Geological Society of America Special Papers

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Geological Society of America Special Papers 2002;360;259-272
doi: 10.1130/0-8137-2360-4.259

Geological Society of America
Special Paper 360
2002

Seismicity of Chukotka, northeastern Russia

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ABSTRACT

The seismicity of Chukotka forms the central part of a Trans-Bering seismic belt that extends from the Koryak highlands through the Seward Peninsula to central Alaska. The seismicity of the Chukotka section has been recorded teleseismically (1928 to present), using a temporary network (1964–1966), a multiinstrument single station (1966–1982), and a regional network (1980–1993). Three seismic zones are identified within the Chukotka section of the Trans-Bering seismic belt: the Kolyuchin Gulf–Eastern Chukotka zone, a western extension of the rift system of Seward Peninsula, Alaska; the Koryak-Provideniya-Seward zone, representing the transpressional southern boundary of the Trans-Bering seismic belt; and the Anadyr–Amguema–Chukchi Sea zone, a weak, transtensional zone of seismicity forming the northern edge of the Trans-Bering seismic belt. The rest of Chukotka is relatively aseismic; the seismicity reported from the Polyarnyi area is anthropogenic. The Kolyuchin Gulf–Eastern Chukotka zone is a highly active transtensional zone (earthquakes to magnitude 7) with three northeast-striking segments of seismicity that are presumed to be transform faults offsetting rift segments. The Koryak-Provideniya-Seward zone is characterized by thrusting in its southern end, which changes to transform motion in the Gulf of Anadyr, and connects with the east-west–striking rift systems in Chukotka and the Seward Peninsula. The seismicity and focal mechanisms are consistent with the existence of an independent Bering Sea block rotating clockwise with respect to North America about a pole in western Chukotka. The Trans-Bering seismic belt forms the northern border of the Bering Sea block.

Fujita, K., Mackey, K.G., McCaleb, R.C., Gunbina, L.V., Kovalev, V.N., Imaev, V.S., and Smirnov, V.N., 2002, Seismicity of Chukotka, northeastern Russia , *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses: Boulder, Colorado, Geological Society of America Special Paper 360, p. 259–272.

INTRODUCTION

Chukotka is located in northeasternmost Asia across the Bering Strait from Alaska; its seismicity is in the central part of a diffuse belt of earthquakes that extends from northwestern Kamchatka through the Seward Peninsula to central Alaska (Fig. 1; e.g., Mackey et al., 1997; Imaev et al., 1999), and includes the Bering Strait region. We refer to the belt as the Trans-Bering seismic belt, and it is among the most seismically active regions within what is usually considered to be part of the North American plate. The Chukotka part of the Trans-Bering seismic belt has undergone five magnitude 6, and eight magnitude 5, events during the past 75 yr. The region is sparsely populated and, as a result, the area was generally considered only weakly seismic. No macroseismic reports exist from Chukotka prior to 1971, thus seismicity prior to the early twentieth century is unknown.

Traditionally, the seismicity of western Alaska has been interpreted either as intraplate activity (Biswas et al., 1980) or as backarc effects of the Alaska subduction zone (e.g., Nakamura et al., 1980; Biswas et al., 1986a; Estabrook et al., 1988), and not related to the area being part of an extensive seismic belt. The combination of Russian and U.S. data, however, indicates that the diffuse seismicity of western Alaska is continuous with that in northeastern Russia (Fig. 1); thus the tectonics of the Trans-Bering seismic belt should be examined as a whole. Based on the combined data set, Lander et al. (1996) and Mackey et al. (1997) suggested that the Trans-Bering seismic belt forms the northern boundary of an independent Bering Sea plate or block that is rotating clockwise relative to North America about an Euler pole in western Chukotka (Fig. 1).

This chapter summarizes the seismicity of the previously poorly studied Chukotka segment of the Trans-Bering seismic belt. The seismicity of the other segments of the belt was described by Biswas et al. (1983, 1986b) for western Alaska and

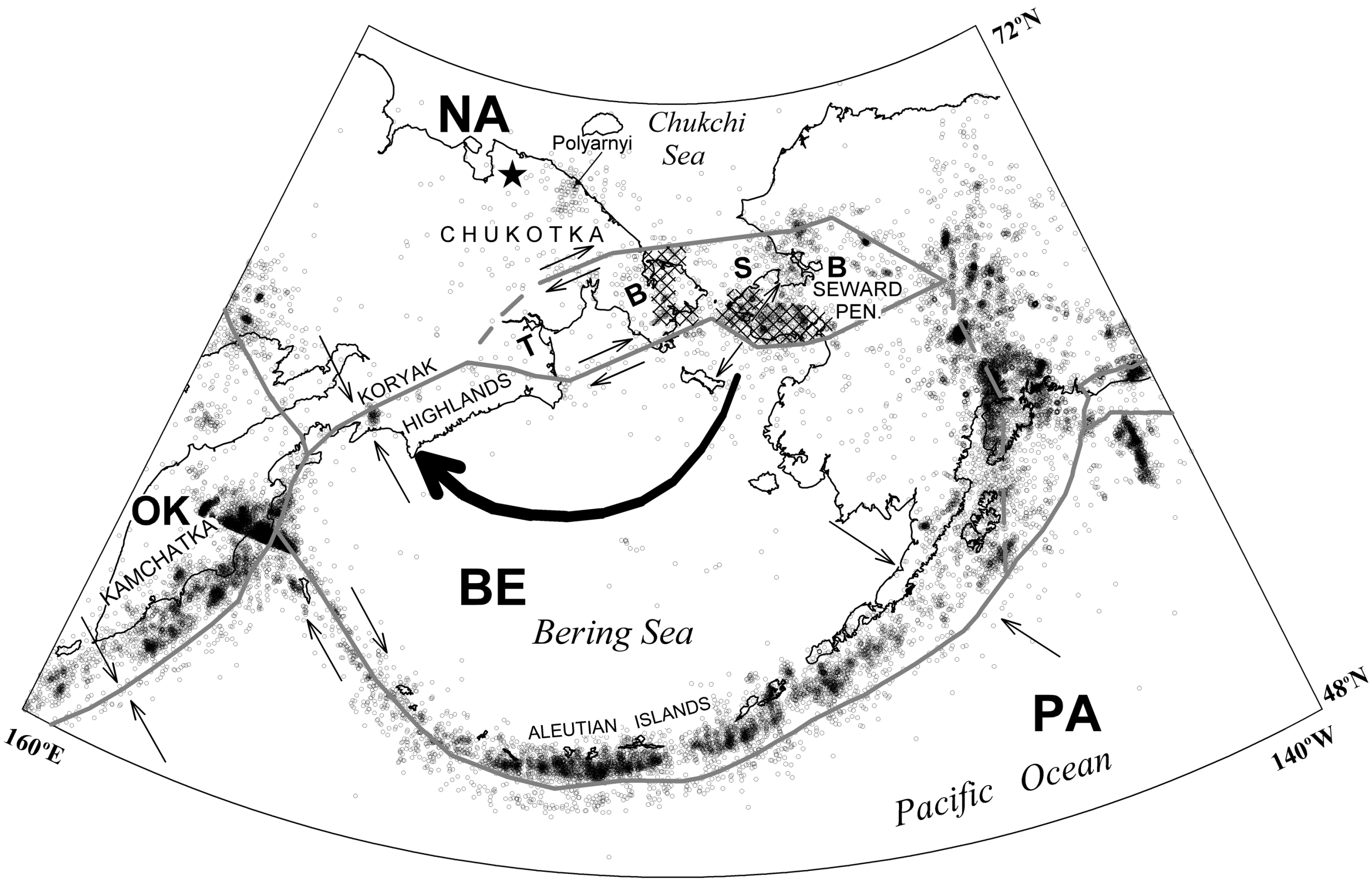

Figure 1. Seismicity map of Trans-Bering seismic belt (TBSB). Major plates and blocks are labeled (NA, North America; OK, Okhotsk block; BE, Bering Sea block; PA, Pacific). Star denotes pole of rotation of Bering block relative to North America (Mackey et al., 1997). Cross hachures indicate extensional areas on Seward Peninsula and in Chukotka. Seismicity around Polyarnyi is anthropogenic in origin (see Appendix). Plate and block boundaries are shown in gray, dashed where uncertain or diffuse. Arrows show relative motions between plates and blocks and large bold arrow shows motion of Bering block. Only teleseismic seismicity is shown south of 56°N in Kamchatka, in the Aleutians, and in Alaska outside of Seward Peninsula.

the Seward Peninsula; by Estabrook et al. (1988) and Page et al. (1991) for north-central Alaska; and by Lander et al. (1996) for the southern Koryak highlands.

SEISMICITY

Teleseismic records

Prior to 1964, all records of Chukotkan seismicity were teleseismic. Figure 2 shows teleseismically located seismicity from 1900 to the present based on data from the International Seismological Summary (ISS), the International Seismological Center (ISC), and the Preliminary Determination of Epicenters (PDE). Two prominent clusters of seismicity are noted, one near the Kolyuchin Gulf, Chukotka, and the other near Cape Prince of Wales, Alaska. Viewed on a broader scale (Fig. 1), however, most of the seismicity occurs in a band, the northern boundary of which passes through the Kolyuchin Gulf and the De Long Mountains, and the southern boundary of which extends from Cape Navarin to the southern Seward Peninsula. When combined with the microseismicity discussed in the following, this defines the Chukotka segment of the Trans-Bering seismic belt.

Teleseismic detection capability for this region has ranged from about magnitude (M) = 6 in the 1920s to M = ~4 today. Location accuracy was ~±100 km in the 1920s to 1950s due to the lack of stations and poor timing, and has decreased to ±15 km today. Based on more recent seismicity, the three large (M = 6–7) events that occurred east of the Kolyuchin Gulf (Fig. 2) in 1928 are probably mislocated from the northeast-striking trend ~50 km to the north. In addition, a number of other early twentieth-century events attributed to this area are also mislocated or spurious; the most significant of these is a spurious event listed in the ISS for May 24, 1927, north of Wrangel Island. There are also two teleseismic events (labeled X in Fig. 2) listed in the ISC bulletin for 1971 that do not appear in any Russian bulletins; these may be a result of misassociated arrivals from events that occurred off the east coast of Kamchatka. All events are assumed to be crustal (10–33 km depth).

NEISRI test network

From late 1964 to early 1966, short-period sensors to record local and regional events were placed in towns throughout Chukotka as part of a larger temporary deployment by the Northeast Interdisciplinary Scientific Research Institute (NEISRI; Andreev et al., 1967). Although a large number of events were recorded, only 12 events were located in Chukotka due to the small number of simultaneously operating stations (Fig. 3).

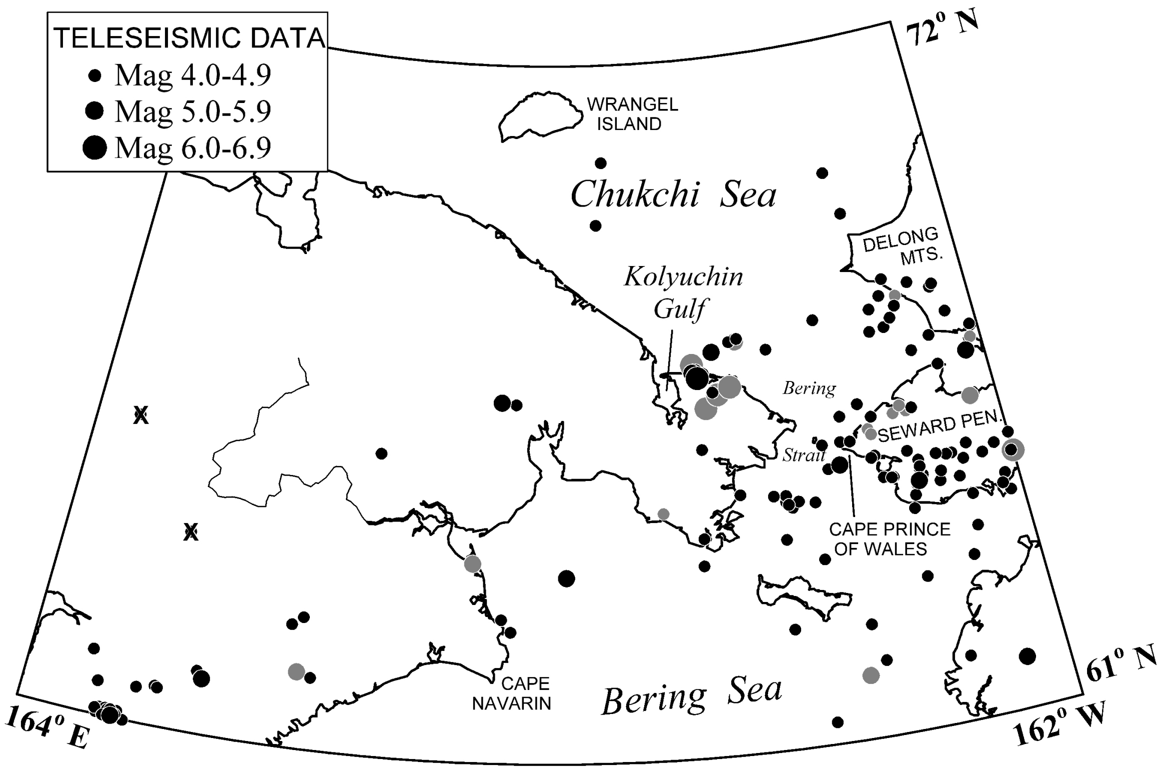

Figure 2. Teleseismically determined epicenters for Chukotka and westernmost Alaska. Events prior to 1964 are shown in gray and have greater location uncertainties. Two events marked X are discussed in text. Magnitude is indicated by size of circle.

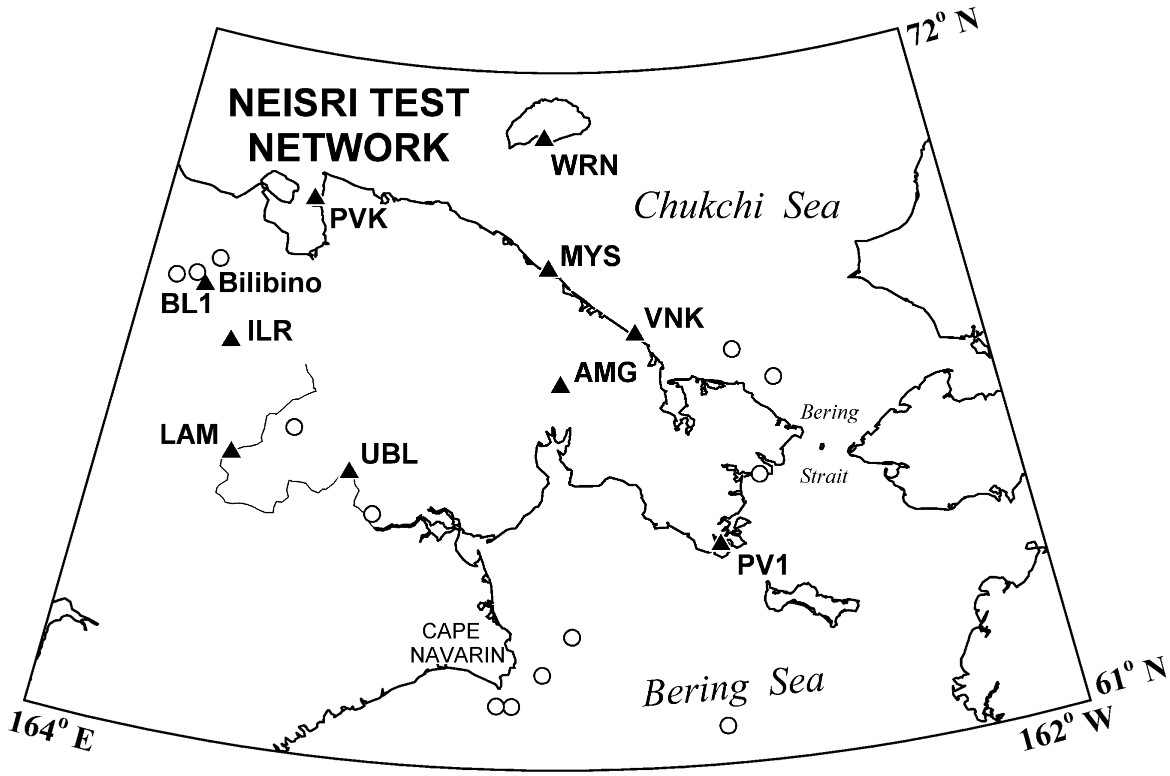

Figure 3. Northeast Interdisciplinary Scientific Research Institute (NEISRI) test network located epicenters (open circles) and station locations (triangles; see text).

Based on time of day and year, the events around Bilibino (BL1) are almost certainly explosions (Andreev et al., 1967; see Appendix). Seismicity was also identified off Cape Navarin, in the Bering Sea, and in the Bering Strait region. As a result of this, a permanent seismic station in Chukotka was deployed.

Iul'tin station

A permanent seismic station, equipped with three-component long- and short-period instruments, was deployed at Iul'tin (Table 1; Fig. 4) by the Institute of Physics of the Earth, Moscow, in March 1966 (Lazareva, 1970, 1973). Epicenters taken from Kondorskaya and Shebalin (1982) and the Arctic section of the annual *Earthquakes in the USSR* (annual, 1961–1989, Nauka, Moscow) are shown in Figure 4. A high level of seismicity was discovered south of Polyarnyi and southwest of the Kolyuchin Gulf. The seismicity south of Polyarnyi is anthropogenic in origin (see Appendix).

From 1966 to 1982, epicentral coordinates were determined for these regional events using the S-P time to obtain the origin time and distance while the azimuth was based on the polarization of the P wave (Lazareva, 1975). All earthquakes were assumed to be shallow (15 km). Only ~7% of the events recorded by Iul'tin were locatable (Avetisov, 1996). The epicentral accuracy was presumed to be ~±50 km, although comparison of locations using Iul'tin data alone and multistation relocations from the western Alaska network, operated by the University of Alaska, for five events in 1981 and 1982 in eastern Chukotka yield differences of as much as 50–100 km. These events are far from Iul'tin, thus events closer in may be better located. There is an abnormal north-south lineation of epicenters directly north and south of the station, suggesting that some locations are poor.

Godzikovskaya and Lander (1991), on the basis of energy envelopes from Iul'tin records that they interpret as lacking crustal phases (i.e., Pg, Sg), suggested that some events in Chukotka have a subcrustal focus. However, these events are at or close to the crossover distance for crustal and mantle phases, thus only one set of phases is likely to be observed. In addition, relocation of an event in 1984, cited as being subcrustal, yields a focal depth of 8 ± 11 km and is probably an explosion in the Polyarnyi mining district. Thus, there is no convincing evidence for subcrustal earthquakes in Chukotka.

NEISRI regional network

In October 1979, the Magadan Experimental-Methodological Seismic Division (EMSD) was organized under NEISRI to operate a regional seismic network. In the fall of 1980, the Magadan EMSD began the deployment of a regional network in Chukotka (Table 1; Fig. 5) with short-period sensors.

TABLE 1. MAGADAN EMSD CHUKOTKA STATION COORDINATES

Code	Station	Lat	Long	Elev	Open	Closed
ANSS*	Anadyr-1	64.77	177.57	40	11.80	1.89
ANYS*	Anadyr	64.734	177.496	55	4.89	7.93
					9.96	Open
BIL*	Bilibino	68.058	166.449	282.6	8.81	4.92
BILL	Bilibino GSN	68.065	166.452	299	8.95	Open
EGV*	Egvekinot	66.323	179.127W	18	1.90	—.94
ILT	Iul'tin	67.87	178.74W	235	3.66	7.93
MKI*	Maiskii	68.97	173.71	261	8.82	7.91
MKV*	Markovo	64.684	170.412	25.2	10.85	4.92
OMO*	Omolon	65.23	160.54	260	6.82	7.93
PVD*	Provideniya	64.427	173.224W	25.5	9.80	12.93
ULN*	Uelen	66.16	169.84W	5	—.81	—.82

Note: ILT was operated by the Institute of Physics of the Earth, Moscow. Asterisk denotes unofficial code. Elev is elevation in meters. Lat and Long are latitude (°N) and longitude (°E unless noted), respectively.
Sources: Yugova et al., 1997; Magadan EMSD.

Epicenters located by the NEISRI network shown in Figure 5 were obtained from the *Earthquakes in the USSR* and the Magadan EMSD network catalog. The seismicity is diffuse, but is concentrated in eastern Chukotka, northwest of Provideniya (PVD, Fig. 5), and in bands that trend from the Khatyrka River basin across the Gulf of Anadyr to the Bering Strait, and from north of Egvekinot (EGV, Fig. 5) to the eastern Chukchi Sea. The 15 events from the Polyarnyi area that are believed to be anthropogenic in origin (see Appendix) are omitted from Figure 5.

From 1983 to 1993, earthquakes were located by graphical methods (Vorob'eva and Yugova, 1988) using the traveltime curve of Andreev (1984), which uses P- and S-wave velocities for the crust of 6.1 km/s and 3.51 km/s and mantle velocities of 8.1 km/s and 4.66 km/s, respectively. Starting in 1982, some

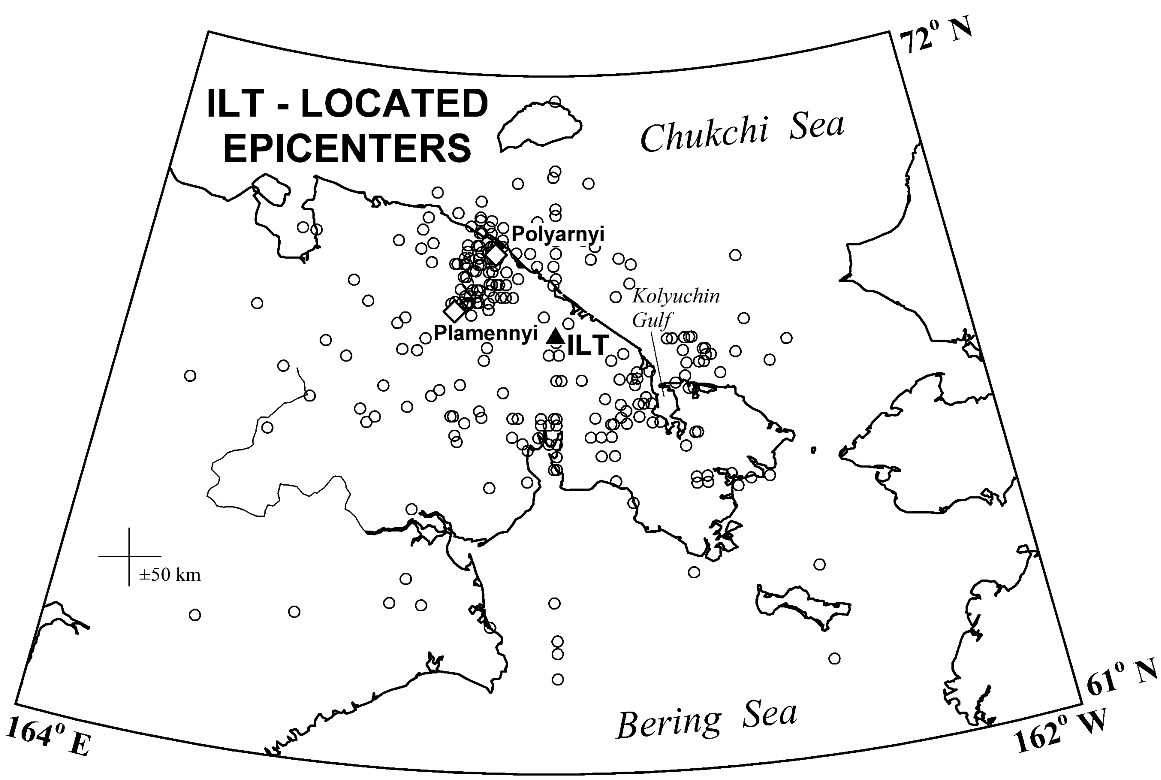

Figure 4. Epicenters (open circles) located using three-component station at Iul'tin (ILT, triangle). Location error shown near lower left.

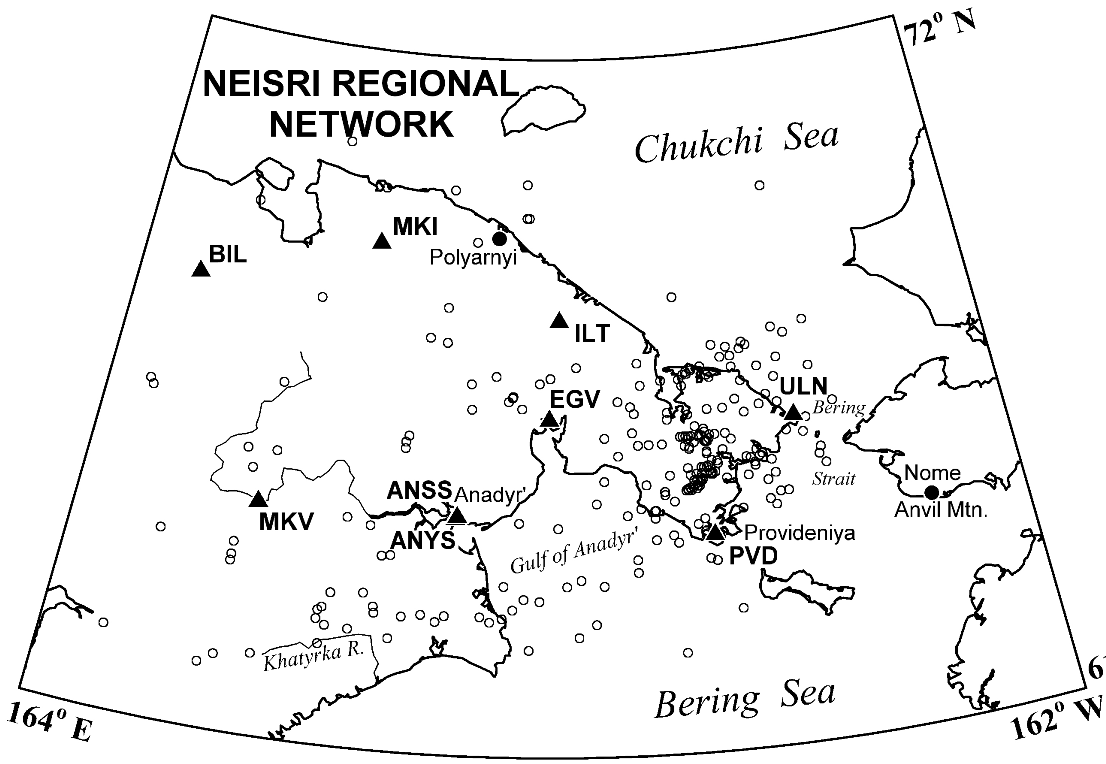

Figure 5. Epicenters (open circles) located by Northeast Interdisciplinary Scientific Research Institute (NEISRI) regional network and station locations (triangles; see text). See Table 1 for station codes. Note that 15 events believed to be of anthropogenic origin near Polyarnyi have been omitted.

larger earthquakes were located using personal computers, and computer-based locations became standard in the early 1990s. Formal errors are ±25–50 km in the early 1980s and ±10–15 km in the late 1980s and early 1990s. The detection level in Chukotka with three to four stations was about M = 3 (Artamonov and Mishina, 1984) and possibly slightly lower during the late 1980s. With the collapse of the Soviet Union, funding decreases resulted in the rapid collapse of the Chukotka regional network in 1992–1993 (Table 1) and an increase in detection levels to about M = 4 throughout the region. All stations were closed by the end of 1993.

About 50 events were relocated by Mackey (1999; mainly from easternmost Chukotka in the mid-1980s) by supplementing the phase data from the Magadan network bulletin with arrivals picked from the develocorder records for Anvil Mountain (Nome), Alaska. The mean relocation distance was ~25 km. Some clear trends become visible in the relocated epicenters (Fig. 6).

SEISMIC ZONES OF CHUKOTKA

The combination of the teleseismic and regional data make the Trans-Bering seismic belt in Chukotka much more prominent (Fig. 7) and suggests there are three zones of elevated seismicity: Kolyuchin Gulf–Eastern Chukotka (zone A, extensional), Koryak-Provideniya-Seward (zone B, transpressional), and Anadyr–Amguema–Chukchi Sea (zone C, transtensional).

Because the seismicity in the Polyarnyi region appears to be strongly contaminated with, if not entirely the result of, explosions, and because of the poor quality and quantity of the NEISRI test network data, these events have been omitted. Epicenters from the western Alaska network within map areas are from Biswas et al. (1983). Iul'tin epicenters are shown in gray due to their greater uncertainties. It is possible that the diffuse seismicity in Norton Sound is part of the Trans-Bering seismic belt; however, detailed studies on this seismicity are lacking.

Kolyuchin Gulf–Eastern Chukotka seismic zone

The Kolyuchin Gulf–Eastern Chukotka zone (Fig. 7, zone A), which we suggest is extensional in nature, is the most active and enigmatic of the seismic zones of Chukotka. The zone extends from the Kolyuchin Gulf in the northwest to the Provideniya area in the southeast. We propose that this zone is a continuation of the rift system of the Seward Peninsula (Fig. 7, zone D) into Chukotka. Zone A is truncated by zone B in the southeast and by zone C in the northwest. The seismicity within zone A defines three short segments, all oriented southwest-northeast, along with additional scattered events (arrows, Fig. 7).

The northernmost segment extends northeastward from the

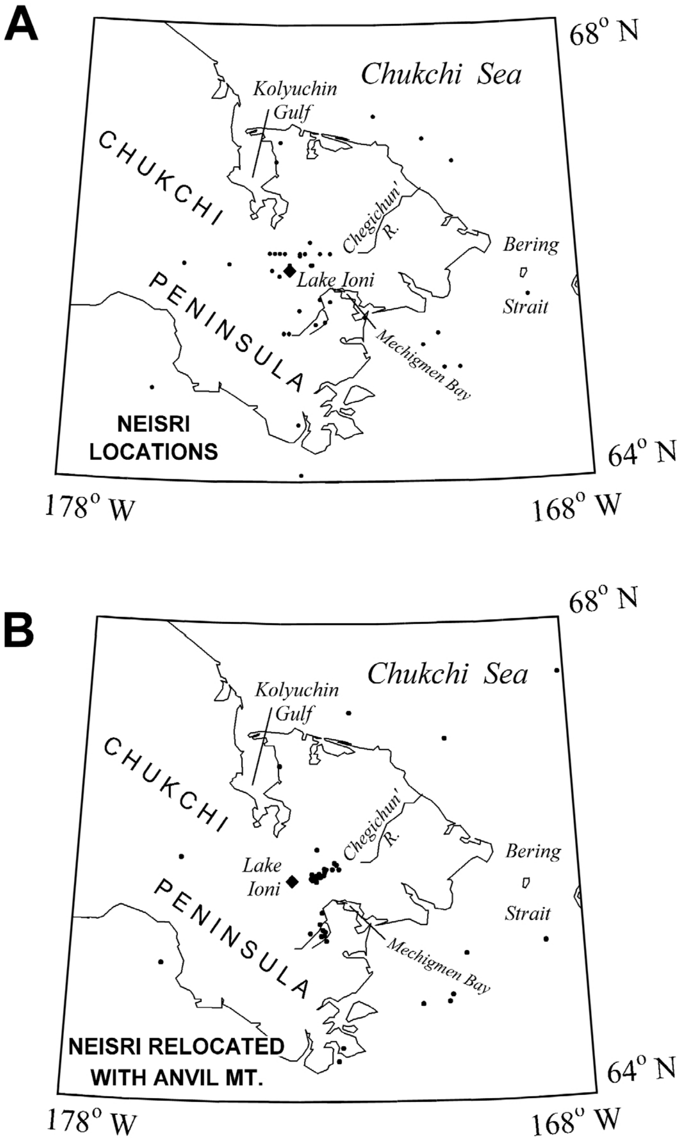

Figure 6. A: Northeast Interdisciplinary Scientific Research Institute (NEISRI) locations. B: Relocated epicenters using additional data from Anvil Mountain, Alaska. Lake Ioni shown by solid diamond.

Kolyuchin Gulf into the Chukchi Sea. The segment is also parallel to the edge of the topographic highlands of eastern Chukchi Peninsula formed by exposures of Precambrian crystalline rocks. Events of magnitude 5–6 occurred along this segment in 1928, 1962, 1971, 1996, and 1997. Three other 1928 events, with magnitudes of 6.2–6.9, are located to the southeast; however, given location accuracy in the 1920s and the lack of present-day activity, it is likely that they also were along this northern segment.

Two moment tensor solutions have been determined for this segment (Fig. 8; Dziewonski et al., 1997b, 1998). Both solutions indicate right-lateral transtension, assuming that the fault plane is the nodal plane (strike, $\varphi = 230°–249°$) striking approximately parallel to the strike of the segment ($\varphi \approx 240°$). The other nodal plane ($\varphi = 127°–134°$) is roughly perpendicular to the segment and parallel to the trend of older tectonic features found ~100 km to the east (e.g., north coast of Chukchi Peninsula and Kotzebue arch, Eittreim et al., 1979). A focal mechanism for the 1971 event based on teleseismic first motions and short-period body-wave modeling using the method of Kroeger (1978) yields a similar solution, although rotated about 20° (Table 2; $\varphi = 267°$). Previous solutions for the 1971 event (Biswas et al., 1986a; Fujita and Koz'min, 1994) are erroneous, probably due to the emergent first motions used from Alaskan stations. Teleseismic P-wave first-motion data and waveform characteristics are similar between the 1971 and 1962 events, thus we presume that they had similar mechanisms; no mechanisms can be constructed for the 1928 events (Fujita and Koz'min, 1994). Thus the northern segment is under north-south-directed extension with a right-lateral strike-slip component.

The central segment of zone A is within the Kolyuchin-Mechigmen graben in a topographically low region filled with Quaternary deposits (Gorodinsky, 1982). Our relocated epicenters define a northeast-southwest trend (Figs. 6 and 7) near Lake Ioni. This trend is colinear with the valley of the Chegichun' River along which Natal'in et al. (1999) mapped a fault with possible right-lateral motion of unknown age. No large events have been recorded from this zone.

The southern segment is partly along a lineament visible on Landsat images that extends southwest from Mechigmen Bay and cuts the strike of the regional topography (Figs. 6 and 7). Relocated events define only the northern end of this trend (cf. Figs. 6 and 7). The seismicity of the northern end of this segment is under Quaternary deposits filling the Kolyuchin-Mechigmen graben, while the southern end is under eroding Cretaceous extrusive volcanics.

On the basis of the focal mechanisms from the northern segment and the topographic depressions linking the northern, central, and southern segments, we propose that zone A represents an extension of the rift system of the Seward Peninsula (Turner and Swanson, 1981) into Chukotka (Mackey et al., 1997). This rift consists of three northwest-southeast–striking rift segments parallel to the overall strike of zone A, offset by strike-slip faults represented by the three northeast-southwest–striking seismically active segments (Fig. 8). As in the Seward Peninsula (Biswas et al., 1986b), the extension is oriented north-south to northeast-southwest. We suggest that the current locus of the rift system follows the Kolyuchin-Mechigmen graben, a fault-bounded lowland (Pol'kin, 1984) that extends from the southern end of the Kolyuchin Gulf to Mechigmen Bay. The graben is asymmetric with a steeper and higher northern side, and the bounding faults are expressed in geophysical fields (Pol'kin, 1984). Based on the southern segment of seismicity of zone A, the southeastern end may be offset farther to the south, but there is no clear topographic basin. However, little seismicity is observed in areas between the segments, i.e., the extensional areas.

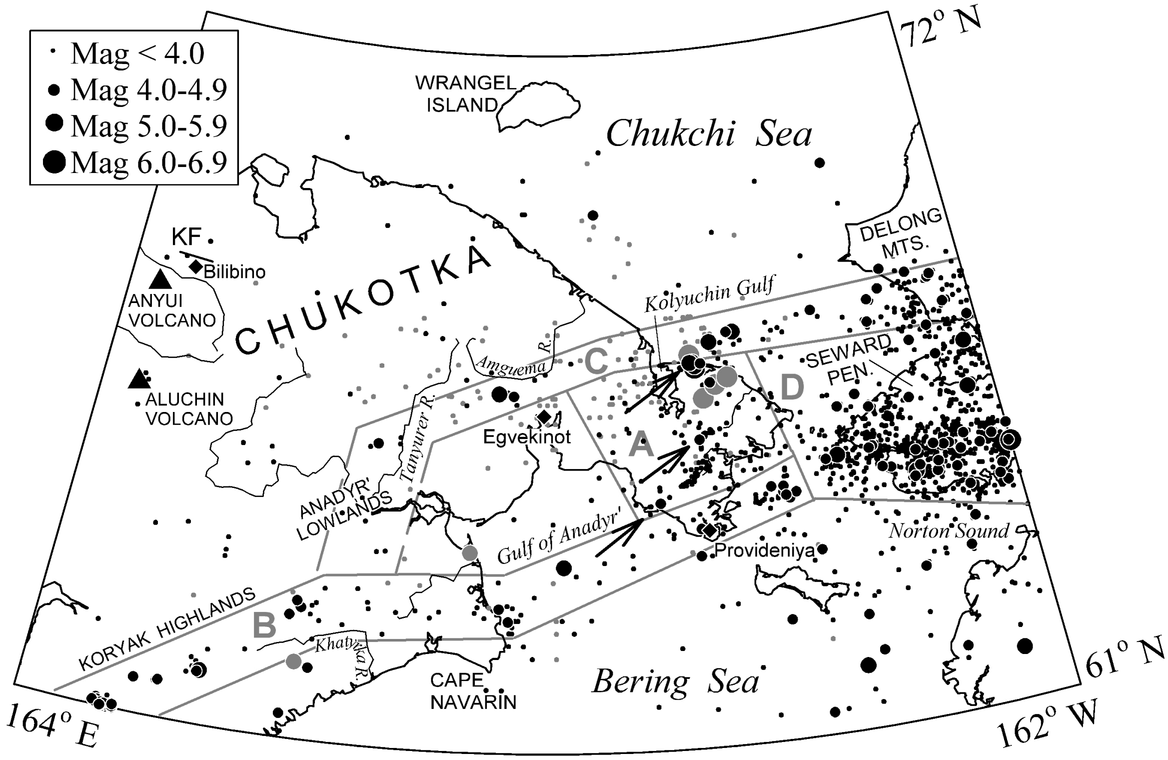

Figure 7. Seismicity map of Chukotka using best available data. Seismic zones defined in text are outlined in gray. A—Kolyuchin Gulf–Eastern Chukotka zone. B—Koryak-Provideniya-Seward zone. C—Anadyr–Amguema–Chukchi Sea zone. Iul'tin determined epicenters and pre-1964 teleseismic epicenters are shown in gray due to lower location accuracy. Arrows in zone A highlight segments discussed in text. Triangles denote Quaternary (?) volcanoes. KF is Keperveyem fault. D—seismic zone of the Seward Peninsula.

This may be due to the fact that the Kolyuchin-Mechigmen graben is an established structure and a zone of relative weakness. In the Seward Peninsula the rift is breaking through an intact Precambrian block (Till and Dumoulin, 1994).

Late Cenozoic alkaline basalts found in the southern Chukchi Peninsula are also indicative of extension (Enmelen volcanics, EV, Fig. 8; Akinin and Apt, 1994), as are hydrothermal areas near Provideniya and in the eastern part of the Kolyuchin-Mechigmen graben (Imaev et al., 1999).

Russian geophysical data suggest that there was a continuation of the rift system into the Chukchi Sea, north of the Kolyuchin Gulf. Shipilov et al. (1989) suggested that there are north-northwest–striking fault-bounded troughs, which may be part of a much larger, now inactive, rift system that extended north from the Kolyuchin Gulf toward Wrangel Island, as well as along the northeast coast of the Chukchi Peninsula. There are no published data to suggest that the Kolyuchin-Mechigmen graben extends to the west of the Kolyuchin Gulf.

Turner and Swanson (1981) summarized the geologic evidence for extension and rifting in the Seward Peninsula. Combined with focal mechanisms determined for the Seward Peninsula by Biswas et al. (1986b), it seems apparent that the Seward Peninsula has been a region of Quaternary extension, which continues to this day. This extensional regime appears to have dominated the Bering Strait region for the entire Cenozoic and perhaps the latest Mesozoic. Dumitru et al. (1995) suggested that extension began as early as 120 Ma. Offshore seismic studies in the Hope basin (Tolson, 1987) and basaltic volcanic deposits in the Seward Peninsula and west-central Alaska (Moll-Stalcup, 1994; Till and Dumoulin, 1994) suggest the continuation of this extension throughout the Cenozoic (Mackey et al., 1997). This extensional regime may also be evidenced by deep reflectors and thinned crust underneath the Bering Strait recorded by the 1994 cruise of the R/V *Ewing* (Brocher et al., 1995; Klemperer et al., this volume, Chapter 1; Wolf et al., this volume).

In Chukotka and the western Chukchi Sea, the timing of extension is less well defined. However, the formation of Kolyuchin-Mechigmen graben is believed to have initiated in Late Cretaceous to Paleogene time (Pol'kin, 1984) and the Enmelen and associated volcanics have been dated as 4–10 Ma based on the K-Ar method and palynology (Akinin and Apt, 1994; Belyi, 1995). Shipilov et al. (1989) also suggested a Late Cretaceous origin for extension in the Chukchi Sea. Thus, the

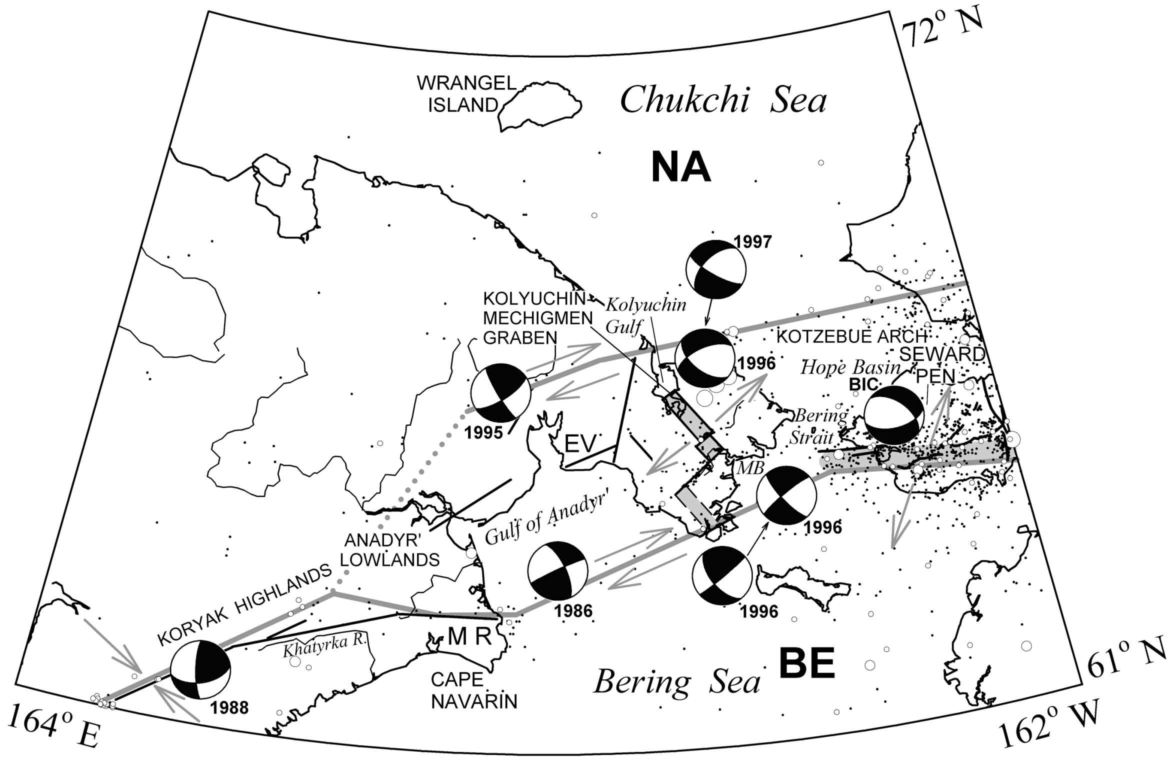

Figure 8. Tectonic map of Chukotka and western Alaska showing proposed tectonic boundaries (gray), earthquakes (open circles), focal mechanisms with year (compressional quadrant solid; see Table 2 for Chukotka mechanisms), and faults visible on space imagery or on topographic maps (black lines). Proposed rift areas are shaded in gray. Focal mechanism labeled BIC is composite mechanism from Biswas et al. (1983) and is representative of Seward Peninsula. MB—Mechigmen Bay. EV—Enmelen volcanics. MR—Meingypil'gyn Range. Large arrows show approximate relative motions. NA is North American plate, BE is Bering Sea block.

extension appears to have started contemporaneously in both Chukotka and the Seward Peninsula. Because the regions of rifting adjoin, we suggest that they form two segments of a unified extensional system, which Dumitru et al. (1995) and Mackey et al. (1997) suggested is related to interactions between the Pacific plate and Alaska, possibly far-field effects of the accretion of terranes in southeastern Alaska.

Koryak-Provideniya-Seward zone

Zone A is truncated on the south by zone B, which extends southwestward from the Bering Strait to the northern Koryak highlands (Fig. 7, zone B). The southern extension of zone B (Lander et al., 1996) traverses the Koryak highlands and connects with the North America–Okhotsk plate boundary (Cook et al., 1986) in northern Kamchatka. Our discussion is restricted to the part of zone B north of 62°N.

The northern end of zone B merges into the seismicity of the Seward Peninsula (zone D, Fig. 7) across the Bering Strait from Provideniya. The northernmost part of the segment is defined by a cluster of seismicity striking northeast. Moment tensors have been determined for three earthquakes that occurred in late 1996 within this cluster; the two larger events (Fig. 8) have solutions consistent with right-lateral strike-slip faulting on a plane parallel to the strike of the cluster ($\varphi = 235°–238°$), and the smallest event is right-lateral transpression along a similar plane ($\varphi = 249°$; Dziewonski et al., 1997b, 1998). To the north of this cluster, zone B trends into the rifts and seismicity of the southern Seward Peninsula described by Biswas et al. (1986b) and Turner and Swanson (1981), and then further into central Alaska (Page et al., 1991). On the basis of the orientation of the seismicity and the focal mechanisms, we suggest that zone B near Provideniya acts as a strike-slip transform fault between the southern part of zone A and the Seward Peninsula rift system (Fig. 8).

To the southwest, in the Gulf of Anadyr, zone B is traced by a band of microearthquakes, with a few teleseisms, that trends toward Cape Navarin and the Koryak highlands. The largest event ($M = 5.3$) in this part of the zone occurred in 1986. The moment tensor solution (Fig. 8; Table 2; Dziewonski et al., 1987) is also a right-lateral strike slip on a plane striking parallel to the seismicity ($\varphi \approx 245°$), although the P-wave first-motion data (Gunbina et al., 1987) admit a more transpressional solution.

No seismic stations have been deployed in the Koryak high-

TABLE 2. FOCAL MECHANISMS OF THE CHUKOTKA-BERING STRAIT REGION

Date			Origin			Lat	Long	Mag	Plane 1			Plane 2			Meth	Ref
88	10	13	00	32	13.	61.85	169.65	5.7	070	53	164	170	77	39	CMT	1
86	10	19	18	30	57.	63.90	–178.69	5.3	336	68	4	245	86	158	CMT	1
									323	50	28	216	69	137	PB	2
95	10	02	01	35	48.3	66.69	179.14	5.1	055	71	170	148	81	19	CMT	1
97	03	24	06	56	13.3	67.07	–173.31	5.1	230	53	–160	127	74	–39	CMT	1
96	10	24	19	31	56.2	67.13	–172.84	6.0	251	60	–138	136	54	–38	CMT	1
71	10	05	01	40	41.6	67.38	–172.57	5.2	267	55	–145	142	50	–40	SYN,P	2
96	08	09	18	33	25.6	64.91	–170.34	4.7	001	50	32	249	66	135	CMT	1
96	08	09	18	45	43.4	64.93	–170.45	4.9	148	58	4	055	86	148	CMT	1
96	11	03	23	24	30.7	64.84	–170.41	5.1	146	76	–8	238	82	–166	CMT	1

Note: Epicenters after ISC, PDE, or Kondorskaya and Shebalin (1982). References: 1—Harvard CMT Catalog (Dziewonski et al., 1987, 1989, 1997a, 1997b, 1998); 2—this paper. Origin time in UTC; Lat and Long are latitude and longitude (north and east positive); Mag is body wave magnitude, Plane 1 and Plane 2 are given in strike, dip, and slip according to standard seismological convention; Meth is method (CMT—centroid moment tensor; PB—P waves from seismograms and bulletins; SYN—short-period synthetics; P—P-wave first motions from seismograms.

lands, thus the detection threshold is higher than in Chukotka, and fewer events have been located. In the Meingypil'gyn Range (MR, Fig. 8; also called the Ukvushvuynen Mountains), the seismicity is approximately coincident with a zone of east-west-striking faults; the faults offset river valleys that can be seen on Landsat images and 1:200 000 topographic maps (Fig. 9, areas A and B). Toward Cape Navarin (Fig. 9, area C), younger faults are superposed on, and offset, a series of faults and the large-scale structural trend of the region (dashed lines in Fig. 9). River valleys are offset as much as 2 km in a right-lateral sense across many of these faults. A total offset of 5–7 km across the entire fault system is estimated. Landslides and similar features, most likely generated by strong earthquakes, have also been mapped in this area by Russian field parties, suggesting that significant faulting continues in this area.

West of 177.3°E, the faults and seismicity curve to a west-southwest strike and the larger river valleys are bent or offset by them in a right-lateral sense (Fig. 9, area D). Farther west, the seismicity continues into a large basin near 175°E filled with Quaternary deposits, and then into the Khatyrka River valley. A magnitude 5.5–5.7 event (March 9, 1934) was located in the Khatyrka River valley, although the epicentral error may be large. A focal mechanism here indicates transpression (Fig. 8; Table 2), which becomes thrusting south of 61°N (Lander et al., 1996).

The neotectonics of this area have not been extensively studied. Examination of presumed peneplanation (accordant summit) surfaces and river terraces has been used by Russian authors to suggest Holocene uplift of as much as 500–1000 m in the seismically active region of the Koryak highlands (Smirnov, 1995), although such surfaces may simply represent equilibrium surfaces (Keller and Pinter, 1996). Based on re-leveling surveys, the Anadyr lowlands, to the north of zone B, are subsiding at rates of ~5–7 mm/yr, while the coastline to the south is subsiding at ~2 mm/yr (Zolotarskaya et al., 1987). The Meingypil'gyn Range is undergoing uplift at 2–5 mm/yr. Uplifted terraces along river valleys show uplift of ~1 mm/yr (Glushkova et al., 1987). These data suggest overthrusting of the Koryak highlands over the Anadyr lowlands. This is consistent with the large number of thrust focal mechanisms from earthquakes farther southwest in the southern Koryak highlands (Lander et al., 1996; Mackey et al., 1997) and with the southward movement of the Gulf of Anadyr region (Fig. 8). Therefore, based on the river offsets and the uplift data, we suggest that the area is under right-lateral transpression.

We also suggest that zone B represents the southern edge of the Trans-Bering seismic belt; right-lateral strike-slip displacement, possibly with a small amount of compression, is occurring in the Gulf of Anadyr and the Bering Strait, and increasing transpression is occurring in the Koryak highlands. This is consistent with the clockwise motion of the Bering Sea plate or block relative to North America about a pole in western Chukotka, as proposed by Lander et al. (1996) and Mackey et al. (1997).

Anadyr–Amguema–Chukchi Sea zone

The Anadyr–Amguema–Chukchi Sea zone (Fig. 7, zone C) represents a band of elevated seismicity that marks the northern edge of the Trans-Bering seismic belt. It extends to the east and west of the northern segment of zone A. Its southern end, near the Anadyr River, is diffuse and has only a little seismicity. It is possible that the zone extends southward to join the seismicity of the Koryak highlands. Teleseisms and microseismicity, largely defined by the Iul'tin data, suggest that zone C extends from the Tanyurer River valley to the north of Egvekinot. From there, zone C is more clearly defined as the northern edge of scattered seismicity across Chukotka to the Kolyuchin Gulf, where it joins the northern segment of zone A. The seismicity then crosses the Chukchi Sea, where there are several teleseismic events, to the De Long Mountains of Alaska.

The moment tensor solution for a magnitude 5.1 event

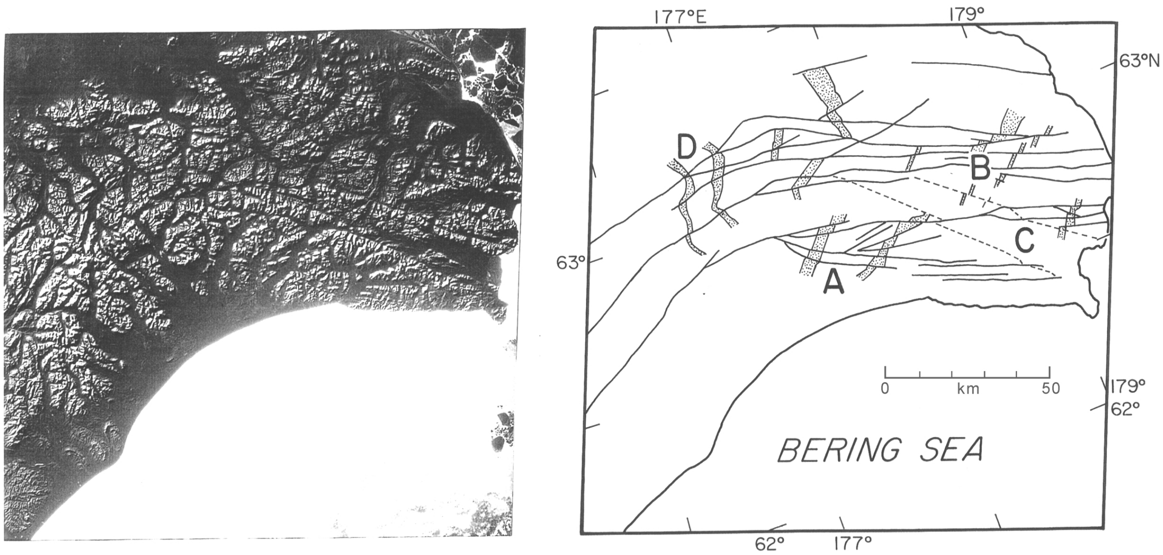

Figure 9. Left: Landsat image of western Koryak highlands and (right) interpreted faults (solid lines) and river offsets (valleys stippled). Dashed lines represent older tectonic grain. A–D: Area discussed in text. The line drawing covers the same area as the photograph.

northwest of Egvekinot in 1995 shows right-lateral strike slip (Fig. 8; Dziewonski et al., 1997a), assuming that the northeast-trending plane ($\varphi = 235°$), which roughly parallels the strike of the zone, is the fault plane. The zone passes through several wide river valleys that are filled with Quaternary sediments; thus few lineaments can be clearly suggested to be of tectonic origin.

Although the continuity of this zone is difficult to assess, this may represent the northwestern and northern edges of the currently active rift and transtensional zone and, therefore, the edge of the rigid North American plate. This zone bounds the Kolyuchin Gulf–Eastern Chukotka seismic zone (zone A) on the northwest. The larger transtensional events from the northern segment of that zone may be along this "cold," newly rifting margin, explaining their greater magnitude.

Other regions

The remainder of Chukotka is aseismic with only a weak background of microearthquakes ($M < 3$; Fig. 7). However, there are several volcanoes believed to be young (e.g., Anyui and Aluchin volcanoes, thought to be younger than 1–2 ka; Rudich, 1985; Fig. 7) 100–200 km south of Bilibino. While volcanoes are particularly well preserved in the Arctic (cf. Balagan-Tas, dated as 286 ka by Layer et al. [1993], but originally thought to be a few thousand years old), this does leave open the possibility that there may have been significant tectonic activity in the region thousands to hundreds of thousands of years ago. On the basis of inferred peneplanation surfaces, Kruglyakov et al. (1987) inferred neotectonic offsets of as much as 500 m on the Keperveyem (KF, Fig. 7) and other faults near Bilibino. No detailed evidence of Holocene geologic movements in the Bilibino area has been published. However, recent field work is reported to have identified landslide features that could have been seismically generated. In 1989–1991, a small local network was deployed around Bilibino to investigate the potential seismic risk to the atomic reactor by the Baikal EMSD (Pavlov et al., 1994). No events with $M > 0.7$ were recorded. We cannot, however, exclude the possibility of significant seismic activity in western Chukotka.

CONCLUSIONS

We suggest that the seismicity in Chukotka forms the central part of a Trans-Bering seismic belt and is characterized by three seismic zones: the Anadyr–Amguema–Chukchi Sea zone (zone C) with earthquakes generally of $M < 5$, representing the edge of rigid North America and the northern boundary of the seismic belt; the Koryak-Provideniya-Seward zone (zone B), representing the transtensional northern boundary of the Bering block and the southern edge of the seismic belt, with events, generally strike slip, of $M < 6$; and the Kolyuchin Gulf–Eastern Chukotka rift zone (zone A) within the seismic belt, with extensional to transtensional events of $M < 7$. The seismicity near Polyarnyi is anthropogenic in origin and should not be included in tectonic analyses (see Appendix).

The continuity of seismicity from the southern Koryak highlands, through Chukotka, to the Seward Peninsula and west-central Alaska strongly suggests that the Bering Sea, which is generally aseismic (Fig. 1), represents a rigid block in motion with respect to North America (Mackey et al., 1997). The eastern boundary of this Bering Sea block is considerably more diffuse, as shown by the widely scattered seismicity in southwest

continental Alaska (Fig. 1). Focal mechanisms indicate extension or transtension in Chukotka and the Seward Peninsula and transtension and compression in the Koryak highlands. This is consistent with the clockwise rotation of the Bering Sea block, relative to North America, about a pole in northwest Chukotka. The driving force for the rifting in Chukotka and the Seward Peninsula could be either backarc extension (e.g., Nakamura et al., 1970) or terrane accretion in southeast Alaska (e.g., Page et al., 1991; Mackey et al., 1997), or some combination of both. However, the backarc spreading model cannot explain the thrusting in the southern Koryak highlands. Thus, we prefer the Bering block model. The magnitude of the relative motion across the various segments of the Trans-Bering seismic belt is unknown, but given the levels of seismicity and tectonic activity, it is presumed to be relatively small (millimeters per year), except possibly in the southern Koryak highlands.

The Chukotka rift zone (zone A) is completely within the Trans-Bering seismic belt and is bounded by strike-slip zones B and C. The Trans-Bering seismic belt between zones B and C to the southwest of zone A must be moving more rapidly to the west than the eastern part in order for the rifting in zone A to occur. This is likely due to the drag from the more rapidly moving Bering Sea block slivering the edge of North America proper.

To the east of zone A, the Trans-Bering seismic belt is dominated by north-south extension (Page et al., 1991). If this region is an analog of the extrusion tectonics of Southeast Asia, as proposed by Mackey et al. (1997), zones B and C are the equivalent of some of the large strike-slip faults of Southeast Asia with a zone of extension between them (e.g., Peltzer and Tapponier, 1988). Alternatively, zone A may represent a region of weakness where differential motions of small blocks and slivers within the Trans-Bering seismic belt result in extension.

Studies are currently in progress to remove the artificial data barrier that existed between far-eastern Russia and Alaska until the 1990s; this will greatly improve our knowledge of how the seismicity of Chukotka relates to that of the Seward Peninsula. Additional phase data will be required before meaningful relocations of western Alaskan and Trans-Bering events can be obtained; previously determined epicenters are known to have significant location errors (Page et al., 1991; Mackey, 1999). The reopening of Bilibino as an Incorporated Research Institutions for Seismology Global Seismic Network station in 1995, and of Anadyr (ANYS, Fig. 5) in 1997 by the Magadan EMSD, and future cooperation between Alaska and northeastern Russia in data exchange will, undoubtedly, improve our understanding of the seismicity of this complex region.

ACKNOWLEDGMENTS

This study was conducted as part of a cooperative research program between the University of Alaska, Michigan State University, the Northeast Interdisciplinary Scientific Research Institute (Magadan, Russia), and the Yakutian Institute of Geological Sciences (Yakutsk, Russia). We thank David Cook, Alexandra DeJong, Dimitry Gunbin, Boris Koz'min, Paul Layer, Erin Lynch, Melissa McLean, Elizabeth Miller, Ken Ridgway, David Stone, Jaime Toro, Guy Tytgat, Bruce Watson, Robert Young, the late Lev Zonenshain, and two anonymous reviewers for helpful discussions, comments, and criticisms on various parts of this work. This research was supported by National Science Foundation grants OPP- 94–24139 and OPP-98–06130. Data acquisition was supported by the Incorporated Research Institutions for Seismology Joint Seismic Program.

APPENDIX: CONTAMINATION OF THE SEISMICITY CATALOG BY EXPLOSIONS

With the opening of the Iul'tin station, considerable seismic activity was located near the Polyarnyi placer gold mining district and in the Ekvyvatap Range, ~200 km northwest of Iul'tin (Fig. 4). The events were located from 1969 to 1982. Based on these data, this region was considered the most seismically active in Chukotka. However, this activity is coincident with the expansion of mining at Polyarnyi starting in 1968 and is likely to be anthropogenic.

The anthropogenic nature of the events near Polyarnyi can be demonstrated by examining the temporal variation in seismicity (Godzikovskaya, 1995; Mackey and Fujita, 1999). Explosions in placer mines are normally conducted in daytime hours in the late winter and spring to break up frozen ground for summer extraction activities; a few night explosions also occur. Figure A1a shows the temporal distribution of Iul'tin-located events for the Polyarnyi region and clearly shows a bias similar to that for known explosions from the NEISRI network period (Fig. A1b). First motions from a sequence of events in 1978 yielded compressional first motions at Iul'tin (Lazareva, 1982), also supporting an explosion origin. Given the location error associated with the single-station Iul'tin epicenters, all of the events in the Ekvyvatap Range can be ascribed to the Polyarnyi gold or the Plammenyi mercury mines (Fig. 4). Explosions here generally yield magnitudes of M = ~2.0 or less (Godzikovskaya, 1995).

The NEISRI network data show very little seismicity in this region. A total of 15 earthquakes are cataloged between Polyarnyi and Plamennyi in the same areas as the Iul'tin-located events. These events are also the same size (M = 2.0–2.3) and have the same temporal distribution as known explosions. Other events with explosion characteristics within a few hundred kilometers of a station are identified as such by NEISRI network operators and excluded from seismicity catalogs.

Extension of the temporal analysis to other parts of Chukotka shows no significant biases in the Iul'tin or NEISRI data sets except for a few explosions associated with exploratory drilling for the construction of a hydroelectric station across the Amguema River (Godzikovskaya, 1995) in 1981–1984.

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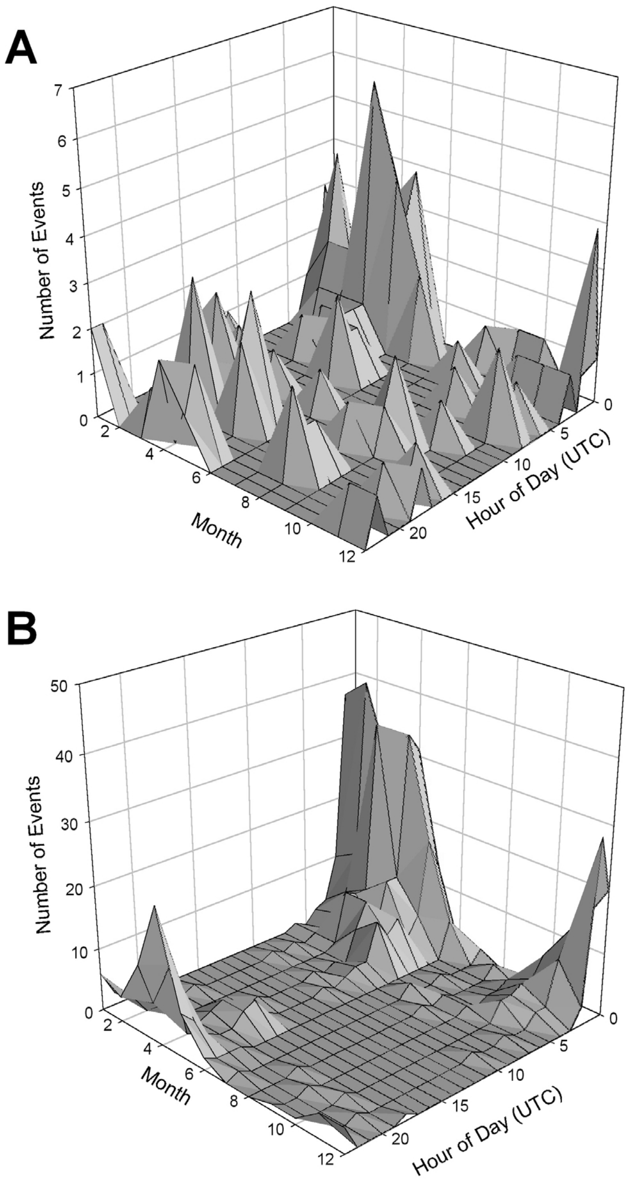

Figure A1. Temporal distribution of (A) events from Polyarnyi region located by Iul'tin station (1966–1982) and (B) explosions identified by Northeast Interdisciplinary Scientific Research Institute (NEISRI) station operators (1983–1996).

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Manuscript Accepted by the Society May 15, 2001.

Printed in the U.S.A.