Alaska Earthquakes—1994

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ABSTRACT

Alaska is one of the world's most seismically active regions associated with subduction and volcanism. Earthquakes occur over practically the entire state. The greatest concentration of earthquakes is along the Pacific margin, where the Pacific plate is being subducted beneath southern Alaska and the Aleutian Islands. Historical and current seismicity along the Aleutian volcanic arc is dominated by activity west of the Alaska Peninsula. In 1994, 79 of the 103 magnitude 4.5 and larger shocks located in Alaska and western Canada occurred in the Aleutian Islands. The largest shock located during 1994 was a shallow, body-wave magnitude (m_b) 6.0 event in the Fox Islands, but the most widely felt earthquake was an m_b 5.4 event located 77 kilometers (km) southwest of Anchorage at a depth of 49 km. Two notable earthquakes are (1) the largest, well-constrained deep shock yet located in the Aleutian Wadati-Benioff zone east of longitude 156°W., an m_b 4.6 event at 219-km depth, and (2) the largest crustal shock ever located beneath the edifice of Mount Spurr volcano, a magnitude (M_L) 2.8 event at a depth of 1 km below the top of the volcano. The Alaska Earthquake Information Center (AEIC) located more than 4,400 earthquakes in 1994 using data recorded by the joint U.S. Geological Survey/University of Alaska seismograph network.

INTRODUCTION

Alaska spans 4,800 km of the seismically active boundary between the oceanic Pacific and continental North American plates (fig. 1) and has one of the world's highest levels of earthquake activity associated with subduction and volcanism. The historical record indicates that approximately 11 percent of the world's earthquakes occur in Alaska, even though the land area of Alaska is only about three-tenths of 1 percent of the surface area of the world (Davies, 1984). Magnitude 7 and larger shocks are about three times more frequent in southern Alaska than in California (Page, 1994). Three of the ten largest earthquakes in the world in this century originated in Alaska on the boundary between the Pacific and North American plates (Kanamori, 1977; Johnson and others, 1994). In 1964, the eastern end of the Aleutian subduction zone spawned the moment magnitude (M_W) 9.2 Prince William Sound earthquake (fig. 2), the second largest earthquake of this century. The other two earthquakes occurred in the western and central parts of the Aleutian Islands—the 1965 M_W 8.7 Rat Islands earthquake (rank no. 5) and the 1957 M_W 8.6 Andreanof-Fox Islands earthquake (rank no. 7).

The seismicity of Alaska stems primarily from the interaction of the Pacific and North American plates. The northwestward motion of the Pacific plate relative to the North American plate (fig. 2) is accommodated by right-lateral, strike-slip faulting in western Canada and southeast Alaska on the Queen Charlotte–Fairweather fault system; by underthrusting and subduction of the Pacific plate along the Aleutian main thrust zone (megathrust), which extends from the eastern Gulf of Alaska to the central Aleutians; and by right-lateral, strike-slip faulting in the western Aleutians (Estabrook and Jacob, 1991). The Aleutian megathrust intersects the seafloor at the Aleutian trench, which forms part of the near-surface expression of the Pacific–North American plate boundary. In the northeastern Gulf of Alaska (fig. 1), between the Fairweather fault and the eastern end of the Aleutian trench, the plate boundary is transitional and complex. The relative motion is distributed among at least three fault systems (Lahr and Plafker, 1980). At the northern end of the Fairweather fault, the primary component of plate motion is transferred to the Chugach–St. Elias fault, then to a series of thrust faults between the Pamplona and Kayak Island zones, and finally to the Aleutian megathrust. Much of this complexity arises from the collision between the North American plate and the Yakutat terrane, a composite oceanic-continental terrane sutured to the top of the Pacific plate (Plafker, 1987). The Yakutat terrane is subducting beneath the North American plate to the west of longitude 144°W. and accreting to the North American plate to the east (Page, 1994). The horizontal compressional stress resulting from this collision is transmitted inland across the eastern half of the State and also

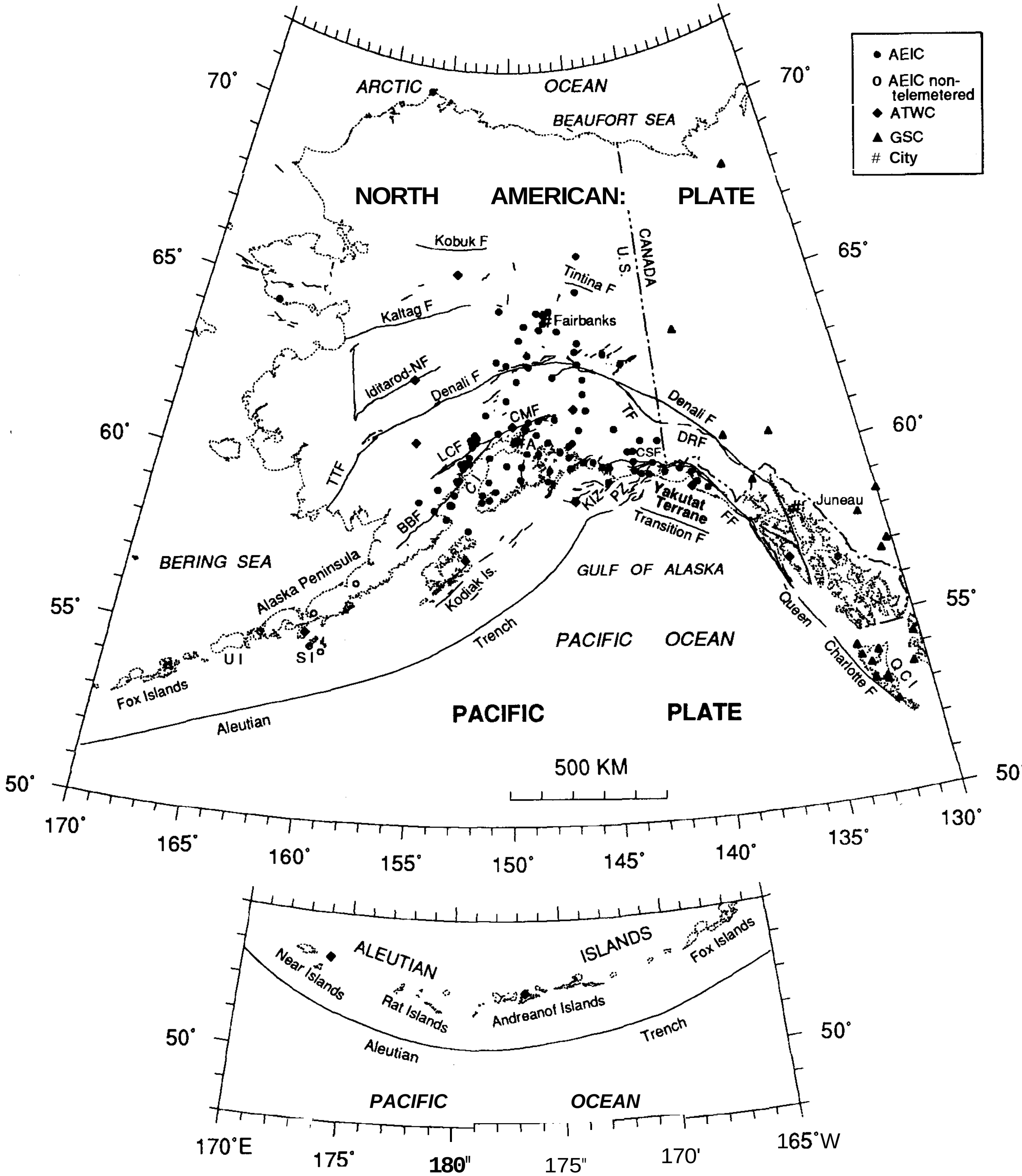

Figure 1. Map of seismograph stations in Alaska and western Canada operated during 1994. Symbol type corresponds to operating institution as indicated: AEIC, Alaska Earthquake Information Center; ATWC, Alaska Tsunami Warning Center; GSC, Geological Society of Canada. Solid lines show Neogene and younger faults (from Plafker and others, 1994). Fault abbreviations: BBF, Bruin Bay fault; CMF, Castle Mountain fault; CSF, Chugach–St. Elias fault; DRF, Duke River fault; FF, Fairweather fault; LCF, Lake Clark fault; Idatarod–NF, Iditarod-Nixon Fork fault; KIZ, Kayak Island zone; PZ, Pamplona zone; TF, Totschunda fault; TTF, Togiak-Tikchik fault; Also: A, Anchorage; CI, Cook Inlet; QCI, Queen Charlotte Islands; SI, Shumagin Islands; UI, Unimak Island.

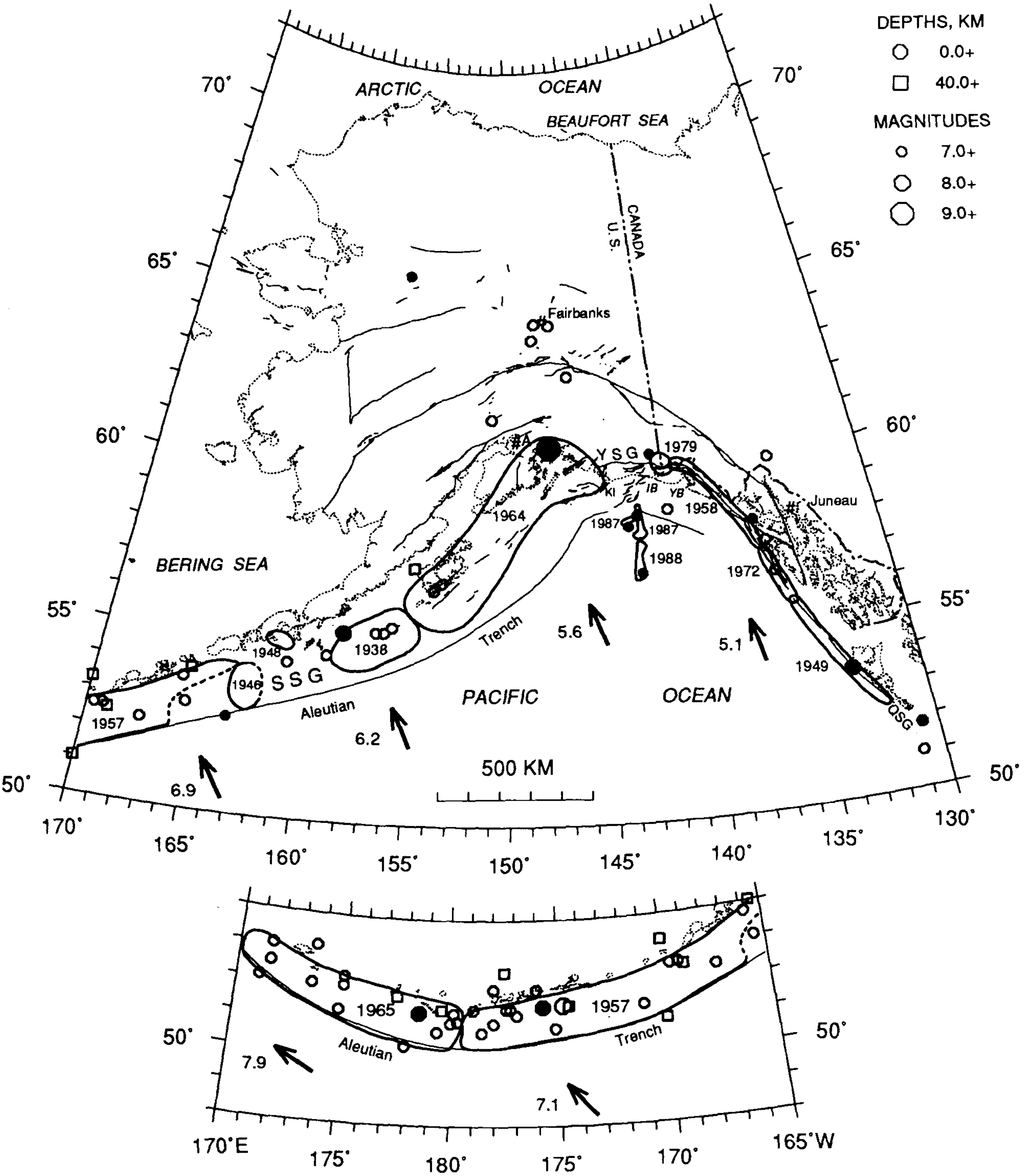

Figure 2. Epicenters of 73 magnitude 7.0 or greater earthquakes from 1900 to 1994 (modified from Plafker and others, 1994) and aftershock zones (heavy line, dashed where inferred) of the largest earthquakes to have ruptured each segment (year of event listed) of the plate boundary (modified from Davies and others, 1981; Rogers, 1986). Solid symbols are earthquakes referred to in the text. Arrows show motion of Pacific plate relative to North American plate, with velocities in centimeters per year (DeMets and others, 1990). Symbol type corresponds to depth, and size is proportional to magnitude. Faults as in figure 1. Abbreviations: A, Anchorage; IB, Icy Bay; KI, Kayak Island; YB, Yakutat Bay; QSG, Queen Charlotte Islands seismic gap; SSG, Shumagin seismic gap; YSG, Yakataga seismic gap.

seaward into the Pacific plate (Lahr and others, 1988; Page and others, 1991; Estabrook and Jacob, 1991).

The seismicity related to various tectonic elements can be divided into five distinct source zones: (1) plate-boundary earthquakes along the interface between the Pacific plate and the North American plate, (2) trench and unsubducted oceanic intraplate earthquakes within the Pacific plate beneath or seaward of the Aleutian trench and the Transition fault, (3) Wadati-Benioff zone (WBZ) earthquakes within the subducted part of the Pacific plate landward of the Aleutian trench, (4) North American plate earthquakes, exclusive of those along the Aleutian and Wrangell volcanic axes, and (5) volcanic-axis earthquakes within the North American plate along the axis of active volcanoes.

Annual reviews of the seismic activity in Alaska are necessary in order to build a sound seismological basis for evaluating the State's long-term and intermediate-term earthquake potential. The purpose of this paper is to review the 1994 seismicity located in Alaska and western Canada by the Alaska Earthquake Information Center (AEIC) and the U.S. Geological Survey's National Earthquake Information Center (NEIC). We also provide an overview of the tectonics of Alaska and western Canada, a description of the functions of the AEIC, and summaries of much of the previous work on Alaskan and western Canadian seismicity for the benefit of readers who are not familiar with these topics.

ALASKA EARTHQUAKE INFORMATION CENTER

The AEIC monitors earthquakes in Alaska, provides rapid information on felt earthquakes, and disseminates information about earthquakes and seismic hazards to government officials, the media, the public, and the earth-science community worldwide. Established in 1988, the AEIC is operated cooperatively by the U.S. Geological Survey (USGS) and the Geophysical Institute of the University of Alaska (UAGI). The main center of operations is located at the Geophysical Institute in Fairbanks.

Most of the earthquakes located by the AEIC originate in a "core" area in central and southern Alaska, between latitudes 57°N. and 67°N. and longitudes 135°W. and 156°W. (approximately 1,300,000 krn^2 or 500,000 mi^2). The AEIC reports also routinely include earthquakes provided by the NEIC for the larger region, between latitudes 48°N. and 75°N. and longitudes 130°W. to 170°E. Since 1990, the AEIC has located approximately 24,000 earthquakes in Alaska and western Canada.

Three types of reports are issued regularly by the AEIC: 1. Information Release—a one-page release is issued via fax and electronic mail within two hours of the occurrence of any shock with magnitude ≥ 4.0 or for events smaller than magnitude 4 when they are felt. This release contains the preliminary hypocenter parameters, distances to nearby cities, and felt information (104 releases were issued in 1994, of which 44 contained felt information). 2. Weekly Seismicity Report—a several-page document is mailed within seven days of the end of each week. This report include highlights of recent activity, epicenter maps, a preliminary listing of events, and felt reports and magnitudes augmented by the NEIC Quick Epicenter Determinations (QED). The first formal report in this series (no. 33-93) is for the week of August 13–19, 1993 (33rd week); however, weekly seismicity reports have been informally released since November 1989. 3. Earthquakes in Alaska—this multipage monthly report is issued about seven months following the close of a particular month. It includes epicenter maps and hypocenter cross sections, as well as locations, felt reports, and magnitudes based on additional information from the NEIC monthly Preliminary Determination of Epicenters (PDE) reports and from other seismic observatories (Fogleman and others, 1994).

The AEIC normally analyzes data from the joint USGS/UAGI seismograph network, which currently incorporates 117 stations, and from 15 stations operated by the Alaska Tsunami Warning Center (ATWC) in Palmer, Alaska. Most of the stations are located in central and southern Alaska (fig. 1). The majority of the 155 channels of data recorded at the AEIC are from short-period, vertical-component analog stations. Data are also received from 8 short-period, three-component analog stations, 5 short-period, vertical-component digital stations, and 4 broadband, three-component digital stations. Eight digital, three-component broadband stations were also operated by the UAGI along the Alaska Peninsula and in the Shumagin Islands during 1994 but were not recorded locally in Fairbanks. Waveforms and phase readings from these stations were occasionally combined with the data processed in Fairbanks. Phase readings obtained from data recorded by seismographs (instruments used to record the passing of seismic waves) located in western Canada and operated by the Geological Survey of Canada (GSC) are routinely combined with the AEIC data.

Shallow (depth < 30 km) shocks in southern coastal Alaska cannot be routinely determined by the AEIC regional network with sufficient precision to attribute individual shocks to the subducting plate, the interplate megathrust, or the overriding plate. The NEIC routinely fixes focal depths to 33 km for earthquakes whose character on seismograms (records of earthquakes produced on seismographs) indicates a shallow focus but whose depth is not satisfactorily determined by the data. Focal mechanisms and depth phases such as pP give information about the fault planes and stresses sufficient to determine the responsible source zone. The NEIC routinely interprets data from broadband displacement seismograms to obtain focal depths (for events with $m_b \geq 5.8$). The pP depth phase is a seismic wave that is reflected from the surface of the earth at a point near the epicenter and follows the initial P-wave by an interval proportional to the depth of the source.

Focal mechanisms are usually based on the first arrival times of P-waves and their corresponding directions of motion (first motions), which are traced back to a hypothetical focal sphere (a small imaginary sphere enclosing the earthquake focus). The first motion of each P-wave is alternately a compression or a dilatation. Their distribution (radiation pattern) on the sphere is used to divide the area surrounding the focus into four quadrants (such that adjacent quadrants have opposite polarities) separated by two orthogonal planes. Since the P-wave motion is null along these planes, they are called nodal planes. One of these planes corresponds to the fault plane; the other plane is perpendicular to the direction of fault movement and is called the auxiliary plane. Additional information such as geological trends, linear aspects of aftershock distributions, etc., is necessary to select which plane is the proper fault plane. The style of faulting, the direction of the fault slip, and the orientation of the P- (pressure) and T- (tension) axes can be inferred from these fault planes. The P- and T-axes are the bisectors of the dilatational and compressional quadrants of the focal mechanism, respectively, and provide the compressional and extensional strain directions for the two possible faults (Zoback and Zoback, 1991).

An alternative method to derive the source mechanism of an earthquake is based on the analysis of radiation patterns of long-period body waves (waves that travel from the earthquake source through the body of the earth), surface waves (waves that travel only in the outermost layers of the earth), and free oscillations (vibrations of the earth as a whole at different frequencies called normal modes) of the earth. By calculating the excitation of the normal modes from a particular earthquake source, an iterative inversion procedure can be used to derive the earthquake mechanism and total moment (Gilbert, 1971). The Harvard University centroid moment tensor (CMT) solutions reported in this paper use the long-period body- and mantle-wave moment-tensor inversion method of Dziewonski and others (1981). Moment-tensor solutions are generally limited to earthquakes with magnitudes exceeding 5.5 (Dziewonski and others, 1981).

Various magnitude formulas or scales are used to calculate the size of earthquakes. Each scale is defined for use with a particular type of seismograph and recording range and has its own inherent limitations; however, when used properly, each can be viewed as an extension of the previous one. The local magnitude (M_L) scale, which is an approximation of the original Richter scale (Richter, 1958), is used for earthquakes recorded at seismic stations less than 600 km from the earthquake's epicenter. M_L magnitudes are usually reported for events with magnitudes smaller than 4-6. Beyond 600 km, body-wave (m_b) and surface-wave (M_S) magnitudes are used. These magnitudes are not typically calculated below magnitude m_b 3.5 and M_S 4.0. The m_b and M_S scales are equal at magnitude 6.75; above this value, $M_S > m_b$, and below it, $M_S < m_b$ (Richter, 1958). Consequently, the m_b scale is used below magnitude 6.75 and M_S above. Kanamori (1977) showed that the M_S scale tends to saturate (underestimate the magnitude) for earthquakes beyond about magnitude 8 and thus introduced the moment magnitude (M_W) scale for such great earthquakes. Unlike the other magnitude scales which are based upon the ground-motion amplitudes of seismic waves as measured on seismographs, the M_W scale is based upon the seismic moment. The seismic moment is directly proportional to the product of the average displacement (slip) and rupture area (mainshock-aftershock zone) on the fault and the rigidity of the rock that was faulted. M_W magnitudes are often reported for shocks smaller than magnitude 8 when they have been calculated.

The term "intensity," as applied to earthquakes, represents a subjective number based on the observed effects and damages on people, human-made structures, and the Earth's surface at a particular location. Intensities assigned by the AEIC and NEIC are based on the Modified Mercalli (MM) intensity scale of 1931 (Wood and Neumann, 1931), which ranges in steps from I to XII. The subjective effects on people described in the MM intensity scale of 1931 are not reliable considerations for assigning values above the intensity IV level (Stover and Coffman, 1993). Intensities of V and above are assigned primarily on the effects on human structures and their contents; this has been the practice of the USGS for the last decade. The abridged version of the scale is given in table 1. MM intensities of IV and larger observed for 1994 earthquakes are reported in this paper. Lower intensities are reported in addition when needed to depict the extent of the felt area.

NOTABLE LARGE EARTHQUAKES DURING 1994

The overall pattern of seismicity for Alaska during 1994 is best examined using 103 events greater than or equal to magnitude 4.5, the approximate magnitude level at which the earthquake catalog is complete for the entire state (fig. 3). These shocks include 31 with magnitudes m_b 5.0 to 6.0 (table 2). The seismicity is dominated by activity along the Aleutian arc west of long 160°W., where 79 of the shocks with M_L or m_b magnitudes ≥ 4.5 and 27 shocks with m_b 5.0 to 6.0 occurred. The largest 1994 shock in Alaska, a shallow m_b 6.0 earthquake, occurred

Table 1. Modified Mercalli intensity scale of 1931 (modified from Stover and Coffman, 1993, p. 6–7)

I.	Not felt -- except rarely, under especially favorable circumstances.
II.	Felt indoors by few, especially on upper floors. Hanging objects sometime swing.
III.	Felt indoors by several; motion usually rapid vibration. Duration estimated in some cases. Hanging objects may swing slightly. Vibration is like passing of light, or lightly. loaded trucks.
IV.	Felt by many to all. Hanging pictures swing in numerous instances. Trees and bushes shake slightly. Vibration is like passing of heavy truck. Standing motor cars rock noticeably. Buildings shake moderately to strongly. Walls creak loudly. Observers describe the shaking as "strong."
V.	Hanging pictures fall. Trees and bushes shake moderately to strongly. People have difficulty standing or walking. Felt moderately by people in moving vehicles. Some dishes and glassware break. Occasional cracked windows. Many small or unstable objects overturn.
VI.	Many small objects fall from shelves and (or) many glassware items or dishes break. Damage slight in poorly built buildings. Plaster falls or cracks in small amounts. Furniture overturns in many instances. Moderately heavy furnishings move.
VII.	Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, and considerable in poorly built or badly designed buildings. adobe houses, old walls, spires. etc. Many chimneys crack, as do some walls. Plaster falls in considerable to large amounts. as does some stucco. Numerous windows and some furniture break. Cornices from towers and high buildings fall. Heavy furniture overturns, with damage from breaking. Concrete irrigation ditches have considerable damage.
VIII.	Trees shake strongly -- branches and trunks break off, especially in palm trees. Sand and mud ejects in small amounts. Flow and temperature of spring and well waters change temporarily or permanently: dry wells renew flow. Slight damage in hick structures built to withstand earthquakes and considerable in ordinary substantial buildings. Partial collapse in racked, tumbled-down wooden houses in some cases. Panel walls in frame structures are thrown out, breaking off decayed piling. Solid stone walls crack and break severely. Wet ground observed to some extent. Chimneys, columns, monuments, factory stacks, and towers twist or fall. Very heavy furniture conspicuously moves or overturns.
IX.	Damage considerable in masonry structures built to withstand earthquakes. Some wood-frame houses built to withstand earthquakes thrown out of plumb. Damage great in substantial masonry buildings with some collapse. Frame buildings wholly shift off foundations. Reservoirs have serious damage. Underground pipes sometimes break. Ground cracks are conspicuous.
X.	Damage serious to dams, dikes, and embankments and severe to well-built wooden structures and bridges, with some destroyed. Dangerous cracks occur in excellent brick walls. Most masonry and frame structures and their foundations are destroyed. Railroad rails bend slightly. Buried pipelines tear apart or crush endwise. Open cracks and broad wavy folds appear in cement pavements and asphalt roads. Ground cracks, especially where loose and wet, up to widths of several inches; fissures up to a yard in width run parallel to canal and stream banks. Sand and mud shift horizontally on beaches and flat land. Water level changes in wells. Water is thrown on banks of canals, lakes, rivers. etc.
XI.	Damage severe to wood-frame structures and great to dams, dikes, and embankments. Few, if any, masonry structures left standing. Large well-built bridges destroyed by the wrecking of supporting piers or pillars. Wooden bridges are affected less. Railroad rails bend greatly and thrust endwise. Buried pipelines completely put out of service. Ground disturbances are frequent and widespread, varying with type of material. Water ejects in large amounts charged with sand and mud. Significant sea waves (tsunami) occur.
XII.	Nearly all structures damaged greatly or destroyed. Ground disturbances great and varied, with numerous shearing cracks. Fault slips in firm rock, with notable horizontal and vertical offsets. Surface and underground water channels disturbed and modified greatly. Lakes dam and rivers deflect. Waves seen on ground surfaces. Objects thrown into the air.

on July 29 in the Fox Islands. Three aftershocks with m_b 5.0, 4.3, and 5.4 occurred in the first six hours after the mainshock. The depths of the mainshock and of the m_b 5.4 aftershock were constrained by NEIC to 11 km (using broadband displacement seismograms) and to 22 km (using *pP* phases), respectively. The Harvard CMT solutions (reported by the NEIC) for the mainshock and for the m_b 5.4 aftershock exhibit reverse faulting on a shallow plane dipping to the north-northwest and striking to the west-southwest. The CMT solutions of the mainshock and largest aftershock suggest that these shocks were thrust events on the plate-boundary interface.

The second largest shock of 1994 (m_b 5.8) struck on April 5 in the Andreanof Islands. The NEIC reported a depth of 20 km from broadband displacement seismograms. The April shock was preceded by two possible foreshocks—an m_b 5.3 shock on March 13 in the same location as the mainshock and an m_b 5.0 event on March 18 approximately 20 km southwest of the mainshock—and was followed by an m_b 4.6 shock on July 18. The Harvard CMT solution from the NEIC for the April earthquake suggests shallow-angle, reverse faulting on a west-southwest-striking, north-northwest-dipping plane, which is compatible with the occurrence of the event on the Aleutian megathrust.

Two other magnitude 5.5 or larger shocks occurred in the Aleutians in 1994: an m_b 5.5 event on May 4 in the Fox Islands slightly landward of the Aleutian trench and an m_b 5.6 event on October 10 in the Andreanof Islands. The Harvard CMT solution for the May 4 shock exhibits almost pure normal faulting on either of two moderately-dipping planes that strike northeast-southwest approximately parallel to the local strike of the Aleutian trench. Normal slip is typical in the central and eastern Aleutians for shocks located near the trench; the inferred rupture planes for these shocks trend strictly trench-parallel (Taber

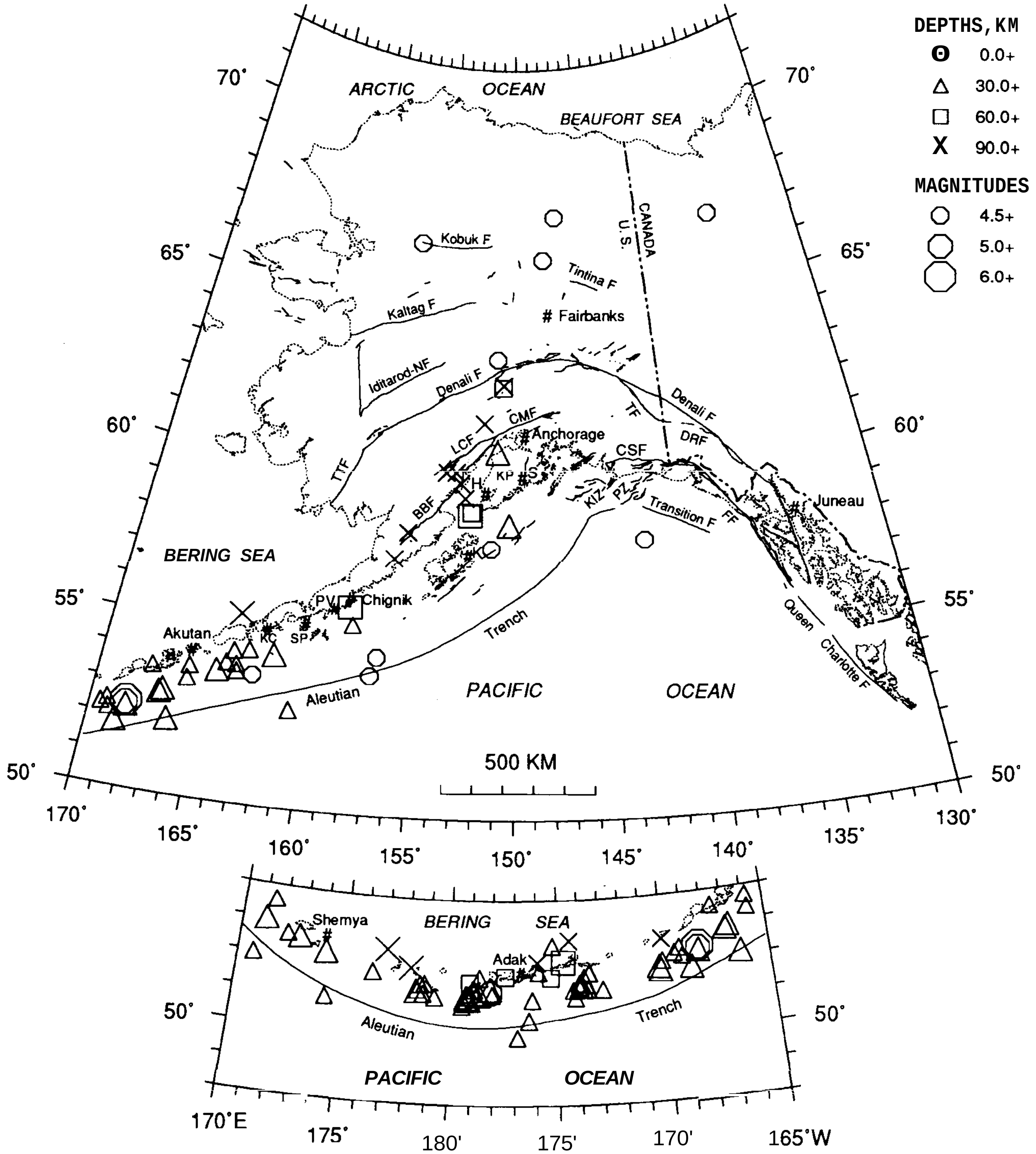

Figure 3. Epicenters of 103 earthquakes with magnitudes of 4.5 and larger in Alaska and western Canada for 1994: 47 in upper plot, 69 in lower plot (13 events common to both). Aleutian arc events west of long 160°W. are National Earthquake Information Center epicenters. Symbol type corresponds to depth, and size is proportional to magnitude. Faults and fault abbreviations as in figure 1. Abbreviations: H, Homer; K, Kodiak; KC, King Cove; KP, Kenai Peninsula; PV, Perryville; S, Seward; SP, Sand Point.

Table 2. Source parameters of magnitude 5.0 or greater earthquakes in Alaska for 1994

[Events are listed in chronological order. The following data are given for each event:
1. Date And Time in Coordinated Universal Time (UTC): month (Mo), day (Dy), hour (Hr), minute (Mn), and second (Sec). To convert to Alaska Standard Time (AST) or Alaska Daylight Time (ADT), subtract 9 or 8 hours, respectively.
2. Latitude and Longitude of epicenter in degrees (Deg) and minutes (Min).
3. Dep, depth of focus in kilometers (Km). One kilometer equals 0.62 mile. Symbols after the depth indicate the following:
   N = Depth was fixed at 33 km for earthquakes whose character on seismograms indicates a shallow focus but whose depth is not satisfactorily determined by the data;
   D = Depth was restrained by the computer program based on two or more compatible pP phases and (or) unidentified secondary arrivals used as pP;
   G = Depth was fixed by a geophysicist at other than 33 km.
4. Mag, the AEIC local magnitude M_L is the preferred magnitude, unless it is unavailable or the NEIC reports a body-wave magnitude m_b ≥ 4.5 (the magnitude level at which the earthquake catalog is complete for all of Alaska). All magnitudes reported in this table are NEIC m_b magnitudes.
5. Region, region of occurrence.
6. MM Intensity Report, felt report from the NEIC PDE reports. Intensities assigned by the NEIC are based on the Modified Mercalli (MM) intensity scale of 1931 (table 1).]

Date		Time			Latitude		Longitude		Dep	Mag	Region and MM Intensity Report
Mo	Dy	Hr	Mn	Sec	Deg	Min	Deg	Min	Km	m_b	
2	5	23	49	13.77	51	48.48N	170	08.70W	33N	5.1	Fox Islands.
2	6	05	55	08.27	51	54.84N	170	12.72W	33N	5.1	Fox Islands.
3	13	03	11	28.68	51	24.00N	178	08.94W	33N	5.3	Andreanof Islands.
3	18	00	11	54.79	51	14.70N	178	40.20W	33N	5.0	Andreanof Islands.
4	5	09	35	44.88	51	17.76N	178	09.12W	20G	5.8	Andreanof Islands.
4	16	08	37	32.98	52	27.72N	176	57.72E	139	5.1	Rat Islands.
4	20	16	8	41.40	52	54.36N	166	48.00W	33N	5.0	Fox Islands.
4	21	16	55	27.56	52	35.10N	172	47.88E	33N	5.0	Near Islands.
4	25	00	19	07.78	60	48.82N	151	01.54W	49	5.4	Kenai Peninsula. Felt V Anchorage, Cooper Landing. Fort Richardson and Kenai; IV at Big Lake, Butte, Eagle River, Hope, Niilchik, Palmer, Seward, Seward, Sheep Creek, Sterling, Tyonek, and Wasilla; 111 at Homer and Soldotna; II at Fairbanks.
5	4	11	47	20.39	51	49.26N	168	41.10W	33N	5.5	Fox Islands.
6	25	12	15	13.62	58	58.53N	152	28.11W	66	5.2	Kodiak Island region.
7	14	18	38	09.83	55	24.18N	163	48.84W	167D	5.2	Unimak Island. Felt IV at King Cove; 111 at Akutan and Sand Point.
7	29	00	17	45.41	52	23.88N	168	19.98W	11G	6.0	Fox Islands.
7	29	01	13	01.21	52	17.04N	168	.18.96W	33N	5.0	Fox Islands.
7	29	05	42	27.63	52	20.58N	168	20.52W	22D	5.4	Fox Islands.
8	5	08	14	10.30	52	13.80N	174	14.70E	33N	5.1	Near Islands. Felt IV on Shemva.
8	5	18	28	10.21	51	08.04N	179	17.64W	33N	5.2	Andreanof Islands.
8	6	01	02	52.04	51	05.10N	179	10.32W	33N	5.1	Andreanof Islands.
9	1	01	17	47.25	52	46.20N	166	59.22W	33N	5.2	Fox Islands.
9	1	16	15	17.37	52	06.18N	166	21.24W	33N	5.3	South of Aleutian Islands.
9	3	02	53	03.08	51	17.52N	178	56.04W	33N	5.1	Andreanof Islands.
9	5	02	59	41.47	55	59.22N	158	26.16W	62D	5.3	Alaska Peninsula. Felt V at Chignik. IV at Chignik Lagoon and Perryville; 111 at Sand Point.
9	11	14	52	52.43	51	56.34N	178	09.30E	99D	5.1	Rat Islands.
9	15	19	48	23.40	54	21.42N	161	51.56W	50D	5.2	Alaska Peninsula. Felt V at King Cove; IV at Cold Bay and Sand Point.
9	19	19	35	26.00	52	10.38N	174	44.46W	64D	5.1	Andreanof Islands. Felt IV on Adak.
9	28	05	37	35.00	51	18.17N	178	23.28E	33N	5.1	Rat Islands.
10	10	21	06	53.70	51	28.32N	173	53.16W	33N	5.6	Andreanof Islands.
10	12	10	33	21.37	51	39.06N	173	54.24W	33N	5.1	Andreanof Islands.
12	8	03	29	11.90	52	59.40N	171	05.76E	33N	5.0	Near Islands.
12	15	04	42	12.26	58	41.30N	150	16.81W	39	5.0	Gulf of Alaska. Felt IV at Birchwood. Homer and Seward; 111 at Anchorage, Cooper Landing, Kasilof. Kodiak and Nininchik.
12	26	03	08	17.78	53	41.28N	164	28.80W	33N	5.3	Unimak Island Region.

and others, 1991; Estabrook and Jacob, 1991). The m_b 5.6 October event had five aftershocks (m_b 4.3, 4.9, 4.5, 4.7, and 5.1) within 48 hours; all six of these shocks had depths fixed at 33 km. The CMT solution exhibits low-angle, reverse slip on a west-northwest-striking, north-northeast-dipping plane, which suggests that the shock occurred on the Aleutian megathrust.

The largest shock in 1994 beneath continental Alaska (m_b 5.4) occurred on April 25. Its location, approximately 77 km southwest of Anchorage at a depth of 49 km, places it within the subducting Pacific plate. The moderately well-constrained focal mechanism has a tension axis (T-axis) aligned west-northwest in the dip direction of the subducted plate similar to that found for. events in the

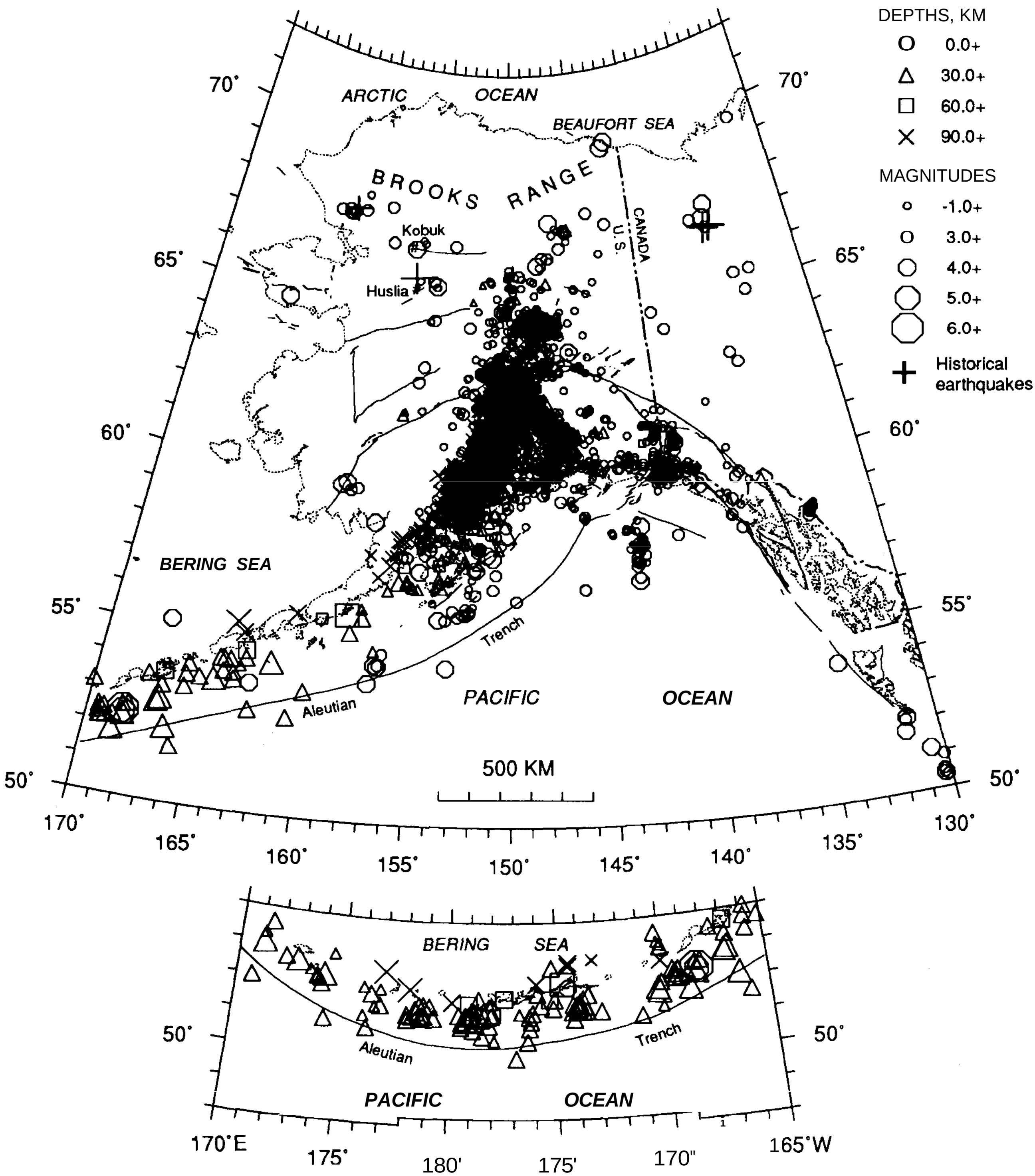

Figure 4. Epicenters of 4,626 earthquakes in Alaska and western Canada for 1994: 4,523 in upper plot, 129 in lower plot (26 events common to both). Events along the Alaska Peninsula and Aleutian arc west of long 160°W. are provided by the National Earthquake Information Center. The magnitude level for which the earthquake catalog is complete varies across the state owing to uneven station spacing. Earthquake data are more complete and hypocenters are more accurate in regions where station density is greatest (fig. 1). Symbol type corresponds to depth, and size is proportional to magnitude. Epicenters of 4 historical earthquakes in northwest Canada and western Alaska referred to in the text are indicated by plus symbol, "+." Faults as in figure 1.

Aleutian WBZ beneath southern Alaska (Lahr and others, 1993, 1994). The earthquake triggered an unusually vigorous aftershock sequence for a WBZ shock in the Cook Inlet region; 22 events of magnitude M_L 1.5 to 2.3 occurred within 24 hours. Typically few, if any, aftershocks are detected for such events. In an article published in the Anchorage Daily News, the AEIC requested information from people who felt the earthquake. In response, 397 earthquake questionnaires were returned. They were supplemented with 19 questionnaires that had been sent by the NEIC to post offices, fire stations, and police stations in and near the felt region. While only 8 percent of the questionnaires have been assigned an intensity value to date, preliminary results show that the event was felt over an area of approximately 120,000 km^2 (46,000 mi^2) in southern and central Alaska. It caused MM intensity V effects in Kenai, Cooper Landing, Anchorage, and Fort Richardson (32 km southwest, 75 km southeast, 77 km northeast, and 88 km northeast, respectively, of the epicenter), intensity IV effects as far as Seward to the south (118 km away) and Palmer to the northeast (135 km away), and intensity II effects as far as 500 km away in Fairbanks.

Two other magnitude 5 or greater shocks occurred in southern Alaska during 1994. On June 25, an m_b 5.2 event occurred beneath southern Cook Inlet at a depth of 66 km. It was followed by two shocks on July 2 and 9 with M_L 2.4 and 3.2, respectively. The poorly controlled focal mechanism suggests strike-slip faulting with a small dip-slip component. The subhorizontal T-axis is aligned northwest-southeast in the dip direction of the subducted plate, and the P-axis is aligned with the strike of the subducted, plate. These orientations of the T- and P-axes are similar to those found by numerous authors for Aleutian WBZ shocks beneath Cook Inlet (Lahr, 1975; Engle, 1982; Pulpan and Frohlich, 1985, Lahr and others, 1993, 1994).

The second notable event is an m_b 5.0 earthquake that occurred on December 15, in the Gulf of Alaska south of the Kenai Peninsula at a poorly constrained depth of 39 km. The earthquake was felt with MM intensity IV effects at Homer and Seward (128 km northwest and 165 km northeast, respectively, of the epicenter) and intensity III effects as far away as Kodiak and Anchorage (160 km southwest and 283 km north, respectively, of the epicenter). The December 15 shock is the largest event to occur within a 100-km radius from its epicenter since an m_b 5.5 event in 1973. The 1973 shock occurred at a depth of 12 km and was about 50 km southeast of the 1994 shock. The poorly controlled focal mechanism of the December 15 event suggests normal, oblique faulting with an east-west-oriented subhorizontal T-axis and a P-axis with an intermediate dip to the north-northwest. The orientations of the T- and P-axes are consistent with the axes orientations found by Lahr and others (1994) for earthquakes at approximately 50-km depth in the Aleutian WBZ (southern Alaska segment).

OTHER FEATURES OF THE 1994 SEISMICITY

For 1994, the AEIC analyzed more than 7,000 recorded events (many of which were noise, calibration signals, glacierquakes, quarry or mine blasts, teleseisms, etc.) and located 4,427 earthquakes. The NEIC reported an additional 185 regional shocks located primarily along the Aleutian Islands, and the Pacific Geoscience Center (PGC) of the Geological Survey of Canada provided locations for 14 events in southeastern Alaska. The magnitude level for event location varies across the state due to uneven station spacing and hypocenter depth. Within the area where the regional network is densest (roughly a triangle bounded by: latitude (lat) 59.5°N., longitude (long) 139.0°W.; lat 59.0°N., long 155°W.; and lat 66.0°N., long 148.0°W.), the 1994 catalog is reasonably complete for shallow (depth < 30 km) earthquakes of about magnitude M_L 2.0 and larger. The magnitude threshold at which the catalog is complete increases with increasing depth for the events in the WBZs. For earthquakes deeper than 100 km in the southern Alaska segment of the Aleutian WBZ, the catalog is complete above about magnitude M_L 2.7. Focal depths for shallow shocks generally are not well constrained owing to the relatively large distances between stations and the misfit of the regional velocity models to the actual velocities within the crust.

PLATE-BOUNDARY EARTHQUAKES

Historically, most of the seismic energy in Alaska and western Canada is released in earthquakes of magnitude 7 and greater that occur on the primary plate interface as right-lateral, strike-slip events in western Canada, southeast Alaska, and the western Aleutians, and as thrust-type earthquakes from the Gulf of Alaska toward the central Aleutians (Taber and others, 1991; Page and others, 1991; Rogers and Horner, 1991). The dip of the plate boundary along the Aleutian trench varies from a minimum of 4-5° in the Gulf of Alaska to a maximum of 25-30° in the central Aleutians (Taber and others, 1991). Beneath a certain depth, estimated to be about 40 km in the Aleutian arc (Davies and House, 1979) and about 20 km in the northern Prince William Sound region (Page and others, 1989, 1992), the interface is believed to slip aseismically.

Nearly the entire 5,300-km-long plate boundary in Alaska and western Canada north of lat 50°N. has experienced a series of shocks in this century ranging in size from M_S 7.0 to M_W 9.2 (fig. 2; Page and others, 1991; Taber and others, 1991; Rogers and Horner, 1991). The rupture zones of these large events, defined by the extent of their aftershock zones, tend to abut rather than overlap, except for several small regions that have been identified as "seismic gaps." Seismic gaps are areas of seismically active plate margins that have not recently ruptured, but where future large earthquakes are expected (for example, Mogi, 1968; Sykes, 1971; Kelleher and Savino, 1975; McCann and others, 1980). Three seismic gaps have been identified in Alaska and western Canada: the Shumagin; the Queen Charlotte Islands, and the Yakataga seismic gaps (fig. 2).

The Shumagin seismic gap in the Shumagin Islands region south of the Alaska Peninsula extends about 225 km from the east end of the aftershock zone of the 1946 M_S 7.4 earthquake (near long 161.5°W.) and the western end of the 1938 M_W 8.2 earthquake (near long 158.4°W.; Taber and others, 1991). The largest shock to occur in the Shumagin seismic gap in 1994 was an m_b 5.2 shock at a depth of 50 km on September 15 (fig. 4). The Harvard CMT solution suggests strike-slip faulting on near-vertical planes striking northwest-southeast and northeast-southwest. The location, depth, and CMT solution of this event places it within the subducting Pacific plate and not on the Aleutian megathrust.

The Queen Charlotte Islands seismic gap in western Canada extends from the south end of the aftershock zone of the 1949 M_W 8.1 Queen Charlotte Islands earthquake (near lat 52.4°N.; fig. 2) to the epicenter of the mainshock of the 1970 M_S 7.1 Cape St. James earthquake (near lat 51.8°N.; Rogers, 1986). An earthquake of magnitude 7.5 or greater would be required to completely fill this 75-km-long seismic gap and can be expected to have a combined strike-slip and thrusting mechanism with a minor thrust component similar to the 1970 Cape St. James earthquake immediately to the south (Rogers, 1986). The largest shocks to occur within this seismic gap since 1954 are in the magnitude 4 class (Rogers, 1986). The most notable seismicity in 1994 near the Queen Charlotte-Fairweather fault system (fig. 4) occurred within and around the Queen Charlotte Islands seismic gap (10 shocks with magnitudes from M_L 3.2 to m_b 4.2). Three events with m_b magnitudes of 3.5, 4.0, and 4.1 occurred within the southern half of the seismic gap (near lat 52°N., long 131.5°W.). The largest shock in the tight cluster of earthquakes near lat 50.3°N. and long 130.3°W. was an m_b 4.2 event on July 15. This event was preceded by two events on July 10 and 11 (M_L 3.2 and m_b 3.5, respectively) and was followed by an m_b 3.8 shock on November 2. An isolated m_b 4.2 event occurred on July 7 off the northwest end of Graham Island (lat 53.9°N., long 133.9°W.). All of the earthquakes along the Queen Charlotte fault in 1994 had focal depths fixed at either 10 or 18 km.

The Yakataga seismic gap, which extends for about 175 km along the coast of southern Alaska from the western limit of the 1979 M_W 7.3 St. Elias earthquake aftershock zone (Stephens and others, 1980; Estabrook and others, 1992) near Icy Bay to the eastern extent of the 1964 rupture near Kayak Island (fig. 2), experienced two M_W 8.1 shocks in 1899 that ruptured the transitional segment between Kayak Island and the western extent of the 1958 M_W 7.7 Fairweather Fault earthquake near Yakutat Bay (McCann and others, 1980; Page and others, 1991). This seismic gap is considered a likely site for an M_S 7.8 or greater thrust earthquake within the next few decades (McCann and others, 1980; Lahr and others, 1980; Jacob, 1984).

Seismicity of the Yakataga seismic gap region has been monitored nearly continuously since 1974 (Fogleman and others, 1993). During this period (1974–1994), the spatial distribution of seismicity, in a belt extending 90 km inland from the coast, has remained relatively stable. It is characterized by broad concentrations of shallow seismicity (fig. 5) beneath Icy Bay, Waxell Ridge, and the Copper River Delta separated by areas of relative quiescence. The most active area has been the aftershock zone of the St. Elias earthquake, both prior to and since 1979, which involved low-angle, north-northwest-directed thrusting (Estabrook and others, 1992) at depths between 10–15 km (Stephens and others, 1980) in a zone that is, at least locally, no more than 2-3 km thick (Page and others, 1984). Stephens and others (1992) found that hypocenters of better-recorded shocks in the diffuse patch of seismicity near Waxell Ridge, at the center of the Yakataga seismic gap, are concentrated near a depth of 12 km, comparable to the depth of the Aleutian megathrust as defined by the seismicity beneath the St. Elias area. The largest earthquakes located within the gap since 1971 are in the magnitude 4 class. Two shallow magnitude 3 shocks were located within the gap in 1994: an M_L 3.4 shock that occurred on January 3, with an epicenter about 25 km east of the Waxell Ridge concentration of seismicity (lat 60.4°N., long 142.3°W.), and an M_L 3.2 event that occurred on July 3 southwest of Waxell Ridge (lat 60.4°N., long 143.6°W.). The shallow foci computed for these two events (5 and 0 km, respectively) are poorly constrained; consequently, it is uncertain whether these events originated in the overriding plate or on the megathrust.

TRENCH AND UNSUBDUCTED OCEANIC INTRAPLATE EARTHQUAKES

The apparent rate of historical (Taber and others, 1991; Page and others, 1991) and current seismicity for earthquakes within the Pacific plate beneath or seaward of the Aleutian trench and the Transition fault is low compared with other parts of the subduction zone (figs. 3, 4). The most active area encompasses the aftershock zones (fig. 2) of the 1987 (M_W 7.2 and M_W 7.8) and 1988 (M_W 7.7) Gulf of Alaska earthquakes (Lahr and others, 1988; Hwang and Kanamori, 1992). These major intraplate, strike-slip oceanic events occurred in the northern Gulf of Alaska along conjugate trends in a region where seismicity had not been previously located. The two largest events ruptured a composite, 250-km-long, north-striking fault in the Pacific plate south of the Yakataga seismic gap and are among the largest oceanic intraplate earthquakes ever recorded (Page and others, 1991). Large oceanic intraplate shocks are rare and usually involve normal or thrust faulting away from the trench within the unsubducted portion of the plate (Lahr and others, 1988). Lahr and others (1988) suggested that these events reflect shear stress in the Pacific plate seaward of the boundary between the locked Yakataga seismic gap and the Aleutian megathrust segment that slipped in the great 1964 earthquake. The latitudes and magnitudes of the largest shocks located in 1994 in the aftershock zones of the 1987–1988 shocks are 58.7°, 58.1°, 57.1°N., and M_L 4.0, 4.5, 4.0, respectively (figs. 4, 5). The focal depths of trench and unsubducted oceanic intraplate earthquakes located by AEIC are routinely fixed at 10 km below sea level owing to poor hypocentral control.

In contrast to the Gulf of Alaska shocks, which extend as far as several hundred kilometers south of the Aleutian trench, most of the events detected along the rest of the Aleutian arc during 1994 (fig. 4) extend only 50 to 60 km oceanward of the trench. This pattern is consistent with the results of an ocean-bottom seismometer (OBS) study in the central Aleutians (Frohlich and others, 1982), where events were shallower than 20 km and extended up to 10 km landward and 60 km oceanward of the trench axis. Focal mechanisms of historical and 1994 events oceanward of the trench in the Aleutian Is-

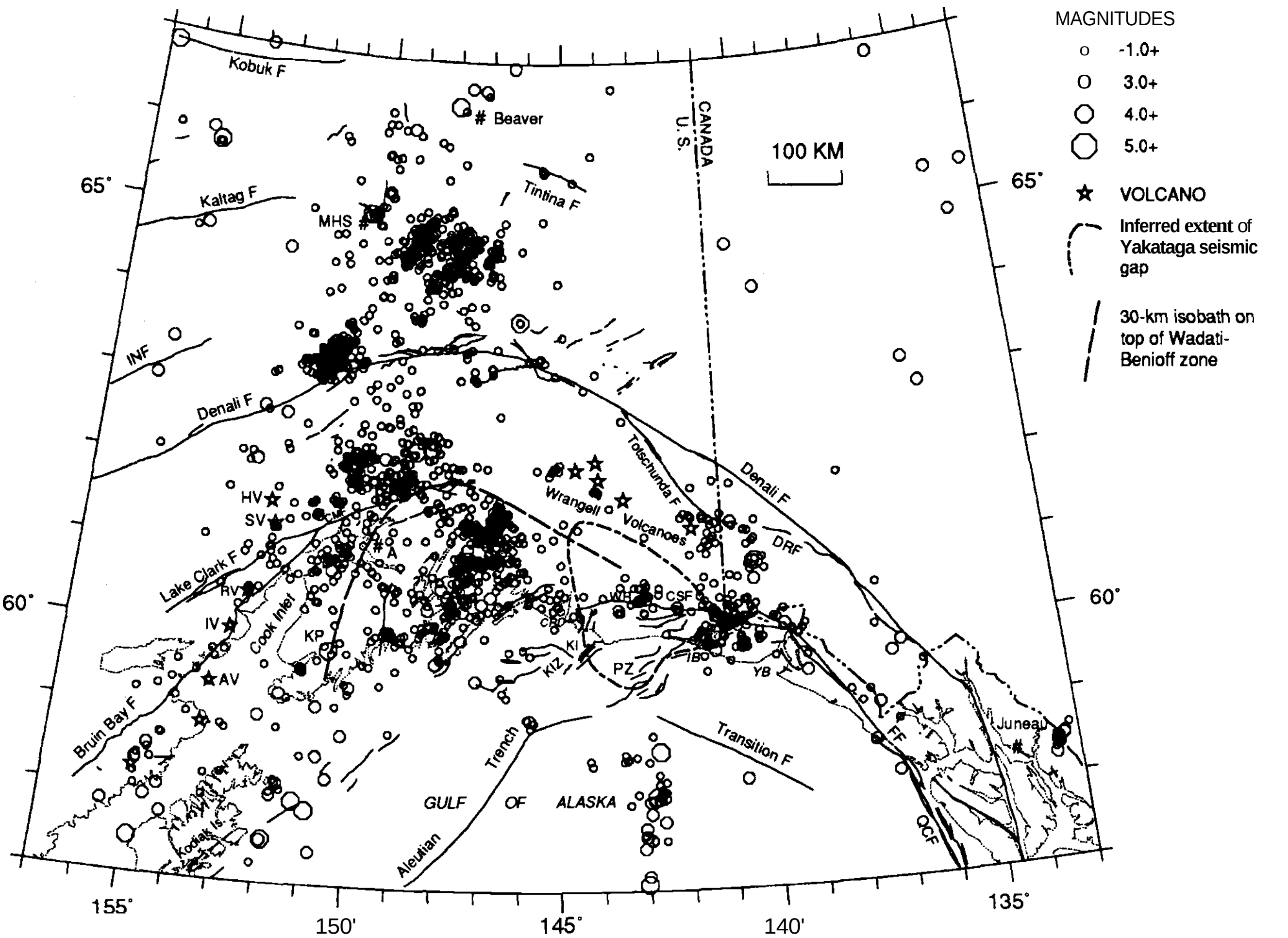

Figure 5. Epicenters of 1,959 earthquakes with depths shallower than 30 km in southern and central Alaska and western Canada for 1994. Earthquake data are more complete in regions where station density is greatest (fig. 1). Quaternary volcanoes (stars): AV, Augustine volcano; HV, Hayes volcano; IV, Iliamna volcano; RV, Redoubt volcano; SV, Spurr volcano. Also: CMF, Castle Mountain. fault; CSF, Chugach–St. Elias fault; DRF, Duke River fault; FF, Fairweather fault; INF, Iditarod–Nixon Fork fault; KIZ, Kayak Island zone; PZ, Pamplona zone; QCF, Queen Charlotte fault; A, Anchorage; CRD, Copper River Delta; IB, Icy Bay; KI, Kayak Island; KP, Kenai Peninsula; MHS, Manley Hot Springs; WR, Waxell Ridge; YB, Yakutat Bay.

lands are consistent with normal faulting, and the tension axis is approximately perpendicular to the trench (Taber and others, 1991). The trench-parallel normal faulting may reflect either spatial-temporal variations of bending stresses related to the earthquake cycle of great earthquakes at each plate boundary or may be a stationary feature related to permanent differences along the arc in the degree of coupling at the plate interface (Taber and others, 1991; Estabrook and Jacob, 1991).

The largest shock beneath or seaward of the Aleutian trench during 1994, an m_b 5.3 shock on September 1 (fig. 4), occurred beneath the trench (lat 52.1°N., long 166.3°W.) and was preceded by an m_b 4.4 event on July 7 (approximately 70 km southeast of the September shock). A notable, diffuse cluster of earthquakes occurred in 1994 centered near lat 54.5°N. and long 156.8°W. The largest shock in this cluster, an m_b 4.9 earthquake on October 24, occurred slightly landward of the trench. This event was followed within 8 minutes by an M_L 3.9 aftershock (approximately 20 km north-northeast of the mainshock) and was preceded by an M_L 3.2 foreshock on October 22 (about 5 km west of the mainshock). The October earthquakes were preceded by two nearby earthquakes: an M_L 4.1 shock on January 13 and an m_b 4.7 shock on September 5 (approximately 5 km east and 60 km southwest, respectively, of the m_b 4.9 October 24 event).

WADATI-BENIOFF ZONE EARTHQUAKES

Wadati-Benioff seismic zones are associated with both the northwest- to north-dipping Aleutian volcanic arc and the north-northeast-dipping Wrangell volcanic arc (fig. 6). Although the Aleutian volcanic arc terminates at Hayes volcano (lat 61.6°N., long 152.4°W.; fig. 6), the associated WBZ continues about 350 km farther north to lat 64.25°N. (fig. 6). Along the Aleutian WBZ west of long 156°W. (fig. 4), relatively few events can clearly be identified as WBZ activity owing to poor depth resolution (the majority of the events are held to 33-km depth by the NEIC.) The largest shocks in 1994 west of long 156°W. with depths greater than 33 km were six magnitude 5 events (fig. 3; table 2): (1) an m_b 5.1 shock on April 16 at 139-km depth in the Rat Islands (lat 52.5°N., long 177.0°E.); (2) an m_b 5.2 event on July 14 at 167-km depth north of Unimak Island (lat 55.4°N, long 163.8°W.), which was felt at King Cove (110 km southeast of the epicenter) with MM intensity IV effects; (3) an m_b 5.3 earthquake on September 5 at 62-km depth beneath the Alaska Peninsula (56.0°N., 158.5°W.), which caused MM intensity V effects at Chignik and intensity IV effects at Chignik Lagoon and Perryville (34 km north, 41 km north, and 45 km west, respectively, of the epicenter); (4) an m_b 5.1 earthquake on September 11 at 99-km depth in the Rat Islands (lat 51.9°N., long 178.2°E.); (5) an m_b 5.2 shock on September 15 at 50-km depth south of the Alaska Peninsula (lat 54.3°N., long 161.9°W.), which was felt with MM intensity V effects at King Cove and MM intensity IV effects at Cold Bay and Sand Point (83 km north-northwest, 108 km northwest, and 140 km northeast, respectively, of the epicenter); and (6) an m_b 5.1 event on September 19 at 64-km depth beneath the Andreanof Islands (lat 52.2°N., long 174.7°W.), which caused MM intensity IV effects at Adak (139 km west-southwest of the epicenter). The largest WBZ shocks east of long 156°W. in 1994, the m_b 5.4 shock on April 25, the m_b 5.2 event on June 25, and the m_b 5.0 December 15 earthquake, were previously discussed in the section on notable large earthquakes.

West and north of the Cook Inlet region, the distribution of earthquakes in 1994 below 30-km depth is dominated by activity within the Aleutian WBZ (fig. 6). This zone dips 8-10' west-northwestward beneath the Kenai Peninsula and Anchorage and steepens to a 50" dip west of Cook Inlet (fig. 7, sections C–C', D–D', E–E'). The apparent steepening of the dip to nearly 90° at the deep end of the sections is an artifact of locating events using a flat-layered velocity model (McLaren and Frohlich, 1985). The Aleutian WBZ west of Cook Inlet dips at an angle between 30° (Davies and House, 1979) in the Shumagin Islands and 60° (Engdahl and Gubbins, 1987) in the Adak region. Beneath both the southern Kenai Peninsula and Anchorage, the upper surface of the Aleutian WBZ is at a depth of 29 to 35 km, whereas beneath the volcanic arc west of Cook Inlet, it is at a depth of about 100 km. The average dip of the shallow (depth $<$ 30 km) part of the zone is about 7° beneath Prince William Sound (Page and others, 1991). On a regional scale using only events with well-constrained focal depths, the thickness of the Aleutian WBZ ranges from 10 to 15 km beneath Prince William Sound (Page and others, 1994) and from 15 to 35 km beneath the western Kenai Peninsula, Cook Inlet, and the volcanoes west of Cook Inlet (fig. 7, sections C–C', D–D', E–E'). The maximum focal depth for 1994 earthquakes in southern Alaska varies along the length of the WBZ from 219 km near Iliamna volcano (fig. 7, section E–E') to 150 km beneath Hayes volcano (fig. 7, section D–D') and 151 km beneath the Alaska Range (fig. 7, section C–C'). The deepest shocks in the Aleutian WBZ west of long 160°W. for 1994 were at depths of 210 and 200 km beneath the Bering Sea (lat 52.75°N., long 174.4°W.) on June 24 (m_b 4.1) and December 27 (m_b 4.7), respectively. The maximum focal depth of earthquakes in the Aleutian Islands from previous years varies from 250 to 300 km (Taber and others, 1991).

The geometry of the Aleutian **WBZ** changes along strike, as documented by studies of teleseismically and regionally recorded earthquakes (Van Wormer and others, **1974; Lahr, 1975;** Davies, **1975;** Agnew, **1980; Pulpan** and Frohlich, **1985).** At approximately lat **59°N.** in lower Cook Inlet, the strike of the **WBZ** abruptly changes direction from about **40°** east of north to **25"** east of north, coincident with a similar northward bend in the strike of the associated chain of volcanoes (fig. **6).** About **400** km farther north along strike (near lat **62.5°N.**), the strike changes trend from about **25°** east of north to **60°** east of north. The Aleutian **WBZ** seismicity east of the Cook Inlet region ends abruptly along a northwest-trending line that approximately parallels the direction of plate convergence.

The rate and character of the **1994** seismicity in the shallow and deep (depth **<** **45** km) parts of the Aleutian **WBZ** are significantly different, with a higher level of activity in the deep part of the zone beneath the western Kenai Peninsula, Cook Inlet, and the volcanic arc. The distribution of seismicity exhibits a significant component of spatial and temporal clustering. Clustering is more common in the shallow **WBZ,** where significant aftershock sequences occur as exemplified by those following the two m_b **6.2 1983** Columbia Bay earthquakes (fig. **6,** near lat **61.0°N.,** long **147.2°W.**). These earthquakes involved **normal** faulting on a steeply **northwestward-dipping** plane between depths of **22** to **35 km** (Page and other, **1985, 1989).** In contrast, few, if any, aftershocks are typically detected following shocks in the deep part of the **WBZ.** The north-northeast-trending swath of seismicity centered at lat **61.5°N.**, long **146.5°W.** beneath the Tazlina Glacier (figs. **5, 6),** is a persistent but diffuse concentration of events not associated with an aftershock

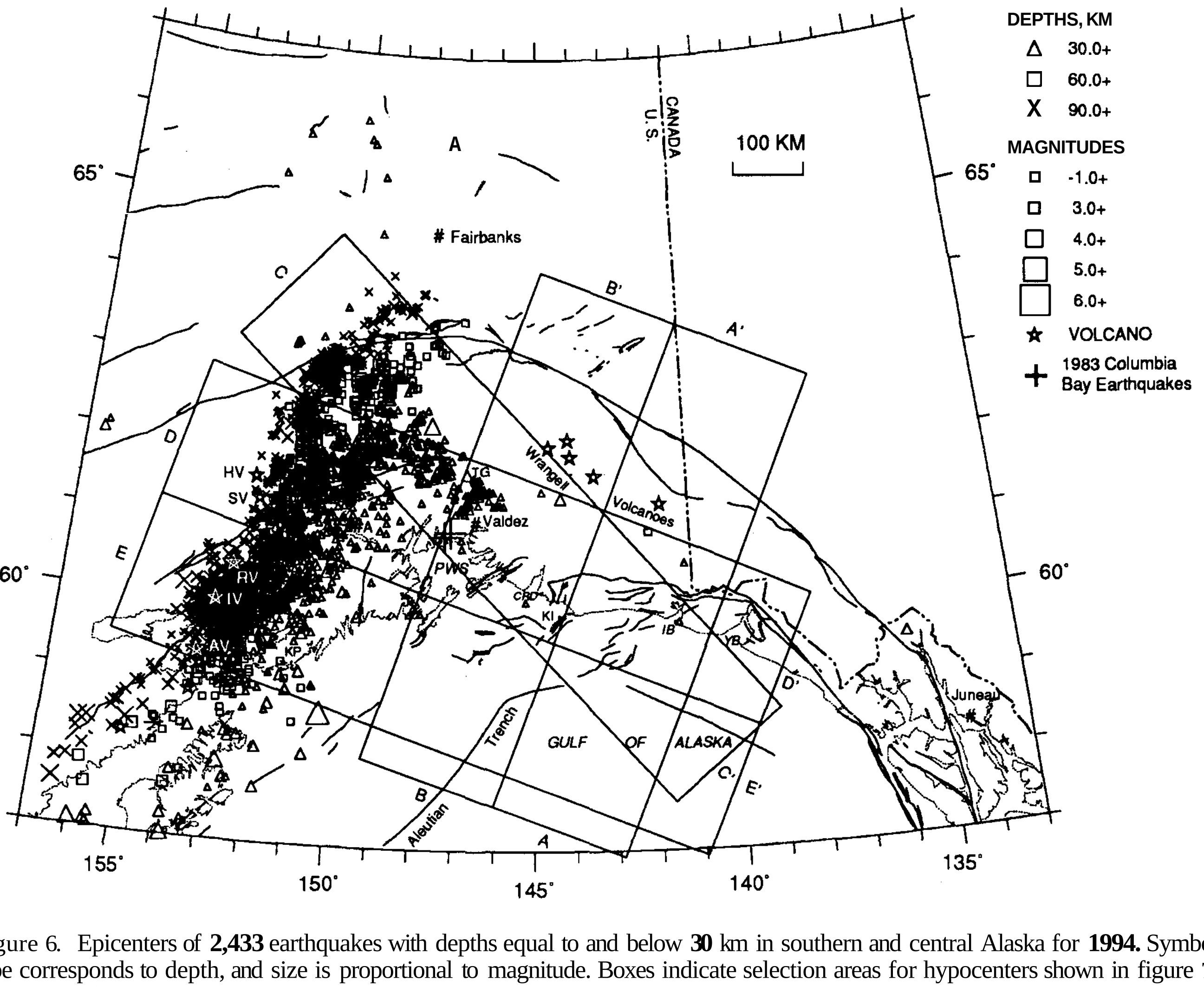

Figure 6. Epicenters of **2,433** earthquakes with depths equal to and below **30** km in southern and central Alaska for **1994.** Symbol type corresponds to depth, and size is proportional to magnitude. Boxes indicate selection areas for hypocenters shown in figure 7. Faults as in figure 5. Abbreviations: AV, Augustine volcano; HV, Hayes volcano; IV, Iliamna volcano; RV, Redoubt volcano; SV, Spurr volcano; CRD, Copper River Delta; IB, Icy Bay; KI, Kayak Island; KP, Kenai Peninsula; PWS, Prince William Sound; TG, Tazlina Glacier; YB, Yakutat Bay.

sequence. Relocated events in the Tazlina Glacier cluster have depths between 25 and 45 km (Page and others, 1989). Spatial clustering in the WBZ west of Prince William Sound is conspicuous (fig. 6) with concentrations of events deeper than 30 km about 60 km north-northwest of Anchorage (lat 61.7°N., long 149.6°W.) and events deeper than 110 km beneath Iliamna volcano (lat 60°N., long 153°W.) and Mt. McKinley (lat 63°N., long 150.3°W.). Some regions are relatively quiet, such as in the vicinity of the two points lat 60.8°N., long 152.5°W. and lat 62.5°N., long 150.2°W.

An unusually deep (219 km), moderate size (m_b 4.6) earthquake occurred in 1994 on December 10 in the Aleutian WBZ east of long 156°W., about 250 km southwest of Anchorage. Only three other shocks with well-constrained depths greater than 200 km have been located in the WBZ in southern Alaska since 1971, when the USGS seismic network began operation (Fogleman and others, 1993). A moderately well-constrained focal mechanism for the recent event indicates that its T-axis is oriented about 15" counterclockwise of the dip direction of the WBZ beneath Cook Inlet and that its P-axis trends north-south. These axis orientations are consistent with what Lahr and others (1994) found for WBZ shocks in southern Alaska below about 75-km depth.

Relatively few events occurred in 1994 in the weakly active Wrangell WBZ (fig. 6; fig. 7, sections A–A', B–B'), which dips to the north-northeast beneath the Wrangell volcanoes (Stephens and others, 1984; Page and others, 1989; Fogleman and others, 1993). The difference in the rates of seismicity between the Wrangell and Aleutian WBZ zones may be due to thermal or age differences in the descending plate (Stephens and others, 1984), or to the relatively small component of plate convergence (about 3.7 cm/yr) in the downdip direction of the Wrangell WBZ (Estabrook and others, 1992). Page and others (1989) found that the seismicity in the Aleutian and Wrangell zones appears to be continuous, at least in the depth range 20–45 km, and may define adjacent limbs of a buckle in the subducted Pacific plate. The largest shock located in the Wrangell WBZ during 1994 is an M_L 3.1 event on August 24 at 42-km depth (lat 61.5°N., long 144.3°W.). The moderately well-constrained focal mechanism exhibits predominantly strike-slip faulting with an east-west-trending, subhorizontal T-axis and a north-south-trending P-axis oriented downdip. Although few well-constrained solutions are available for the Wrangell seismic zone, the axis orientations of the August shock are compatible to those found by Page and others (1989) for the largest (m_b 4.6) Wrangell shock (52-km depth) yet recorded by the regional network. The stress field within the Wrangell WBZ is unknown because of the low level of seismicity (Page and others, 1989).

The stress orientation within the Aleutian WBZ east of long 156°W., inferred from focal-mechanism solutions of earthquakes since 1970, generally is characterized by in-plane, downdip tension (Page and others, 1991; Lahr and others, 1994). This stress orientation is consistent with the idea that the Pacific plate acts as a stress guide that propagates the body forces upward from the deeper parts of the subducted slab (Lahr and others, 1994). The stress orientation of the Aleutian WBZ west of long 156°W., inferred from historical focal mechanisms, varies in both time and space along the arc (Taber and others, 1991) and cannot be simply characterized.

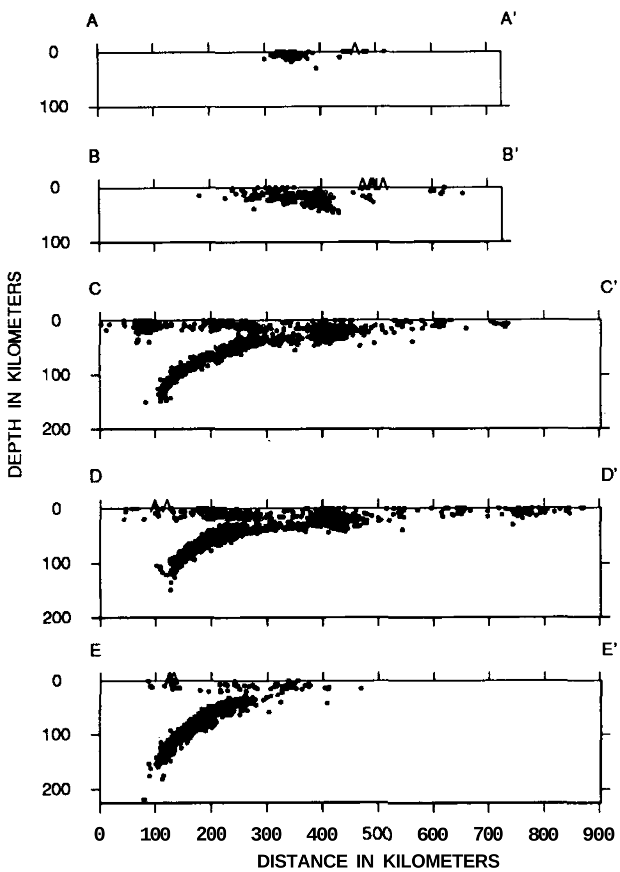

Figure 7. Vertical cross sections of better-constrained hypocenters (horizontal errors ≤ 5 km, vertical errors ≤ 10 km) in southern and central Alaska for 1994. Section locations indicated in figure 6. Quaternary volcanoes plotted as triangles above zero depth. No vertical exaggeration.

NORTH AMERICAN PLATE EARTHQUAKES

Crustal earthquakes within the North American plate occur over most of the state (figs. 3–5). Seismicity is highest in southern and central Alaska and decreases northward away from the plate boundary. Historically, the only region of Alaska that appears to be aseismic is the North

Slope (Page and others, 1991), the part of Alaska north of the Brooks Range. The fault-plane solutions from the historical data in southern, central, and northern Alaska typically indicate strike-slip and reverse-slip motion with northwest- to north-oriented compressional axes, whereas solutions from west-central Alaska generally indicate normal-slip motion with northerly oriented tensional axes (Page and others, 1991; Estabrook and Jacob, 1991). Both the distribution of historical seismicity and the available focal mechanisms are consistent with the theory that the seismicity within the North American plate, excluding west-central Alaska, results from stresses arising from the collision of the Pacific and North American plates along the northern Gulf of Alaska (Lahr and Plafker, 1980; Davies, 1983; Estabrook and others, 1988; Page and others, 1991; Estabrook and Jacob, 1991). Page and others (1995) offer a seismotectonic model for east-central Alaska that attributes the seismicity east of about long 150°W. to the clockwise rotation of elongate, northeast-oriented blocks caused by right-lateral shear between the bounding right-lateral strike-slip Denali and Tintina fault systems in response to convergence between the Pacific and North American plates. The rotation is manifest by left-lateral faults striking northeast to north-northeast at a high angle to the bounding right-lateral fault systems.

The distribution of 1994 crustal seismicity is diffuse and the majority of the events cannot be clearly associated with mapped fault traces (figs. 3–5). The diffuse character of the seismicity outside of the densest part of the regional network may be partially attributed to the degraded detection capability of the network. Shallow (depth < 30 km) shocks located seaward of the 30-km isobath on the Aleutian-Wrangell WBZ in southern Alaska in 1994 (fig. 5) are discussed in the sections on plate-boundary and WBZ shocks. Shallow shocks located landward of the 30-km isobath and landward of the Queen Charlotte–Fairweather fault system in 1994 are in the North American plate. Several conspicuous concentrations are seen in southern and central Alaska in the 1994 data (fig. 5): (1) a diffuse group of shocks along and south of the Duke River fault on the U.S.-Canada border, (2) a diffuse north-northeast-trending band of seismicity near long 150°W. beneath the upper Cook Inlet, (3) a east-west-trending zone of shocks north of the Castle Mountain fault, (4) a northeast-trending cluster of epicenters about 80 km long north of the Denali fault near long 151°W., and (5) a broadly distributed pattern of activity in the Fairbanks area with a general northeast-southwest grain and several distinct zones.

To some degree, the apparent scatter of the seismicity in eastern Alaska and western Canada near the Duke River fault reflects errors in the locations of the epicenters. Recent shocks located from both regional (Horner, 1983) and local (Power, 1988) recordings reveal that the seismicity is mostly concentrated in the vicinity of the Duke River fault. An unusual crustal shock of magnitude M_L 4.3 occurred on February 2 south of the Duke River fault (lat 61°N., long 140.2°W.) in an area devoid of mapped Neogene and younger faults. This event had a poorly constrained depth (nominally at 0 km) and was followed within 6 hours by three aftershocks with magnitudes M_L 2.4, 3.1, and 2.0.

The north-northeast-trending zone of diffuse seismicity beneath northern Cook Inlet and the east-west-trending zone north of the Castle Mountain fault (fig. 5) clearly lie above the Aleutian WBZ (fig. 7, sections C–C', *D*–D'). The northern Cook Inlet activity follows a broad fold and thrust belt. Two new stations, one three-component and one single-component vertical, were installed near Anchorage in the summer of 1994 to help investigate the nature of the persistent seismicity and to evaluate the hazard that buried faults within this zone may pose to Anchorage and the surrounding area.

The rate of activity for magnitude 2 and smaller shocks in the northeast-trending cluster of epicenters north of the Denali fault near long 151°W. (fig. 5) appears to have increased threefold since November 1993 relative to the previous four years. The rate of magnitude 3 and larger shocks has remained constant since at least 1990. The cause of the apparent increase in microseismicity is under investigation. Two magnitude 4 shocks occurred in November in this cluster within a few kilometers of one another (lat 63.5°N., long 151.1°W.). The m_b 4.6 mainshock on November 7 occurred at a depth of 12 km. It was preceded 50 minutes earlier by an M_L 2.4 foreshock and followed within 4 hours by three aftershocks with magnitudes M_L 2.4, 2.0, and 2.7. The M_L 4.3 shock of November 17 occurred at a depth of 11 km. This event was preceded 18 hours earlier by an M_L 2.9 foreshock and followed within 20 hours by five aftershocks with M_L 1.8, 2.6, 2.8, 2.0, and 2.2. The patterns of P-wave first motions for the mainshocks are almost identical. Although the focal mechanisms are poorly controlled and allow either reverse or strike-slip solutions, they have horizontal, northwest-trending P-axes that are consistent with the P-axis orientations of historical solutions (Page and others, 1991). The northeast-striking nodal planes for the reverse solution are nearly parallel to the trend of the seismic cluster, which indicates that the events are probably due to reverse-slip motion on a northeast-trending fault.

An M_L 4.0 earthquake occurred in 1994 on October 17 in central Alaska, approximately 50 km north of the Denali fault (lat 64°N., long 146.1°W.). The event was followed 21 minutes later by an M_L 2.8 aftershock. The patterns of first motions for the mainshock and the aftershock are almost identical. The mainshock's well-controlled focal mechanism has a subhorizontal, north-

northeast- to south-southwest-oriented P-axis and allows reverse slip on either a steep southwest-dipping plane or a shallow northwest-dipping plane. The northeast-striking nodal plane for the thrust solution is near a series of northeast-oriented mapped faults, which indicates that the mainshock and aftershock are probably due to reverse-slip motion (with a significant component of left-lateral motion) on a northeast-trending fault.

Activity in the Fairbanks area in 1994 displays a northeast-southwest grain with several noteworthy clusters and trends (fig. 5). The easternmost cluster is the Salcha seismic zone (Biswas and Tytgat, 1988), approximately 40 km southeast of Fairbanks, which is characterized by a conspicuous, narrow band of activity approximately 50 km long. Although the current and historical seismicity suggest the presence of a northeast-trending fault, no fault with Quaternary displacement has yet been recognized (Cluff and others, 1974). Farther west is the Fairbanks seismic zone (Gedney and others, 1980), a diffuse zone of epicenters about 40 km wide and 150 km long. On November 2, an M_L 3.3 shock occurred 12 km northeast of Fairbanks at a depth of 14 km. This quake produced MM intensity III to intensity V effects throughout the Fairbanks area. The quake awakened many residents, rattled houses, knocked items off shelves, and shifted one fuel tank on its mounting. The well-constrained focal mechanism solution for this event indicates left-lateral strike-slip motion on a northeast-striking vertical plane. This solution is consistent with the northeast-southwest trend of seismicity in the Fairbanks area and with the mechanisms for historical activity in the Salcha seismic zone (Wickens and Hodgson, 1967; Hammond and others, 1993) and in the Fairbanks seismic zone (Matumoto and others, 1968). West of the Fairbanks seismic zone is the Minto Flats seismic zone (Biswas and Tytgat, 1988), a diffuse northeast-trending zone of earthquakes about 100 km long. A magnitude M_L 4.0 earthquake occurred in this zone (lat 65.1°N., long 150.4°W.) on December 17 at a depth of 11 km. It was felt with MM intensity III to intensity IV effects at Manley Hot Springs, 14 km southwest of the epicenter. The event was followed 10 hours later by an M_L 3.0 aftershock. An m_b 4.6 event that occurred on March 30 about 180 km north of Fairbanks (lat 66.5°N., long 148.0°W.) has a poorly constrained depth (fixed to 20 km) and was felt with MM intensity IV effects at Beaver, 29 km to the southeast.

Notable crustal shocks in northeast Alaska in 1994 (fig. 4) include an m_b 4.9 earthquake on January 5 in northern Alaska near lat 67.6°N., long 147°W. The mainshock was preceded by an M_L 3.7 foreshock on January 3 and was followed by five aftershocks with magnitudes ranging from M_L 3.8 to 2.5. The northernmost earthquakes located in Alaska in 1994 are an M_L 4.2 shock on July 5 and an M_L 4.3 shock on July 17, both in the northeast Brooks Range (lat 69.7°N., long 143°W.). Correlations between specific shocks and geologic structures for events in northeast Alaska are not possible with the low occurrence rate and poor precision of the historical (Page and others, 1991) and current data.

Earthquakes in western and southwestern continental Alaska include an M_L 4.4 event on February 10, which occurred in southwestern Alaska beneath the Kuskokwim Mountains (lat 59.6°N., long 159.1°W.). It was preceded by two shocks (M_L 4.0 and 3.5) on February 9 and followed by an M_L 3.3 event on February 11. These four earthquakes may be associated with the northeast-southwest-trending Togiak-Tikchik strand of the Denali fault system. On April 10, an M_L 4.6 shock and two aftershocks (M_L 2.5 and 2.6) occurred in western Alaska near the western end of the east-west trace of the Kobuk fault (lat 66.6°N., long 156.5°W.). The fault locally displaces late Quaternary deposits in a dextral sense (Brogan and others, 1975). The mainshock produced MM intensity IV effects at Kobuk, located 10 km to the north-northwest. On September 3, an M_L 4.1 shock occurred 64 km east of Huslia (lat 66°N., long 155.6°W.) near the epicenter of the 1958 M_S 7.3 Huslia earthquake, the largest event in the historical record in western Alaska (Page and others, 1991). The 1958 shock involved normal slip on either a shallow, north-northwest-dipping plane or a steep, south-southwest-dipping plane (Page and others, 1991, fig. 13, p. 64). An unusual swarm of eight events occurred in northwestern Alaska in December 1994 centered near lat 67.5°N., long 162°W. The events ranged in magnitude from 3.0 to 3.8 and had depths fixed at 10 km. The location of this activity is near the epicenter of the 1981 m_b 5.3 earthquake, the largest event in the historical record of continental Alaska north of lat 66.5°N. (Page and others, 1991, table 1, p. 50 and table 2, p. 56; Stover and Coffman, 1993, seismicity map, p. 8). The 1981 shock involved normal slip on either a shallow, south-southwest-dipping plane or a steep, north-northeast-dipping plane (Page and others, 1991, fig. 13, p. 64.)

Among other seismogenic features of note in southern Alaska in 1994 is the moderate level of shallow seismicity south, east, and northeast of Kodiak Island (figs. 4, 5). Four magnitude 4 shocks occurred there where a belt of northeast-trending submarine faults of Quaternary age is mapped. The foci of these shocks are poorly constrained, and it is uncertain whether these events occurred in the North American plate or on the Aleutian megathrust. Elsewhere, an M_L 4.1 shock was recorded on February 1 and located at 10-km depth beneath the southern Kenai Peninsula (lat 59.8°N., long 150.7°W.; fig. 5). It has a well-constrained focal mechanism that indicates almost pure normal-slip motion on either of two moderately dipping, north-northwest-striking planes. This solution is consistent with previous studies of recent seismicity in this area that indicate that the shallow crust above the megathrust is in tension (Stephens and others, 1982).

Relatively few events were located in southeastern Alaska in 1994 (figs. 4, 5). A curious series of events are clustered near the Wright Glacier (lat 58.4°N., long 133.5°W.), about 50 km east of Juneau (Rowe and others, 1994). The historical record indicates that clustered events occur at this location in a repeated cycle: events begin in the late spring (May) of each year and increase in rate through the fall (October), but they are largely absent during other months. The Wright Glacier seismicity cannot be located by the current AEIC regional network. Hypocenters of 14 events from October 1 to 9, 1994, with magnitudes between 1.7 and 3.2 and depths fixed to 5 or 10 km have been provided by Robert Horner of the GSC, Pacific Geoscience Center, Sidney, British Columbia. The cyclic behavior of the cluster is not consistent with regional tectonic stresses being the sole source of the activity. The cluster's proximity to large tidewater and alpine glaciers suggests an ice-related source for the events; however, waveforms of these earthquakes are notably different from other glacier events observed on the southern Alaska coast. Causes for the temporal pattern of events are being investigated and may involve elevated pore pressures at depth related to surface-water input from seasonal glacier melt and rainfall.

The largest earthquakes in northwestern Canada in 1994, an m_b 4.4 shock on May 29 and an m_b 4.7 event on October 10 (near lat 67°N., long 135.5°W.), occurred beneath the Richardson Mountains, Yukon Territory near the two largest historical shocks known to have occurred in the northern Yukon Territory (north of about lat 66°N. and west of about long 134°W.). The May 29 and June 5, 1940 Richardson Mountain earthquakes (M_S 6.2 and 6.5, respectively) were located about 20 km apart (lat 66.8°N., long 135.3°W. and lat 66.9°N., long 135.8°W., respectively) and had focal depths ranging from 15 to 11 km for the May rupture sequence and 10 to 7 km for the June sequence (modeling of teleseismic and regional body waves indicated a complex rupture sequence for each event, consisting of two to three subevents; Cassidy and Bent, 1993). The 1940 shocks were interpreted by Cassidy and Bent (1993) to involve right-lateral motion along a west-dipping, north-south-trending fault plane based on the focal mechanisms, the relative locations of the subevents, and the north-south-trending Richardson fault array (a complex shear zone that extends from the Arctic Ocean in the north to the Mackenzie Mountains in the south near lat 66°N.).

VOLCANIC-AXIS EARTHQUAKES

Small, shallow earthquakes along the volcanic axes of both the Aleutian (Cook Inlet segment) and Wrangell arcs are detected by the AEIC seismograph network. The 1994 shocks along the Cook Inlet segment of the Aleutian volcanic axis form a diffuse band punctuated by clusters beneath Spurr, Redoubt, and Augustine volcanoes (fig. 5; fig. 7, sections D–D', E–E'). The largest shallow earthquake (M_L 2.8) yet located beneath the edifice of Mount Spurr volcano (3,375 m above sea level) occurred on October 28, 1994, at a computed depth of 1 km below the top of the volcano. This event is one of only 15 crustal shocks larger than magnitude 2 since 1971 that have been located by the regional network within a 10-km radius of the summit of Mount Spurr, whose Crater Peak vent last erupted in 1992 (Power and others, in press).

CONCLUSION

The overall pattern of 1994 seismicity in Alaska and western Canada is generally similiar to that observed since at least 1988 when the AEIC was established and the USGS and UAGI seismograph networks were merged. Most of the earthquakes located in 1994 occurred in southern and central Alaska, the Alaska Peninsula, and the Aleutian Islands. The higher rate of earthquake activity in central and southern Alaska (about 85 percent of the total number of earthquakes located in 1994) relative to the Alaska Peninsula and the Aleutian Islands reflects the greater concentration of seismograph stations in those regions.

The 1994 seismicity is best examined using events greater than or equal to magnitude 4.5 (the approximate magnitude level at which the earthquake catalog is complete for Alaska and western Canada). This seismicity is dominated by activity along the Aleutian arc west of long 160°W. where 77 percent of the 103 events with $m_b \geq$ 4.5, 87 percent of the 31 events with $m_b \geq 5.0$, and all four of the events with $m_b \geq 5.5$ occurred. The three largest Aleutian shocks (m_b 6.0, 5.8, and 5.6) probably occurred on the Pacific–North American plate boundary based on their focal mechanisms (low-angle, reverse faulting on north-northwest-dipping plane) and shallow depths. In central and southern Alaska the largest events (m_b 5.4, 5.2, and 5.0) were Aleutian WBZ shocks (depths of 49, 66, and 39 km, respectively). The stress orientation of these events inferred from their focal mechanism solutions is characterized by inplate, downdip tension. This stress orientation is consistent with the pattern seen for Aleutian WBZ shocks in southern Alaska since 1971, when the USGS southern Alaska seismograph network began operation.

Two notable 1994 earthquakes are the largest, well-constrained shock yet located deeper than 200 km in the Aleutian WBZ east of long 156°W. (an m_b 4.6 event at 219 km depth on December 10), and the largest crustal shock ever located beneath the edifice of Mount Spurr volcano (an M_L **2.8** event at **1-km** depth below the top of the volcano on October **28).**

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