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Seismicity Map of Eastern Russia, 1960–2010

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Online material: Large-format downloadable version of the seismicity map and additional discussion about data sources, quality of epicenters and magnitudes, and completeness levels of the seismicity catalogs.

INTRODUCTION AND TECTONIC SETTING

One of the last unknown plate boundaries of the global plate system lies between the North American and Eurasian plates in Eastern Russia. This is a tectonically complex region that is poorly understood (*e.g.*, Chapman and Solomon 1976, Cook *et al.* 1986; Steblov *et al.* 2003; Apel *et al.* 2006) due, in part, to a historic lack of available seismological data, especially within the continental regions. As part of a cooperative program between Michigan State University (MSU) and regional networks and scientific institutes in eastern Russia, we have compiled a detailed database (Eastern Russia Seismicity Database, hereafter ERSD) and seismicity map of eastern Russia. This database covers the region from Lake Baikal to the Bering Strait, using data from local and regional seismograph networks, as well as standard international sources. The distribution of seismicity, though diffuse, improves constraints on the enigmatic plate boundaries in the region.

As with many intracontinental plate boundary regions (*e.g.*, Stein and Sella 2002), the plate boundaries in eastern Russia are diffuse and contain blocks or microplates. Figure 1 shows the three major plates (Pacific, Eurasia, North America) interacting in the region, as well as three of the more commonly proposed microplates between them: Amur (*e.g.*, Heki *et al.* 1999; Mackey *et al.* 2003), Bering (*e.g.*, Mackey *et al.* 1997, 2009; Fujita *et al.* 2002; Cross and Freymueller 2008), and Okhotsk (*e.g.*, Chapman and Solomon 1976; Riegel *et al.* 1993; Seno *et al.* 1996; Fujita *et al.* 2009). We also discriminate a possible block comprising the easternmost Amur plate, separated by the Tanlu fault (Mackey *et al.* 2003), as well as a block in the Laptev Sea (*e.g.*, Avetisov 1996). Recent regional tectonic syntheses based on GPS data (*e.g.*, Steblov *et al.* 2003; Apel *et al.* 2006) and seismicity (*e.g.*, Déverchère *et al.* 1993 and Petit *et al.* 1996 for Baikal; Fujita *et al.* 2009 for the Chersky Range) discuss the motions of these microplates. Figure 1 also shows representative focal mechanisms (*e.g.*, Doser 1991; Fujita *et al.* 2009; Global Centroid Moment Tensor Catalog (GCMT); and many others) along the proposed plate boundaries.

HISTORICAL SEISMICITY

Prior to the 1950s, seismograph stations in eastern Russia were sparsely distributed, and thus only teleseismic activity ($\mathbf{M} > 4.5$) was noted. Large events had occurred (*e.g.*, sequences of $\mathbf{M}$ ~7 near the Lena River delta and off Chukotka in the 1920s); however, only the mainshocks were usually recorded, and even then poorly located. In the 1950s, four seismograph stations were deployed in northeastern Russia, which began to improve seismic coverage of the region; however, as recently as the 1960s, the detection completeness threshold was likely only around $\mathbf{M} = 5$ (Fujita *et al.* 1990).

Figure 2 shows a compilation of historical seismicity through 1959. These epicenters may have errors of ±100 km or more. Pre-instrumental (1725–1920) epicenters, shown in yellow, were often located at the nearest settlement, and thus their epicenters should be viewed with care. Although the general trend of the seismicity is apparent, primarily in the Chersky

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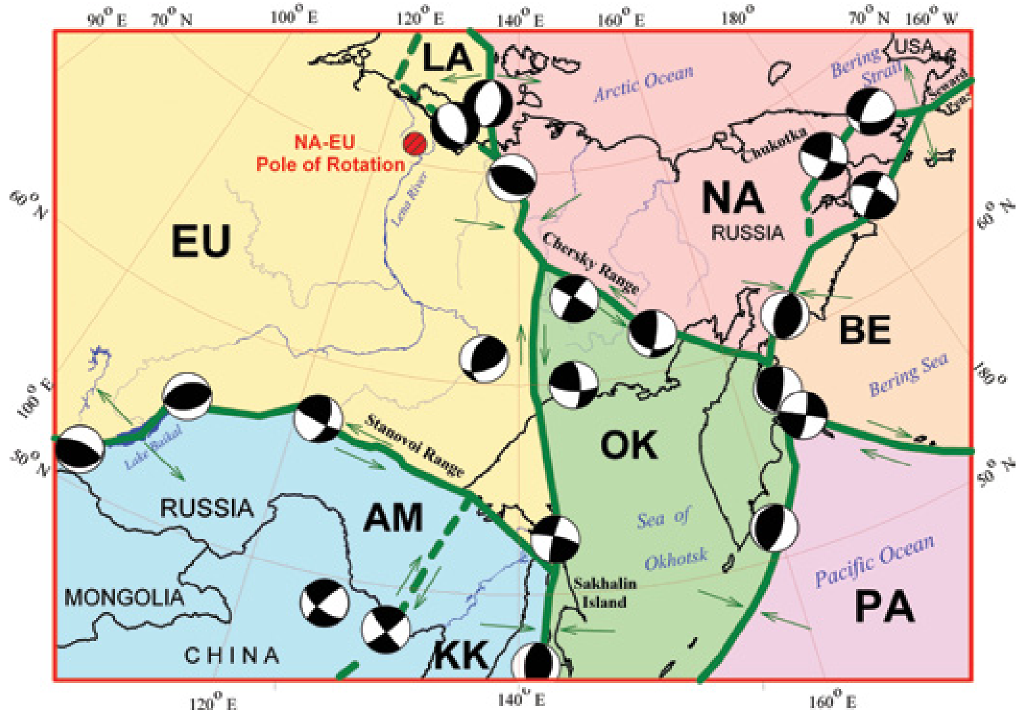
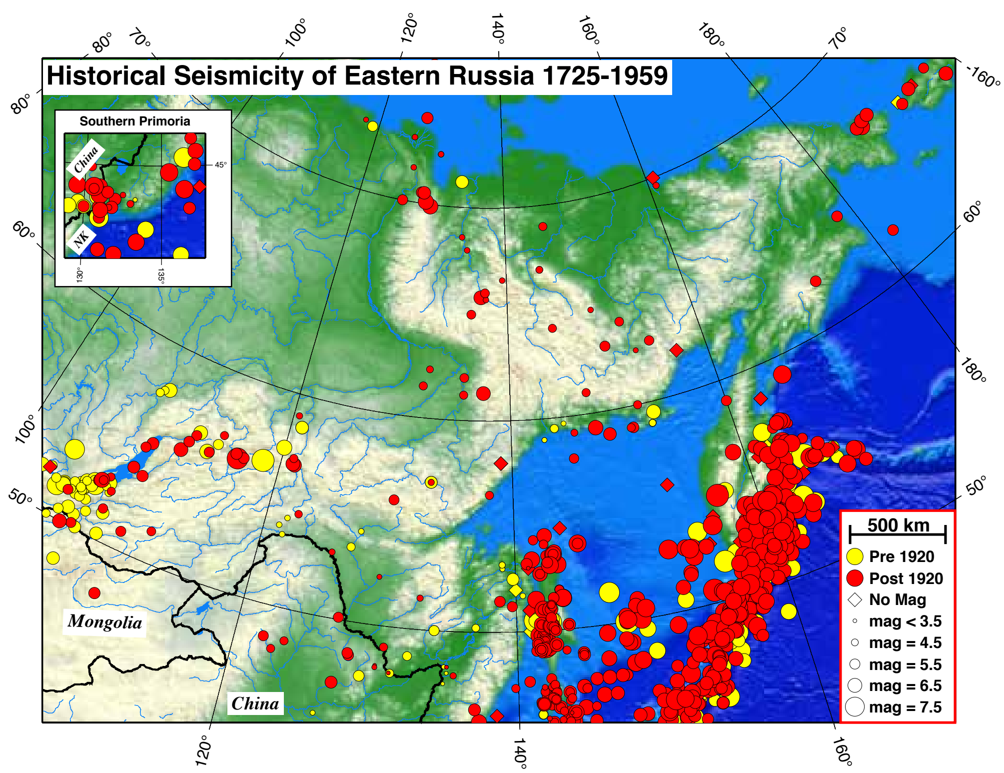
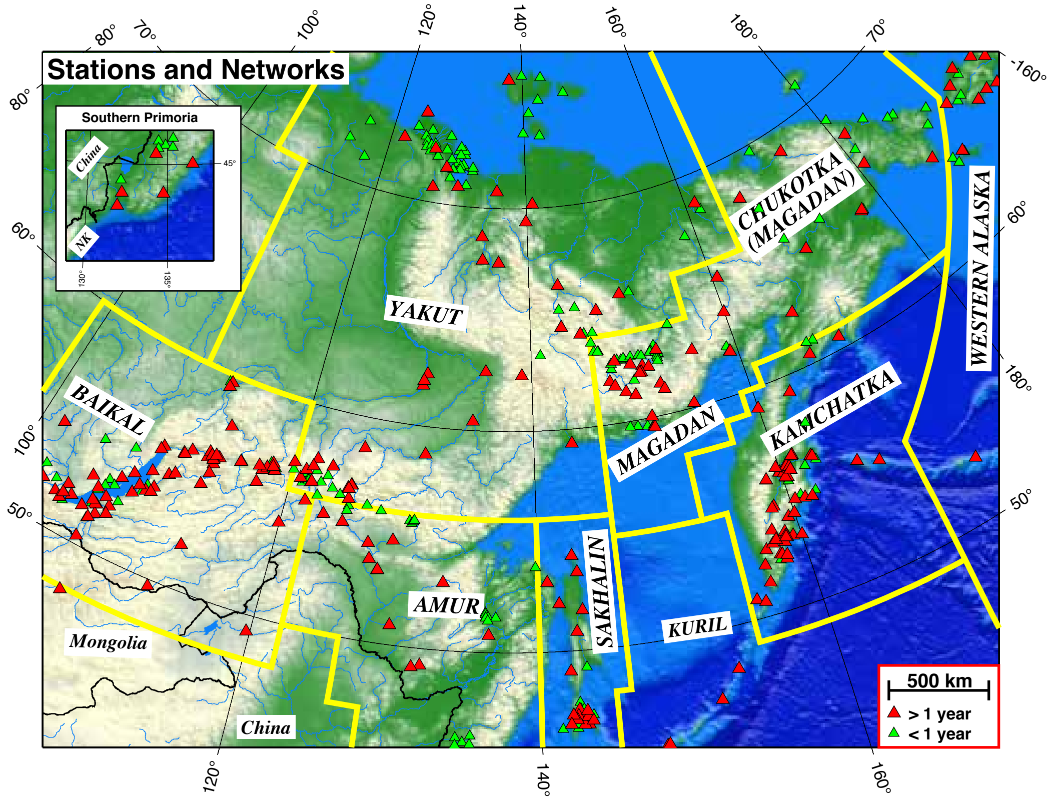


▲ **Figure 1.** Generalized plate tectonic scheme and location map of eastern Russia. Plate and microplate boundaries shown as solid green lines. Dashed green lines show boundaries of possible blocks. Approximate North America–Eurasia pole of rotation shown by red circle (Calais *et al.* 2003; Cook *et al.* 1986). Representative lower hemisphere focal mechanisms for earthquakes are shown (compressional quadrant shaded). Plate abbreviations: NA–North America, EU–Eurasia, PA–Pacific, OK–Okhotsk, AM–Amur, BE–Bering. Blocks: KK–Korea-Khabarovsk, LA–Laptev. International boundaries are in black.



▲ **Figure 2.** Historical seismicity, 1725–1959. Instrumentally recorded (post-1920) events are shown in red and pre-instrumental epicenters (1725–1920) are shown in yellow. Events are not discriminated by focal depth. Dots are scaled by magnitude. Data from Kondorskaya and Shebalin (1977, 1982) and other sources (see electronic supplement).



▲ **Figure 3.** Map of regional networks and seismograph stations in eastern Russia. Network boundaries, which also correspond to seismicity regions, are shown in yellow. Seismograph stations that operated for greater than one year are shown by red triangles. Temporary deployments and stations with operational durations of less than a year are shown by green triangles. Station coordinates are from *Zemletryaseniya v SSSR* and its successor publications (see electronic supplement), regional seismic bulletins, reports, Starovoit and Mishatkin (2001), site visits, and individual network archives. Not all stations or networks operated simultaneously and not all short-term deployments are shown.

Range and from Lake Baikal to Sakhalin, as well as in the subduction zones along the Pacific margin, the level of seismicity is low and the seismically active zones appear discontinuous. There are also events located in regions that have not seen a similar level of activity since 1960, specifically the northern Sea of Okhotsk and western Chukotka.

REGIONAL NETWORKS

Starting in the early 1960s, regional seismograph networks (Baikal, Sakhalin, Kuril, Kamchatka, and Yakut; later Magadan, including Chukotka, and Amur; Figure 3) were deployed throughout eastern Russia. The Kuril and Amur networks were operated by the Sakhalin network. Each network operated independently and used its own location and quantification procedures. Data were often not exchanged between adjoining networks, and thus events at the edges of networks tended to be missed, duplicated, or poorly located. The networks submitted their results to the Institute of Physics of the Earth (later, to the Geophysical Survey of Russia), which used the data to develop annual compilations and seismic hazard maps of the territory (*e.g.*, Medvedev 1976, and subsequent updates).

Figure 3 shows the spatial extent of the areas of responsibility for the regional seismograph networks operating today under the auspices of the divisions of the Geophysical Survey of Russia in eastern Russia, and the distribution of seismograph stations over the period 1960–2008. The network boundaries and seismic regions are described in Kondorskaya and Shebalin (1977, 1982) and Rautian *et al.* (2007) (see electronic supplement).

Short-term and temporary deployments were conducted for detailed seismicity studies for special projects, such as the construction zone of the Baikal-Amur railroad in the Baikal region (*e.g.*, Golonetsky 1978), as well as for experimental deployments at both local and regional levels (*e.g.*, Andreev *et al.* 1967), and aftershock studies (*e.g.*, Koz'min 1984).

PRIOR COMPILATIONS OF REGIONAL SEISMICITY

The seismicity of northeastern Russia (Sakha Republic [Yakutia] and the Magadan district, including Chukotka) was generally considered part of Arctic seismicity and included in early maps and compilations thereof by both Russian and western seismologists (*e.g.*, Linden 1962; Sykes 1965; Tarr 1970).

Maps showing seismicity recorded by the regional networks were published in the annual *Zemletryaseniya v SSSR* starting in 1962; however, no overall, multiyear compilations of this regional data were published in subsequent years. Koz'min and Larionov (1975) published a low-resolution map

of all regional and local seismicity in eastern Russia, which was improved and updated over the years (Koz'min 1984; Parfenov *et al.* 1988; Imaev *et al.* 1990, 2000).

Although the regional seismograph networks have been in operation in the region for nearly 50 years, and volumes of information collected, seismicity data for much of eastern Russia have been sparse in the international bulletins and catalogs from which most seismicity maps have been compiled. Figure 4 shows data available from the *International Seismological Centre (ISC) Bulletin* (1960–2006); some regional network data for larger events from eastern Russia have been contributed to the ISC since the mid-1990s (see electronic supplement).

EXPLOSION CONTAMINATION

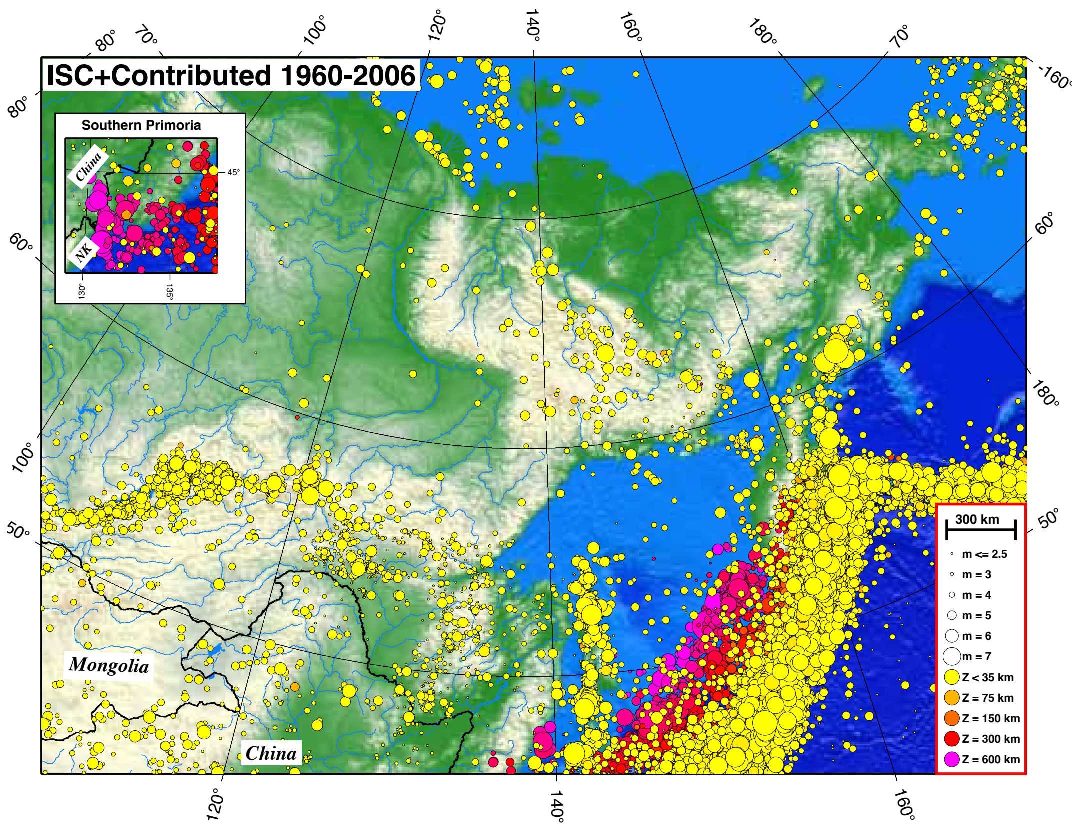
The eastern Russian seismicity catalog is known to be contaminated with small (magnitude < 3) explosions associated with mining and construction (*e.g.*, Godzikovskaya 1995; Odinets 1996; Mackey *et al.* 2003). Although numerous events have been flagged as chemical or industrial explosions in the original Russian data, many were not.

Due to the sheer number of events, it is impossible to individually re-examine seismograms to discriminate explosions and natural earthquakes. To establish areas where the database is contaminated by explosions, we calculated the percentage of daytime and nighttime occurring events in 0.5° latitude by 1° longitude grid boxes. A high fraction of daytime occurring events are consistent with explosions, and not tectonic processes (Mackey *et al.* 2003). Figure 5 shows the distribution of these areas by the percentage of events that occurred during daytime (7 a.m. to 7 p.m. local time, which approximately corresponds to working hours) or nighttime hours. Many of the areas of dominantly daytime seismicity can be associated with specific mines, quarries, or construction projects (Mackey *et al.* 2002, 2003). In seismically active regions, however, the number of explosions, even if they are numerous, may not be significant relative to natural earthquakes; in those areas contamination may not be identified and not shown in Figure 5 (note areas in Figure 5, such as the Chersky Range, with many known chemical explosions, but not identified in our temporal analysis).

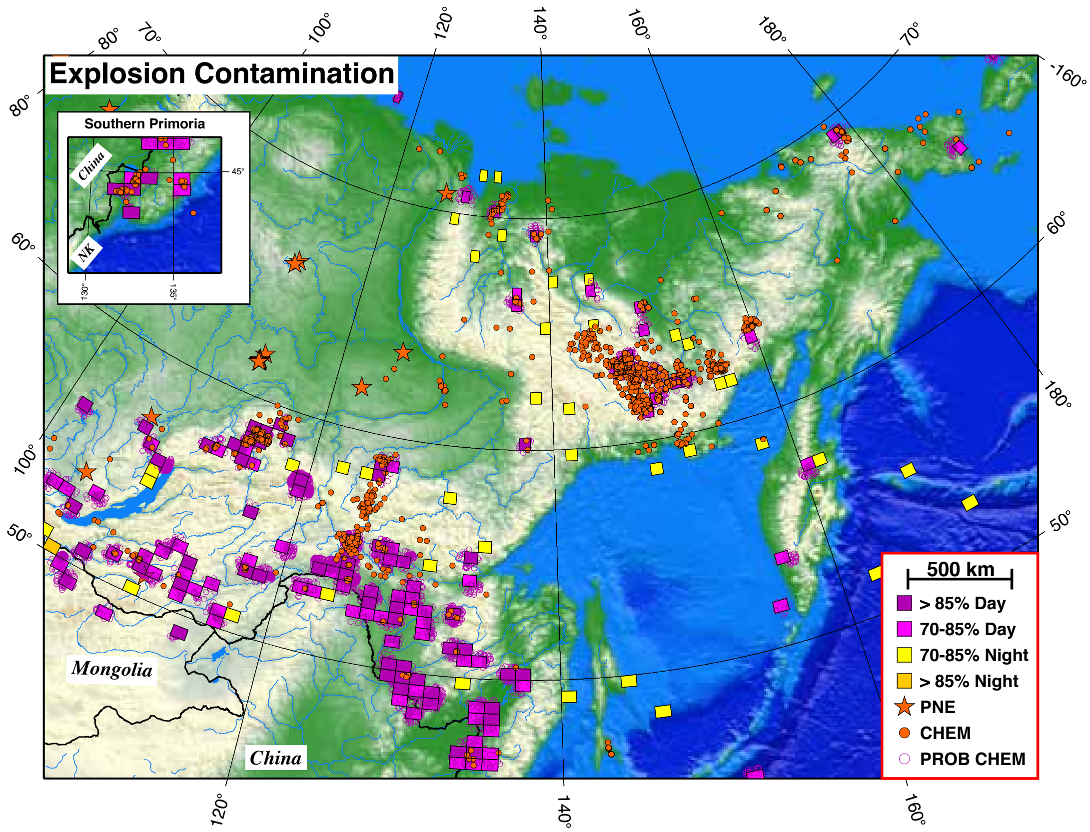
SEISMICITY MAP OF EASTERN RUSSIA

Based on the seismicity catalog developed from the ERSD, we here present a regional seismicity map of eastern Russia for the past fifty years (Figure 6). To avoid the common data gap along the international boundary between the United States and Russia in the Bering Strait region, data from the Seward Peninsula of western Alaska are also included.

Figure 6 depicts more than 333,000 earthquakes that occurred between 1960 and 2010 and shows a level and extent



▲ **Figure 4.** Map of seismicity in eastern Russia as reported in the International Seismological Centre Bulletin, 1960–2006. Events reported by the ISC are shown by circles scaled by magnitude. Generally, the smaller events (**M** < 4.5) are from contributed sources, specifically the Russian regional networks (see electronic supplement).



▲ **Figure 5.** Map of known and suspected explosion contamination in the Eastern Russia Seismicity Database (ERSD). Darker colors of grid boxes (0.5° latitude by 1° longitude) indicate a greater percentage of events occurring in daylight hours. Purple boxes indicate cells with >85% daytime events based on 10 or more events; magenta cells have 70–85% daytime events, yellow cells have 70–85% of events occurring during local nighttime, and orange cells have >85% of events occurring during local nighttime. Areas with >70% daytime events are likely regions where industrial and mining explosions have been included in the ERSD. Daytime events within and near areas having a high percentage of daytime events are shown by purple circles, and are presumed to be chemical explosions (Mackey *et al.* 2002, 2003). Events identified in the Russian sources as chemical explosions are shown as small orange dots. Orange stars indicate "peaceful nuclear explosions" (see Fujita 1995, for events in the Sakha Republic [Yakutia]) detonated for scientific and economic purposes.

of seismicity that is higher than generally recognized in the global seismological community (compare Figures 2, 4, and 6). Most events are plotted according to the epicentral locations provided by the regional networks; however, relocated epicenters were used when available (see electronic supplement). Events in the continental region have crustal focal depths, shallower than 35 or 40 km, and are often fixed at 10 km. Magnitudes were taken from teleseismic sources; for regional and local events, Russian K-class (energy class) values were converted to magnitude using regressions from Rautian *et al.* (2007; also see electronic supplement).

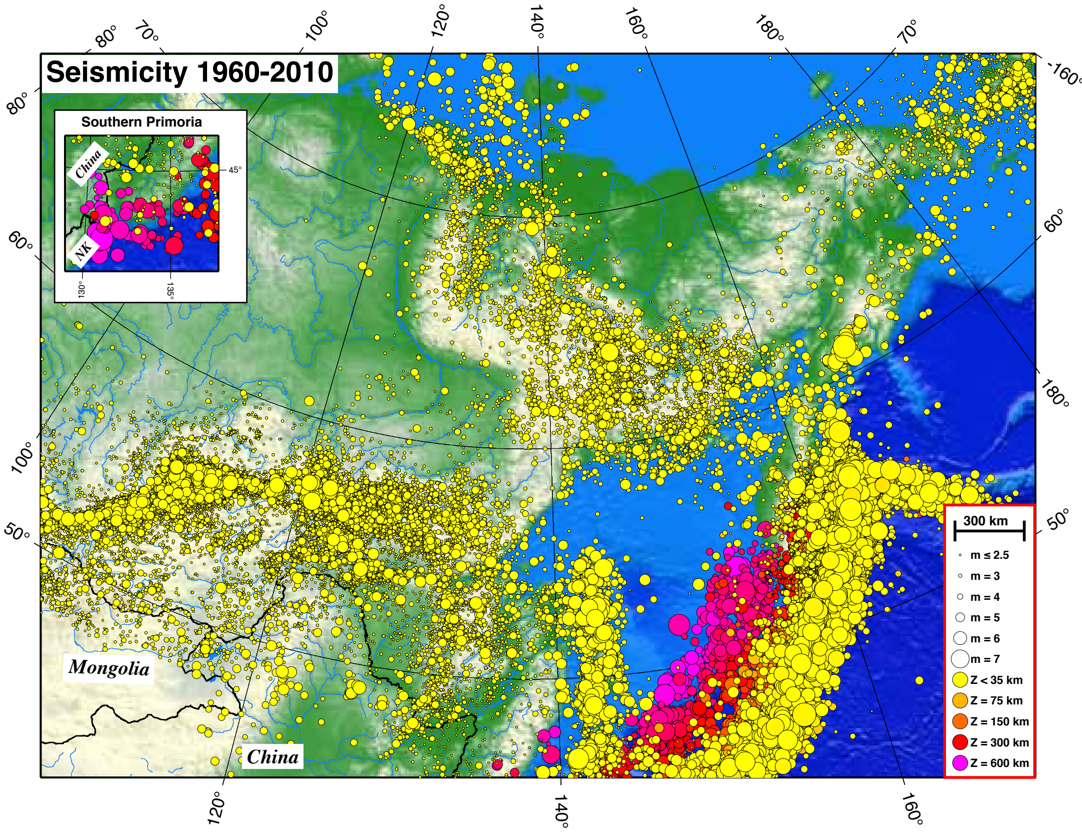
Seismicity shown within China, Mongolia, and the Aleutian Islands (east of the U.S.–Russia border) only include events found in the compiled Russian sources. Events in these areas from international, Chinese, Mongolian, and U.S. sources have not been plotted.

It should be noted that variations in the spatial and temporal distribution of seismograph stations have likely affected the details of the microearthquake seismicity in many areas. In general, the map is probably complete (see electronic supplement) down to the magnitude 3.0–3.5 level since 1970 in continental Asia (Magadan, Yakutia) with higher values for Kamchatka and Sakhalin (about magnitude 3.5–4.0), and the Kuriles (around magnitude 5).

DISCUSSION

The subduction zone beneath Kamchatka and the Kuril Islands is clearly delineated on the map, but there are broad regions of diffuse seismicity in the continental regions that were previously poorly known, and are presumed to represent regions of distributed deformation between the major plates and microplates (Figure 1). However, the interpretation of many of the smaller-scale features that appear in this map should be considered with care in light of the heterogeneous nature of the data set.

Two interesting features of the seismicity distribution in Figure 6 should be noted. First, there is the lack of significant seismicity in the northwestern Sea of Okhotsk along the northern part of the Okhotsk-Eurasia plate boundary (Fujita *et al.*



▲ **Figure 6.** Seismicity map of eastern Russia and adjacent regions, 1960–2010. Symbol size is proportional to magnitude, and focal depth is shown by colors (deeper colors represent deeper events). Known and probable industrial explosions, based on Figure 5, have been omitted.

2009), which has also commonly been used as the boundary between North America and Eurasia (Chapman and Solomon 1976, among many others). Second, there is a diffuse but continuous zone of seismicity that extends northeast from the Kamchatka-Aleutian arc-arc junction toward the Seward Peninsula of western Alaska along the proposed western edge of the Bering Plate (Mackey *et al.* 1997; Fujita *et al.* 2002; Cross and Freymueller 2008).

CONCLUSIONS

This map presents a compilation of the seismicity in eastern Russia that is the result of nearly two decades of cooperation between U.S. and Russian investigators. It demonstrates that the level of microearthquake seismicity in continental eastern Russia is much greater than generally known and that the vast majority of the events fall primarily in diffuse zones that separate major and minor tectonic plates and blocks in the region (compare Figures 1 and 6).

The degree of location accuracy precludes, in most cases, the association of events with specific faults; however, this map indicates that deformation and faulting in the region is complex. Further work is needed to study individual subregions in detail and to explain the details of the seismicity distribution. This map, however, provides an important step in the analysis of the tectonics of this complex region.

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DATA AND RESOURCES

Much of the seismicity data presented here are publicly available. Seismicity catalogs are available through the *International Seismological Centre Bulletin 1964-2007* (http://www.isc.ac.uk/search/index.html); *Zemletryaseniya v SSSR (Earthquakes of the USSR), 1962–1991,* published annually in

Moscow by Nauka (in Russian); and the Geophysical Survey of Russia, the University of Alaska, and the U.S. Geological Survey. Focal mechanism data are available from the *Global Centroid Moment Tensor Catalog* (http://www.globalcmt.org/CMTsearch.html). Other data are from the archives of the regional networks in eastern Russia. Data sources are described more extensively in the electronic supplement.

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