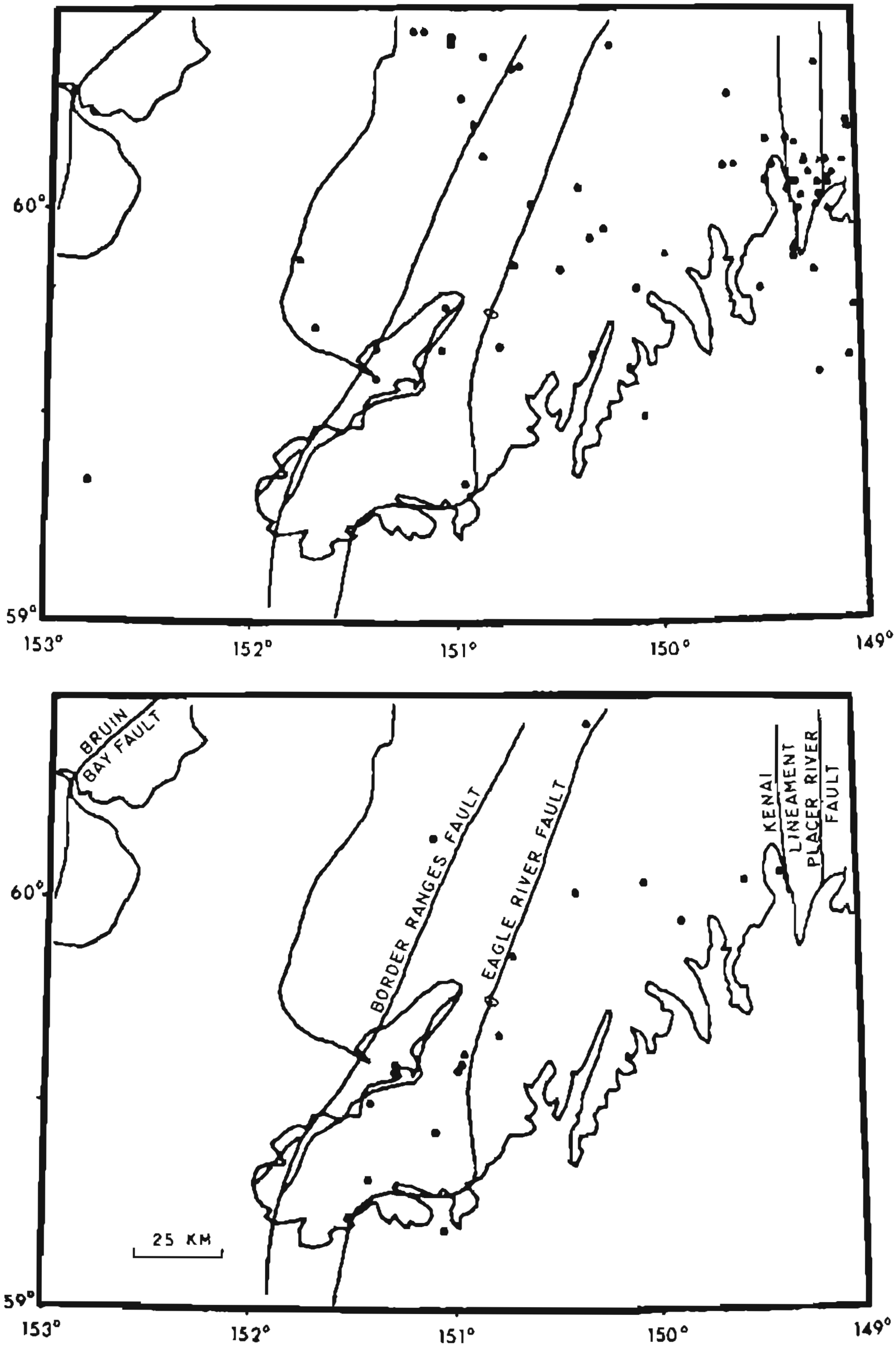


Figure 8. Seismicity in the Bradley Lake region for events less than 20 km deep. The time intervals of upper and lower plots are the same as for Figure 4.

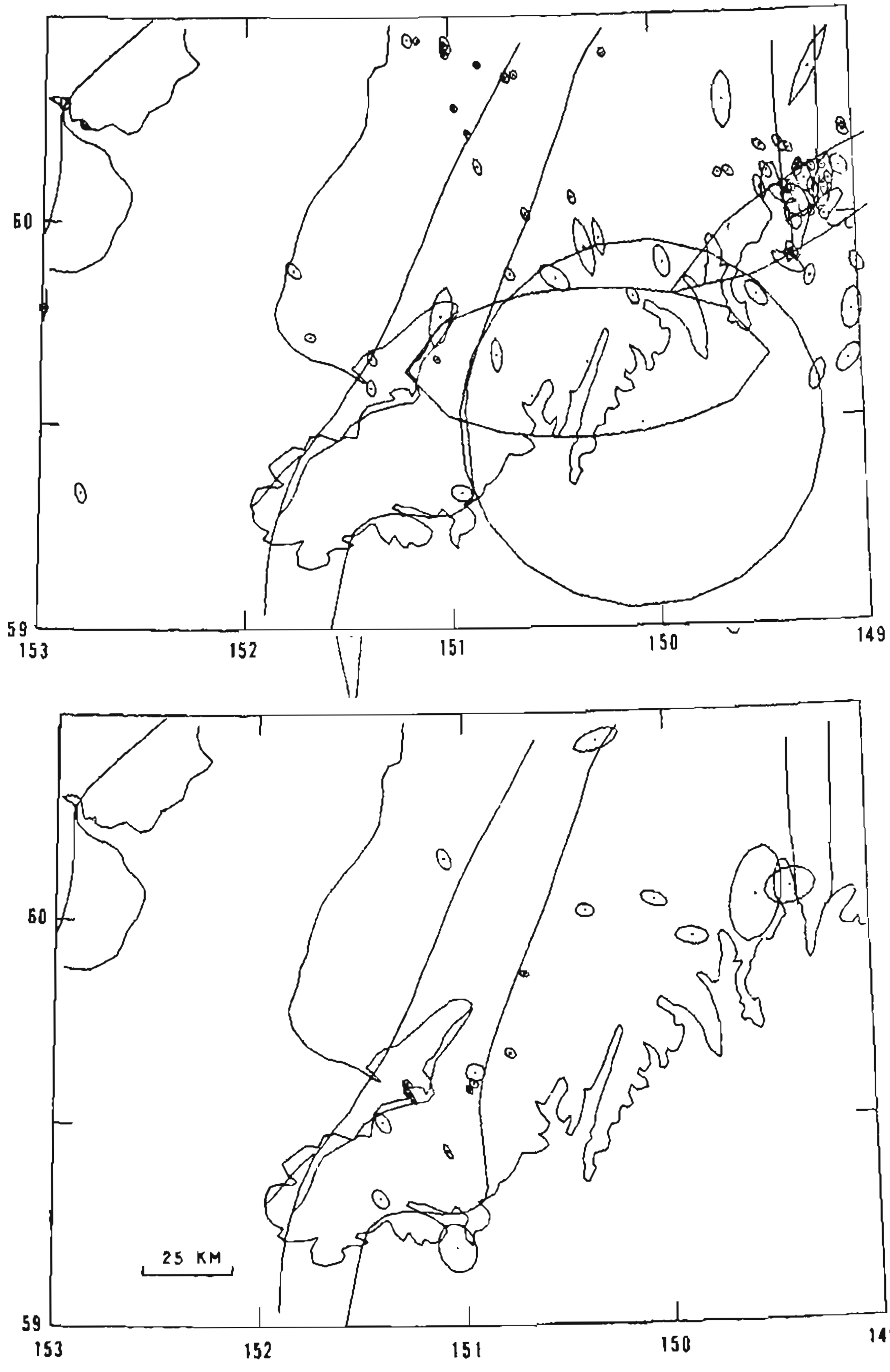
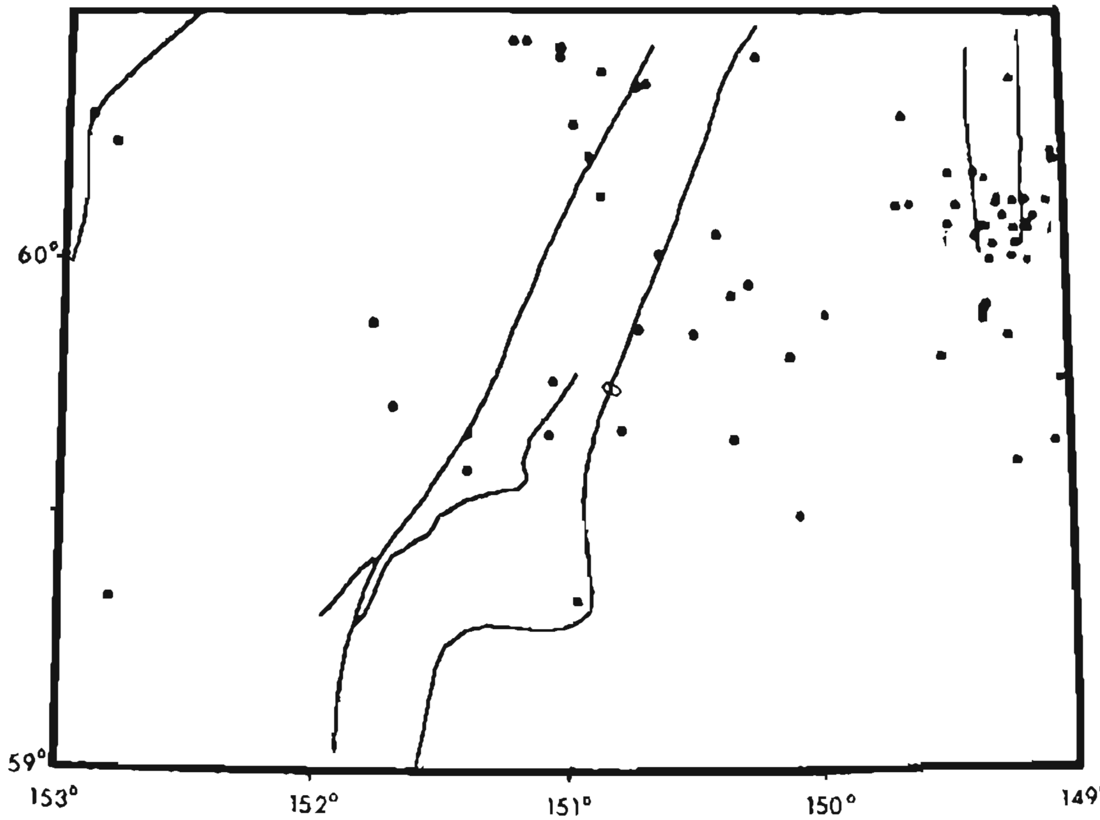


Figure 9. One-standard-deviation error ellipsoids for the shallow seismicity of the Bradley Lake region shown in Figure 8.



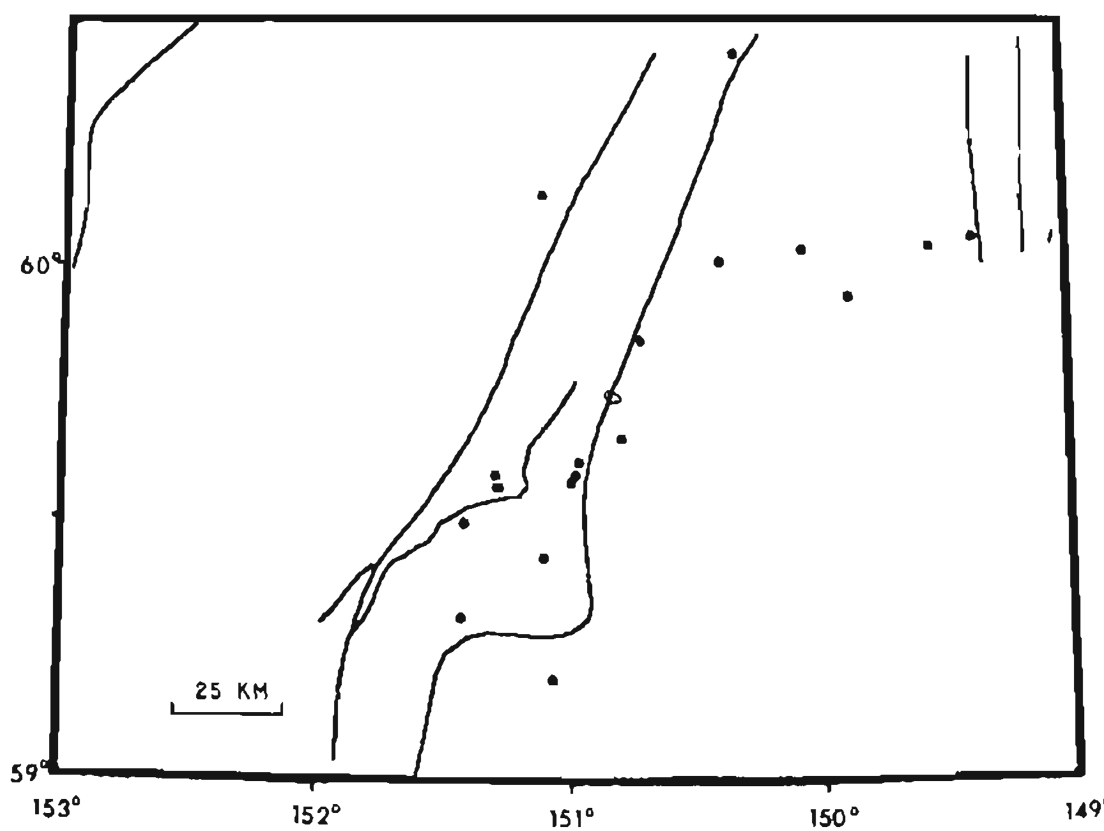


Figure 10. Shallow seismicity of the Bradley Lake region as plotted in Figure 8, but only tne fault lines are shown.

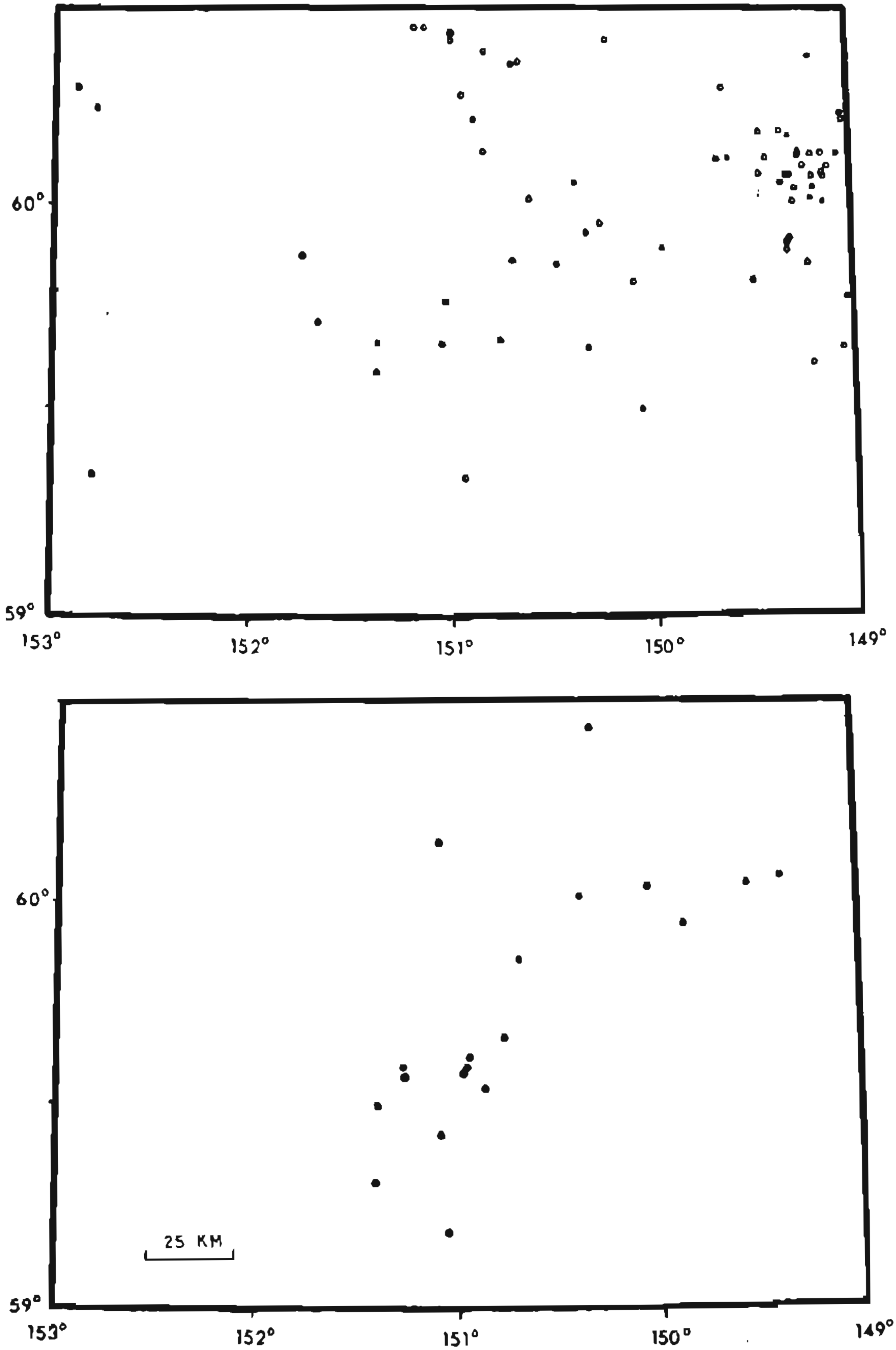


Figure 11. Shallow seismicity of the Bradley Lake region as plotted in Figure 8, but no shorelines or faults are shown.

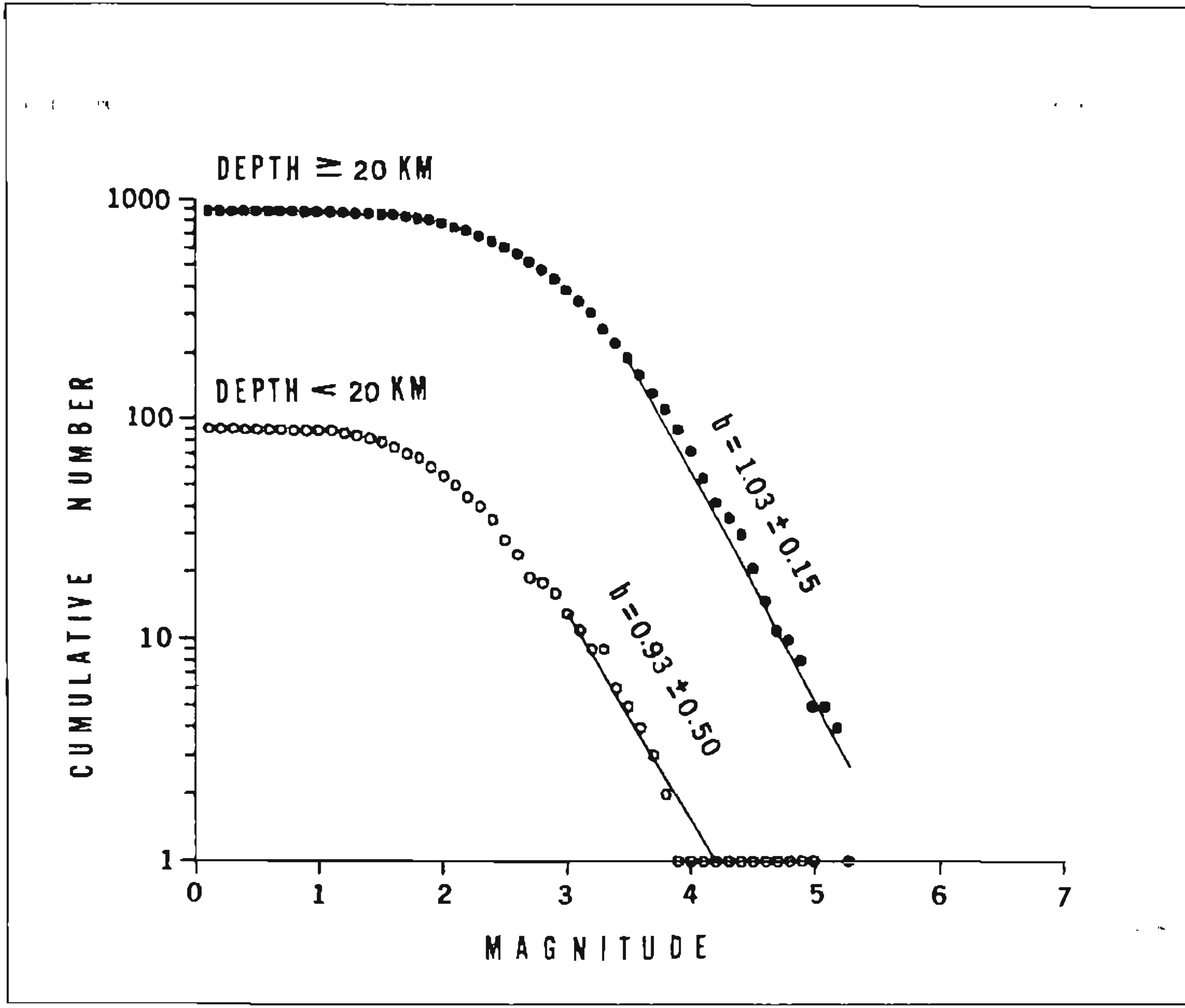


Figure 12. Cumulative frequency-magnitude distributions for data collected in the time interval February 24, 1972, through December 31, 1980. The b-value for the deeper earthquakes (solid symbols) is based upon 192 events with magnitude greater than or equal to 3.5. For the shallower events (open symbols), the b-value is determined from 13 earthquakes with magnitude greater than or equal 3.0. Approximate 95% confidence limits are given.