Challenges in Making a Seismic Hazard Map for Alaska and the Aleutians

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We present a summary of the data and analyses leading to the revision of the time-independent probabilistic seismic hazard maps of Alaska and the Aleutians. These maps represent a revision of existing maps based on newly obtained data, and reflect best current judgments about methodology and approach. They have been prepared following the procedures and assumptions made in the preparation of the 2002 National Seismic Hazard Maps for the lower 48 States, and will be proposed for adoption in future revisions to the International Building Code. We present example maps for peak ground acceleration, 0.2 s spectral amplitude (SA), and 1.0 s SA at a probability level of 2% in 50 years (annual probability of 0.000404). In this summary, we emphasize issues encountered in preparation of the maps that motivate or require future investigation and research.

1. INTRODUCTION

This paper summarizes the recent revision of the earlier seismic hazard map of Alaska and the Aleutians [*Wesson et al*., 2007, 1999a, 1999b] with emphasis on the outstanding geologic and geophysical challenges requiring additional investigation and research. These challenges may be divided into two groups, gaps in data and gaps in understanding, that is, areas in which the current paradigms for seismic hazard estimation require improvement as they are applied in Alaska.

2. EARTHQUAKE HISTORY AND PLATE TECTONIC SETTING

The instrumental seismicity of Alaska and the Aleutians for earthquakes since 1900 greater than or equal to magnitude 5.5 is shown in Plate 1. Clearly, most of the seismicity in the region is associated with the Alaska–Aleutian megathrust fault (Plate 2) that extends eastward along the Aleutian arc into south-central Alaska. The northwestward-moving Pacific plate is subducted along this megathrust beneath the North American plate, with relative plate motions from 47 to 75 mm/yr, giving rise to the Aleutian Trench, islands, and related seismic and volcanic activity. Additional significant seismicity occurs along the Denali fault in south-central Alaska, and along the Fairweather–Queen Charlotte system of right-lateral strike-slip faults that extends southeastward along and offshore from the panhandle of southeast Alaska [*Page et al*., 1991]. This system of faults forms the northeast boundary of the Pacific plate. Additional seismicity also occurs elsewhere in central Alaska.

The estimated rupture zones of the largest earthquakes since 1900 are also shown in Plate 1 [*Plafker et al.*, 1993; *Ratchkovski et al*., 2004]. During this period, virtually the entire plate boundary from the westernmost Aleutian Islands to the Queen Charlotte Islands off British Columbia has ruptured in earthquakes large enough to rupture through the plate. The only three exceptions are areas near the Komandorski Islands (where no large earthquake occurred during this period), near the Shumagin Islands (where the largest

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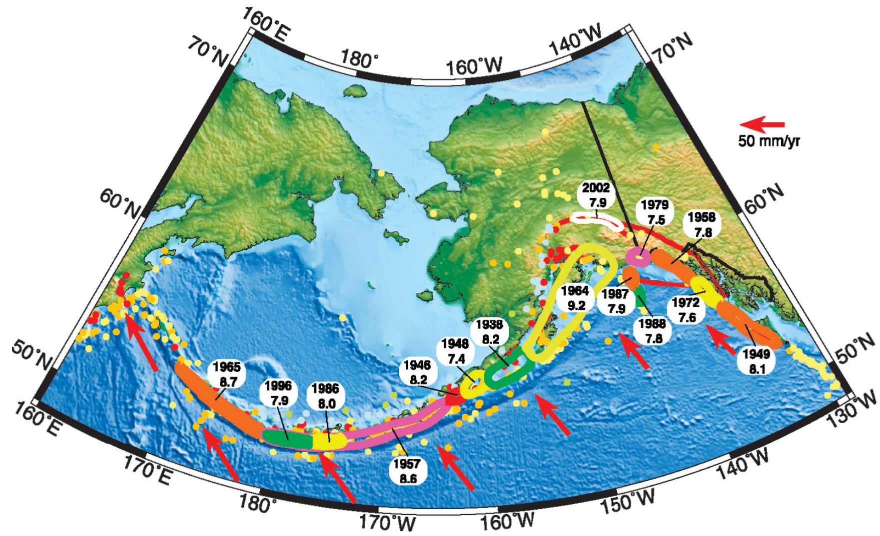

Plate 1. Instrumental seismicity of Alaska and the Aleutian Islands with aftershocks removed. The preparation of this declustered catalog is described by *Wesson et al.* [2007]. Circles show earthquakes with magnitudes $M_w \geq 5.5$ and dates ranging from 1960 to 2004 (depths: yellow, 0–25 km; orange, 25–50 km; red, 50–100 km; light blue, 100–200 km; green, 200–300 km). Rupture areas shown for large earthquakes in Alaska and the Aleutian Islands from 1900 to 2004. Magnitudes adjusted according to *Johnson et al.* [1994]. Principal active faults are shown in red. Arrows show motion of Pacific Plate relative to North America.

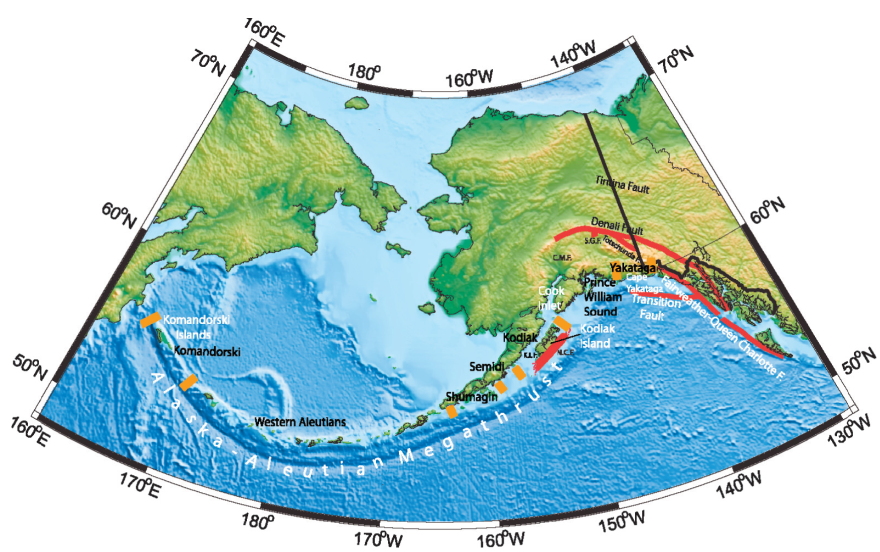

Plate 2. Schematic map of Alaska and Aleutians showing selected crustal faults used in calculation of seismic hazards (shown in red) and geographic features referred to in text and segments of megathrust discussed in text. Neither the Tintina fault (shown in yellow) nor the Susitna Glacier fault (denoted by S.G.F.) is explicitly included in the hazard map. The Castle Mountain, Kodiak Island, and Narrow Cape faults are denoted by C.M.F., K.I. F., and N.C. F., respectively. The offshore extents of the Kodiak Island and Narrow Cape faults are poorly understood. Orange line segments indicate the boundaries of the segments of the megathrust discussed in the text. Segment names are in large black letters.

event in this period was a magnitude 7.4), and near Cape Yakataga [*Sykes*, 1971; *Davies et al*., 1981]. Three large earthquakes occurred in the region of Cape Yakataga and the Transition fault in 1899, but despite recent work [*Doser*, 2006] significant uncertainty remains in their locations.

The broad-scale stress system causing earthquakes in Alaska and the Aleutians can be seen in Plate 1, in which are plotted the motion vectors for the Pacific plate relative to the North American plate from GSRM v1.2 [*Kreemer et al*., 2003; http://sps.unavco.org/crustal_motion/dxdt/model]. Evident in Plate 1 is the gradual transition from near perpendicular subduction in the Prince William Sound and eastern Aleutian regions to oblique subduction in the far western Aleutian and Komandorski Island region.

3. METHODOLOGY

A probabilistic seismic-hazard analysis combines estimates of the frequency of occurrence of earthquakes from possible sources, such as faults, together with estimates of the strong ground motion given magnitude and distance from the source [*Cornell*, 1968; *Frankel et al*., 2002]. Currently, there are no attenuation relations (sometimes referred to as ground-motion prediction equations) specific to Alaska, so relations from other regions are assumed. Details may be found in the report of *Wesson et al.* [2007] and are not discussed further in this paper. Three categories of sources are considered: (1) the Alaska–Aleutian megathrust, (2) well-located active crustal faults, and (3) poorly located or unknown sources. Estimates of future seismicity from the first and second categories are based on source-specific analysis of seismologic and geologic data. Estimates of future seismicity for the third category are based entirely on the statistical treatment of instrumentally observed seismicity. This approach is referred to as "smoothed seismicity" [*Frankel*, 1995].

4. REGIONAL ANALYSIS OF SEISMIC SOURCES

4.1. Megathrust and Subduction Zone

Two particularly troublesome issues that must be faced in assessing the seismic hazard of the Alaska–Aleutian subduction zone are (1) the role of aseismic slip and (2) the question of the persistence of the boundaries between adjacent ruptures. Although the overall rate and direction of slip along the megathrust are well known, a significant but poorly known fraction of the slip occurs without earthquakes, that is, as aseismic slip. This fraction also seems to vary with position along the megathrust. For example, currently most, if not virtually all, of the slip is accommodated by aseismic slip in the Shumagin Island region [*Freymueller and Beavan*, 1999; *Fournier and Freymueller*, 2007], persuading some observers that a very large earthquake is unlikely in this region. In contrast, there is currently almost no aseismic slip occurring in the Prince William Sound region [*Fletcher et al*., 2001; *Cohen and Freymueller*, 2004), site of the 1964 M_w 9.2 earthquake. There are also some indications that the amount of aseismic slip may vary with time [*Bürgmann et al*., 2005]. The presence of a large, but unknown amount of aseismic slip confounds the application of moment balancing schemes to estimate the frequency of large earthquakes, such as are used elsewhere [e.g., *Frankel et al.*, 2002]. In the absence of paleoseismic data, the uncertain amount of aseismic slip motivates estimates of frequency based purely on historical and/or instrumental observations.

Similarly, the classic notion of the characteristic earthquake, as commonly used in hazard analysis, is predicated on the assumption that the limits of ruptures are more or less persistent through time (commonly referred to as fault segmentation). In contrast, the record of large earthquakes in the western Aleutians in the 20th century suggests that the limits of ruptures are not persistent through time, for example, the overlapping ruptures along portions of the western Aleutians in 1957, 1986, and 1996 (Plate 1). The concept does, however, find some support in the eastern part of the megathrust in the Prince William Sound region. Recent studies [*Hamilton and Shennan*, 2005; *Hamilton et al*., 2005; *Shennan and Hamilton*, 2006] refine earlier estimates to suggest six great earthquakes similar to 1964 in a period of 3300 years for an average recurrence time of about 650 years. A complicating factor, however, is that the Kodiak Island region of the megathrust, which ruptured during the 1964 earthquake and is inferred to have also ruptured in previous 1964-type earthquakes, also seems to have ruptured more frequently [*Nishenko and Jacob*, 1990; *Carver et al*., 2003; *Sauber et al*., 2006].

Near the Komandorski Islands, historical records of large earthquakes in 1849 and 1858 at the extreme western end of the arc have been judged as insufficient to conclude that plate-margin-rupturing earthquakes have occurred there [*Sykes et al*., 1981; *Taber et al*., 1991]. At this location, subduction is occurring at a highly oblique angle, and it has been argued that the recurrence properties of large earthquakes here may differ significantly from those elsewhere along the arc. Indeed, *Cormier* [1975] has argued that the region may be incapable of supporting a great earthquake, although in light of the 2004 Sumatra–Andaman Islands earthquake, we chose to revisit this interpretation and to admit the possibility of large earthquakes in this region.

Table 1 summarizes the properties ascribed to portions of the megathrust in the recent revision of the hazard map. We generally followed the approach of *Wesson et al.* [1999], for

Table 1. Summary of Properties Assumed for Different Portions of the Alaska–Aleutian Megathrust

Region	Komandorski Islands	Western Aleutians	Shumagin	Semidi	Kodiak Islands	Prince William Sound	Yakataga
Approximate limits (longitude on north edge of arc)	165°E–171°E	171°E–163°W	163°W–158°W	158°W–154°W	154°W–151°W	151°W–144°W (South); 148°W (North)	145°W–139°W
Largest historic earthquake(s) (M_w) and year	???	8.7 1965 8.6 1957	7.4 1948	8.2 1938	9.2 1964 (together with PWS)	9.2 1964	8.1? 1899?
Current state of coupling	Unknown, but assumed coupled	Assumed high	Significantly uncoupled	Assumed high	Assumed high	Apparently high	Assumed high
Persistence of rupture boundaries	???	Low	Large earthquake assumed not to rupture through region	Assumed high	High, except will rupture with PWS	Assumed high	Unknown
Estimated maximum magnitude	9.2	9.2	8	8.5	8.8 (alone) 9.2 (with PWS)	9.2	8.1
Magnitude–frequency characterization for subregion (*a*, *b*)	8–9.2 2.69, 0.773	8–9.2 3.16, 0.66	7–8 (see note below)	8–8.5 2.4, 0.710	Characteristic 8.8 5.987,1.00	Characteristic (includes Kodiak) 9.2 6.387, 1.000	7–8.1 2.18, 0.666

All segments of the megathrust including the Shumagin and Prince William Sound segments but excluding Yakataga are assumed to produce earthquakes following a truncated Gutenberg–Richter distribution between magnitude 7.0 and 8.0 with aggregate values of *a* and *b* (i.e., for the entire region) of 3.54 and 0.689. PWS, Prince William Sound.

example, combining models for the characteristic behavior on the Prince William Sound portion of the megathrust with truncated Gutenberg–Richter models, and truncated Gutenberg–Richter models alone in the western Aleutians. The parameters for the truncated Gutenberg–Richter models were estimated from the statistics of instrumentally observed earthquakes. Additional details and references are provided by *Wesson et al.* [2007]. Although these properties reflect the best current understanding of the hazard associated with the megathrust, advances in knowledge, particularly related to aseismic slip and the persistence of rupture boundaries, could lead to significant revisions.

4.2. Crustal Faults

4.2.1. Transition fault. The Transition fault is a thrust/oblique-slip fault and likely an important component of the tectonics in the transition from strike-slip displacement along the western margin of the Pacific plate off southeast Alaska, to thrust displacement along the Alaska–Aleutian megathrust to the west. Owing to the fault's location completely beneath the Gulf of Alaska, both the geometry and the slip rate of the fault are poorly understood and in need of further investigation. Given the limited knowledge, this fault might not have been included in the map were it not for its potentially important contribution to the hazard.

Review of the plate tectonic and geodetic constraints on the slip rate [*DeMets and Dixon*, 1999; *Fletcher and Freymueller*, 2003; *Pavlis et al.*, 2004] suggests that the best estimate of the slip rate is 12 mm/yr. The low number of large earthquakes on the fault, however, seems to be at odds with this slip rate, although it is possible that some of the large earthquakes in 1899 could be associated with this fault [*Doser*, 2006]. On the subduction zone to the west, it is clear that a variable, but perhaps substantial, fraction of the slip is accommodated as aseismic slip [*Pacheco et al.*, 1993]. By analogy, but somewhat arbitrarily, we have therefore allowed 50% of the slip across the transition fault to be accommodated aseismically and assume that 6 mm/yr is released in characteristic events of magnitude 8.2 every 325 years (Table 2).

4.2.2. Fairweather and Queen Charlotte faults. Recent plate motion studies [*DeMets and Dixon*, 1999] and GPS

Table 2. Characteristics of Active Faults Assumed for Hazard Analysis

Fault (Segment)	M_{char} (M_{max})	Slip rate (mm/yr)[a,b]	Recurrence time[c] for characteristic earthquake (years)[a]	References
Queen Charlotte	8.1[d]	49	155	1
Fairweather, offshore	7.7[d]	49.5	100	1
Fairweather, onshore	8.0[d]	48	150	1
Denali, southeast	7.9	8.4–2	1065–4465	2
Denali, central	7.9	1–9.4–14.4	15,305–1630–1065[e] 21,430–2280–1490[f]	2
Totschunda	7.9	6	1490	2
Castle Mountain	7.1	0.5–2.9–0.5	4255–730–4255	3
Transition	8.2[d]	6	325	(see text)
Kodiak Island	7.5	1	4435	4
Narrow Cape	7.5	2	2220	4

[a] Range indicates variation along fault from west to east.
[b] Numbers shown are unlikely to be more precise than about 1 mm/yr, but are shown to greater precision to facilitate comparison of calculations.
[c] Recurrence times are estimated from the rate of seismic moment release for earthquakes of the characteristic magnitude required to balance the observed geologic slip rate. They represent recurrence within any section of fault length equal to *Wells and Coppersmith*'s [1994] surface rupture length. Ranges in recurrence time correspond to the ranges in slip rate along the fault.
[d] Characteristic magnitudes estimated from fault length using the *Wells and Coppersmith* [1994] relations.
[e] Recurrence times for ruptures on the Central Denali–Eastern Denali system.
[f] Recurrence times for ruptures on the Central Denali–Totschunda system.
References: 1, *DeMets and Dixon* [1999], *Fletcher and Freymueller* [2003]; 2, *Schwartz et al*. [2005a, 2005b]; 3, *Willis et al*. [2008]; 4, *Carver et al*. [2003].

studies [*Freymueller and Fletcher*, 1999; *Fletcher and Freymueller*, 2003; *Mazzotti et al*., 2003; *Smith et al*., 2003] have led to improved estimates of the seismic hazard attributable to the Fairweather and Queen Charlotte faults. Based on these studies, the best current estimate of the slip rate on the Queen Charlotte fault is taken as 49 mm/yr, decreasing by 1 mm/yr toward the northwestern end of the Fairweather fault. Because of the partitioning of strain between the eastern Denali (2 mm/yr) and Fairweather faults [*Fletcher and Freymueller*, 2003], we have adopted a value of 48 mm/yr for the onshore portion of the Fairweather fault. *Mazzotti et al.* [2003] suggested that a significant component of convergence perpendicular to the fault exists at the southern end of the Queen Charlotte system, although this convergence is not explicitly modeled in the preparation of the map.

Information on the possible segmentation of this fault system is limited to the rupture zones of the earthquakes in 1949, 1958, and 1972. The boundary between the onshore and offshore Fairweather fault segments is taken from the aftershocks shown on the map of *Plafker et al.* [1993], rather than on the extent of rupture shown on the same map that apparently is in error [*Bufe*, 2005]. This leads to longer onshore and shorter offshore Fairweather fault segments compared to the 1999 map. The lack of confidence that this model of segmentation is unique, led us to balance models of characteristic earthquakes fixed on these segments with a model including earthquakes with unknown endpoints ("floating" earthquakes).

4.2.3. Central Denali, Totschunda, and Eastern Denali faults. Results of geologic studies carried out since the 2002 Denali earthquake [*Schwartz et al*., 2005a, 2005b; *Matmon et al*., 2006] suggest that the slip rate on the central Denali increases in an eastern direction along the fault from about 9 mm/yr near the Parks Highway to about 14 mm/yr at the junction with the Totschunda fault. Current understanding suggests that this slip rate is portioned into about 8 mm/yr on the eastern Denali fault and about 6 mm/yr on the Totschunda fault. The slip rate on the eastern Denali fault decreases with distance to the east to values of 2 mm/yr or less in Canada near Kluane Lake, although *Fletcher and Freymueller* [2003] suggest that it may be higher. In the 1999 map, constant slip rates of 10 mm/yr were assumed for the central Denali fault, 2 mm/yr for the eastern Denali, and 11.5 mm/yr for the Totschunda. The new information also suggests that ruptures extending eastward from the central Denali fault are about equally likely to continue onto the eastern Denali or Totschunda faults. Recent analysis (A. Crone, oral communication) also provides evidence that the active portion of the Denali fault extends to the west with a slip rate gradually tapering to zero. Thus, our model tapers the slip rate on the Denali fault linearly from 9.4 mm/year at about 150.2°W to 0 mm/year at about 154.7°W. As described by *Wesson et al.* [2007], our standard hazard codes were modified to accommodate spatially variable slip rate and the possibility of branching ruptures.

The recent paleoseismic studies have begun to unravel a rich history of paleoearthquakes along the fault confirming recurrence times on the order of several hundred years [*Schwartz et al*., 2005a, 2005b]. Whether this record supports a well-developed segmentation of the fault is open to question, but the occurrence of an earthquake in the low magnitude 7 range in 1912, which appears to have ruptured a portion of the fault that reruptured in 2002, argues against this [*Carver et al.*, 2004; *Doser*, 2004].

4.2.4. Castle Mountain fault. The Castle Mountain fault (Plate 2) is particularly important to estimation of the seismic hazard in the vicinity of Anchorage because it is located only about 40 km from the city and even closer to the developing areas to the north of the city. Along the eastern or Talkeetna segment, there is no evidence for surficial displacement younger than Pleistocene [*Detterman et al*., 1976], but *Lahr et al.* [1986] describe an earthquake of M_s 5.2, which suggested slip at a depth of 13–20 km along the segment. In contrast, along the western or Susitna segment, no significant earthquakes have been instrumentally located, although geologic studies indicate Holocene surface displacement [*Detterman et al*., 1974, 1976; *Bruhn*, 1979]. New geologic data for the Castle Mountain fault near Houston, AK, on the Susitna segment [*Haeussler et al*., 2002; *Willis et al*., 2007] suggest a slip rate as high as 3.2 mm/yr, and an average recurrence time of about 700 years based on the interpretation of four paleoearthquakes. We have assumed a rate of 2.9 mm/yr, and the estimate of characteristic or maximum magnitude has been reduced from 7.5 to 7.1. These changes led to a faster slip rate than that assumed in 1999 and somewhat smaller but more frequent events, significantly increasing the seismic hazard from this fault compared with the 1999 map.

4.2.5. Kodiak Crustal faults. Work by *Carver et al.* [2003] on the southeastern edge of Kodiak Island indicates a series of active, left-lateral, strike-slip faults trending northeast, subparallel to the subduction zone trench. Enough information has been compiled on these faults to warrant their inclusion into the current set of maps. We have assigned a slip rate of 1 mm/yr to the Narrow Cape fault and 2 mm/yr to the Kodiak fault, and assumed models of a characteristic magnitude of 7.5 and a truncated Gutenberg–Richter distribution for magnitudes 6.5–7.5 on each fault. It is possible that some of the observed displacement could be coincident with large subduction zone events.

4.2.6. Yakataga region. Although the Yakataga segment is clearly the location of significant north–south convergence and the site of very large earthquakes (e.g., 1899, 1979), details of the faulting are poorly understood. Several east-trending, north-dipping thrust faults are inferred to exist beneath the glacier-covered region. Although some studies have been carried out in this region since 1999 [*Pavlis et al*., 2004], it is not possible at this time to construct a better model of the faulting, and the model assumed is that used in the 1999 map, a flat fault surface (i.e., with a 0° dip) at a depth of 15 km, extending from 59.1°N to 61.0°N and from 139.5°W to 145.4°W. This is nearly identical to the dislocation model proposed by *Sauber et al*. [1997, 1998; see also *Sauber and Molnia*, 2004] to explain GPS observations in this region. *Sauber et al.* [1997] estimate that sufficient strain has accumulated in this region since 1899 to generate an earthquake of magnitude M_w 8.1. They also note that there is evidence for about 15 mm/yr of right-lateral slip in the region extending a few tens of kilometers north of Cape Yakataga.

4.3. Other Sources Modeled With Smoothed Seismicity

Four regions are suspected of having significant earthquake hazard, but for which the geologic evidence is inadequate to develop a specific hazard model. Thus the best estimate of the hazard for these regions must be derived from the smoothed seismicity. Each of these areas can be considered as a gap in data, and/or understanding.

The first of these is a region of strike-slip faults north of and subparallel to the arc at the western end of the Aleutians. In this region of highly oblique convergence, slip partitioning among strike-slip and thrust faults appears highly likely [*Geist and Scholl*, 1994; *Bürgmann et al*., 2005]. Earthquake focal mechanisms and geologic studies, especially from bottom and subbottom profiling, suggest that these faults extend eastward along the arc at least as far as 160° W. Slip rates are unknown for individual faults within this group.

In the Cook Inlet region, recent studies by *Doser et al.* [2004] and *Haeussler et al.* [2000] investigated earthquakes that are associated with crustal faults and folds. Other than for the Castle Mountain fault, insufficient information exists to explicitly characterize the seismic hazard from individual faults.

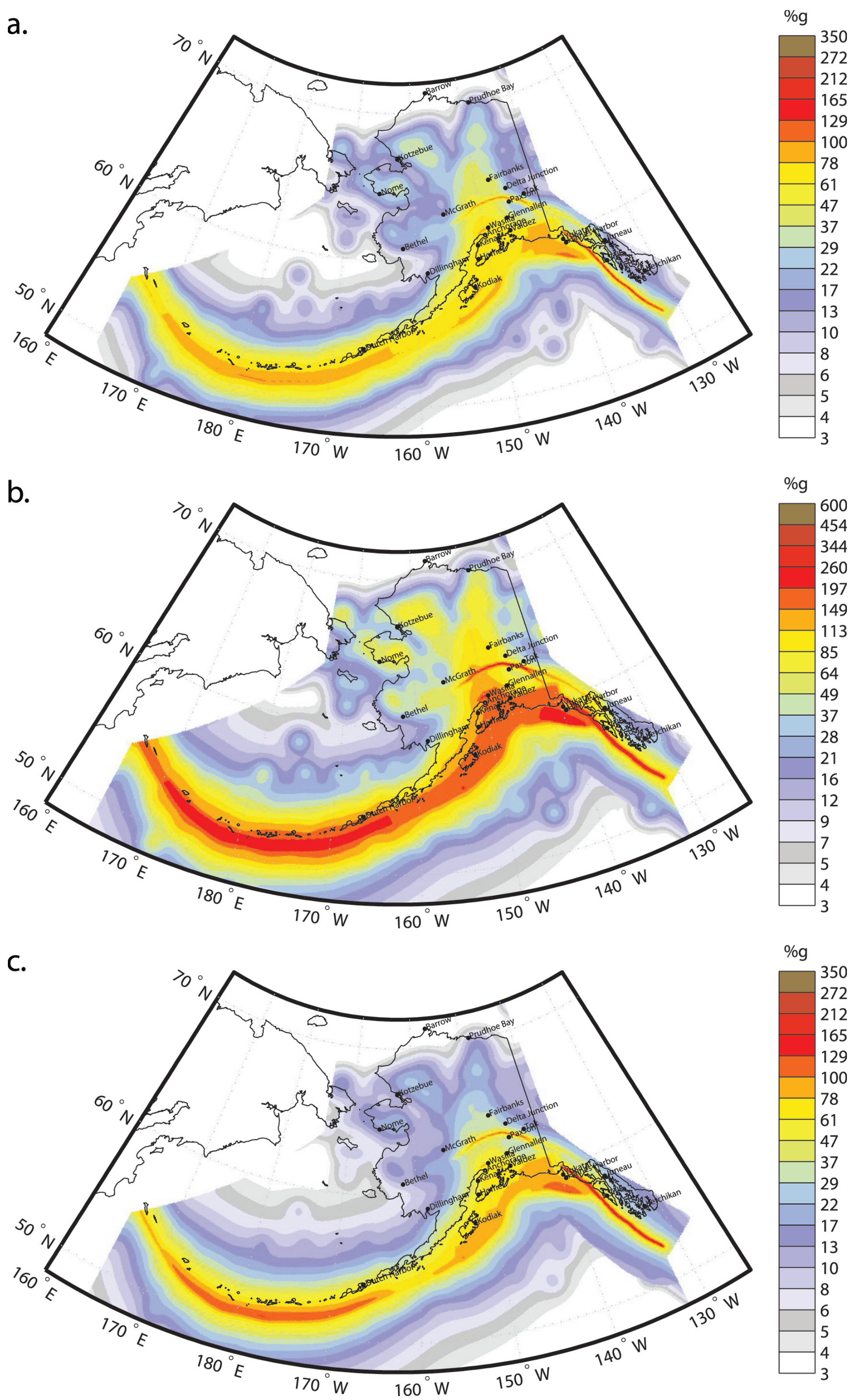

Plate 3. Probabilistic ground motion with a 2% probability of exceedance in 50 years for (a) peak ground acceleration (PGA), (b) 0.2 s spectral acceleration, and (c) 1.0 s spectral acceleration.

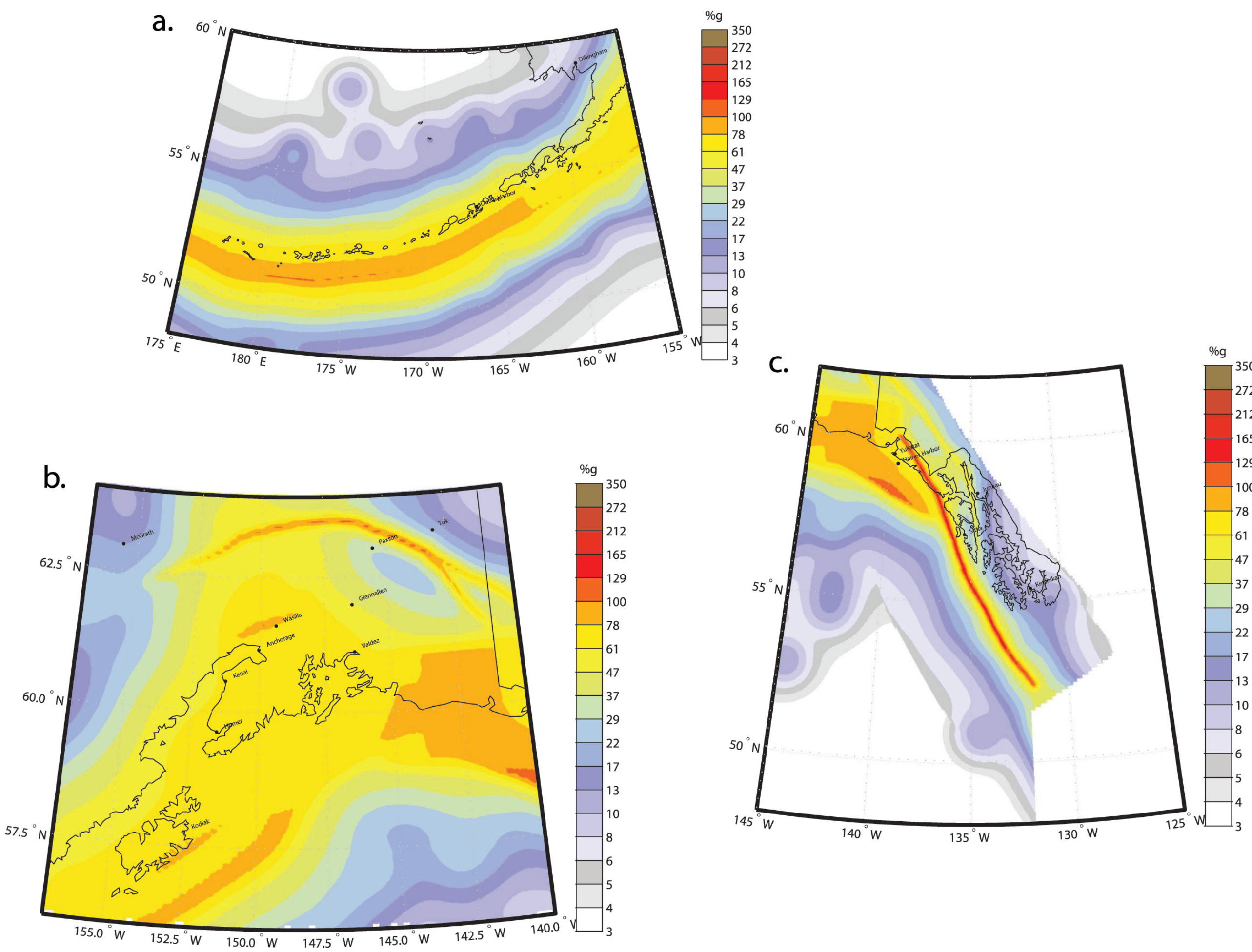

Plate 4. Probabilistic ground motion with a 2% probability of exceedance in 50 years for PGA at larger scales in the (a) Aleutians, (b) south-central Alaska, and (c) southeast Alaska.

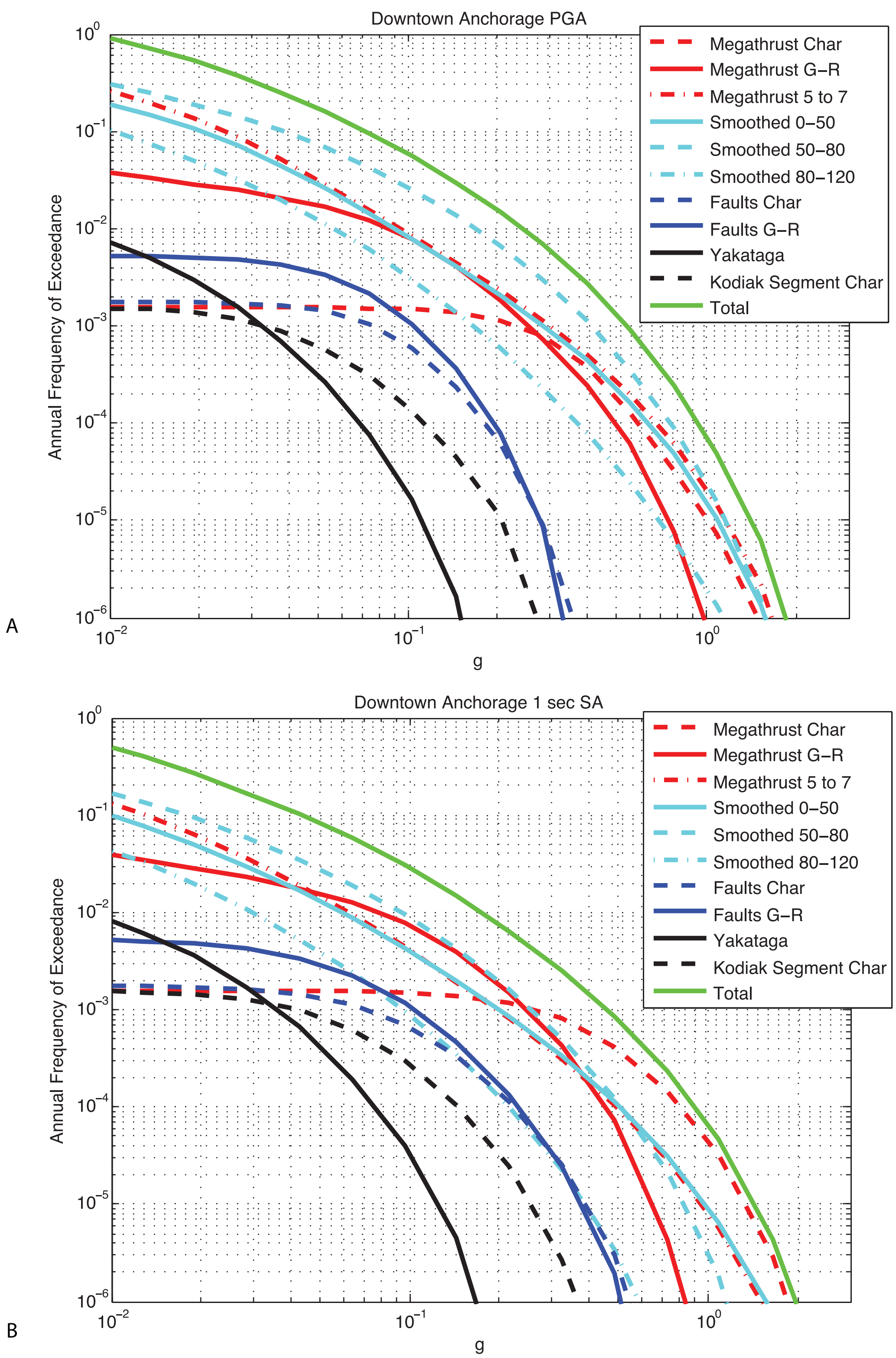

Plate 5. Hazard curves for (a) PGA and (b) 1 s spectral acceleration for a site in downtown Anchorage showing the relative contributions of the various sources to the total hazard. Curves labeled "Char" are for characteristic ruptures; those labeled "G–R" are for a truncated Gutenberg–Richter distribution; those labeled "Smoothed" are for smoothed earthquakes in the depth range indicated in kilometers; "Megathrust 5–7" indicates a Gutenberg–Richter distribution on the megathrust for earthquakes in the magnitude range 5 to 7.

The Tintina fault (Plate 2) is a major right-lateral fault about 1500 km long, extending from north-central Alaska southeastward to British Columbia. The fault displaces mid-Cretaceous rocks and lower Paleozoic facies boundaries by 450 km [*Roddick*, 1967; *Gabrielse*, 1985]. To the southeast, the fault is associated with the Rocky Mountain Trench. Little earthquake activity is associated with this fault in the Yukon [*Hyndman et al*., 2005]. Although there is evidence for late Pleistocene movement along the Kaltag fault (the westward extension of the Tintina) and possibly Holocene activity [*Plafker et al*., 1993], there is insufficient information to include the fault explicitly as a source.

Finally, the region of interior Alaska between the Denali and Tintina/Kaltag faults has experienced several earthquakes in the magnitude 7 range during the 20th century and, in addition, has a number of young faults. The earthquakes include the events of 22 July 1937, 16 October 1947, and 7 April 1958 [*Fletcher and Christensen*, 1996]. Many of the smaller earthquakes in the region are concentrated in three diffuse bands striking north–northeast. Focal mechanisms have also been observed consistent with left-lateral faulting along these trends. The bands have been termed the Minto Flats, Fairbanks, and Salcha seismic zones [*Page et al*., 1995; *Ratchkovski and Hansen*, 2002). To date, none of these bands have been clearly associated with a geologic fault. There are, however, a number of northeast- to north-northeast-striking faults along the north side of the Denali fault with evidence of youthful activity. Primary examples of these include the Donnelly Dome and Canteen faults. Several of these faults have received recent attention [e.g., *Bemis*, 2004; L.S. Cluff et al., oral communication, 2005], but as of this writing, insufficient information is available to include any individual fault explicitly.

5. DESCRIPTION OF MAP

Plate 3 shows the resulting maps for the entire region of Alaska and the Aleutians. Plate 4 shows peak ground acceleration (PGA) for the Aleutians, south-central Alaska and the 1964 earthquake zone, and southeast Alaska at expanded scales.

Overall, relative to the 1999 map, changes in the characterization of the subduction zone were modest, and although judged to have a more satisfactory justification in terms of observation and understanding, the hazard in the subduction zone was little affected. The largest changes in the 2005 map, as contrasted with 1999, are in the vicinity of the Castle Mountain, eastern Denali, and Totschunda faults and the southeastern shore of Kodiak Island. Significant increases in hazard resulted from the following: increased slip rate and decreased recurrence interval on the Castle Mountain fault; addition of the Kodiak Island and Narrow Cape faults on and adjacent to Kodiak Island; increased slip rate and decreased recurrence interval on the eastern Denali fault, extending the active Denali fault to the west; and a slightly shallower depth for the subduction zone beneath Cook Inlet. Decreases in hazard resulted from new attenuation relations, slightly lower slip rate for the southern Fairweather and Queen Charlotte faults, and decreases in the rates of earthquakes along the subduction zone.

5.1. An Example—Earthquake Hazard in Anchorage

As an example, Plate 5 shows hazard curves for the contributions to the total hazard for a site in downtown Anchorage for PGA and 1 s spectral acceleration. The hazard curves show the frequency of exceedance as a function of ground motion. The sum of the frequencies for the various components is the total frequency of exceedance. An annual probability of 2% in 50 years corresponds to a horizontal line on these graphs at a level of 0.000404.

Interestingly, the hazard for PGA is dominated at all but the highest ground motion levels by contributions from background earthquakes in the depth range of 50–80 km (Smoothed 50–80). This is true because of the relatively larger ground motions predicted by the attenuation relations for earthquakes in this depth range. Only at the highest level of ground motions do the shallower earthquakes (the sum of Megathrust 5–7 and Smoothed 0–50) become largest. Also only at ground motions over a few tenths of a *g* do the contributions of the characteristic M_w 9.2 become important.

The hazard curves for 1 s spectral acceleration present a different picture. Although the background earthquakes at 50- to 80-km depth dominate for small ground motions, the contribution from the truncated Gutenberg–Richter distribution on the megathust (Megathrust G–R) is comparable from about 0.1–0.3 *g*. In contrast to PGA, at this longer period the contribution of the characteristic M_w 9.2 dominates the hazard above a ground motion of about 0.3 *g*.

These sets of hazard curves illustrate the complex interplay of the components of the hazard depending on the location of the site in question relative to the sources, the estimated frequencies of occurrence on the sources, and the attenuation relations. The Castle Mountain fault, for example, does not play much role in the hazard at this site, but the story would be much different for a site in the Wasilla–Palmer area, closer to the fault. Also, the curves clearly indicate the importance of the deeper earthquakes to the hazard, and raise the issue of a 2000 Nisqually, WA-type earthquake for the Cook Inlet region. Furthermore, it should be pointed out that discovery of one or more additional shallow crustal faults near Anchorage could significantly affect the hazard.

6. PROBLEMS REQUIRING FUTURE WORK

6.1. Identification and Characterization of Active Faults

Recent paleoseismic investigations have vastly increased information about prehistoric earthquakes along the Denali and Totschunda faults, and in the Cook Inlet region along the megathrust. Paleoseismic information is largely lacking along the Fairweather–Queen Charlotte fault system and along the megathrust west of Kodiak Island. Additional geologic work is also required along the Kaltag–Tintina fault system, and to identify if possible the active faults responsible for the numerous large earthquakes in interior Alaska, particularly along the Minto Flats, Fairbanks, and Salcha seismic zones.

Two areas that lack both data and geologic understanding are the Transition fault and the Yakataga region as discussed at length above.

6.2. Aseismic Slip

The nature of aseismic slip along the megathrust, and its variation in time and space, is a fundamental problem for the assessment of earthquake hazard not only in Alaska and the Aleutians, but along subduction zones in other parts of the world.

6.3. Segmentation and Magnitude–Frequency Relationship

Two very closely related problems are (1) segmentation, or the persistence or lack thereof of the limits of the rupture zones of large earthquakes, and (2) the appropriate statistical relationship between the magnitude and frequency of large earthquakes along a fault. Both problems are fundamental challenges in advancing seismic hazard analysis. These issues are important in Alaska and the Aleutians both along the megathrust, and along the major crustal faults including the Denali, Fairweather–Queen Charlotte, and even the Castle Mountain.

6.4. Slip Partitioning

Commonly, when subduction is oblique to the plate boundary, slip is partitioned into thrusting nearly perpendicular to the trench and strike-slip along faults behind the trench. The role of slip partitioning in large earthquakes along the Aleutians is not yet understood. This topic concerns mainly the western Aleutians and Komandorsky Islands region.

7. CONCLUSIONS

The revision of the probabilistic seismic hazard map for Alaska and the Aleutians summarized here represents the current state of understanding of the earthquake potential of this region, as well as the current state of the means to describe this potential quantitatively. As discussed above, there is a need for additional data to determine the past earthquake history of the subduction zone and crustal faults, and to answer other questions. At a fundamental level, better understanding of aseismic slip, segmentation, and magnitude–frequency relationships is required. In addition, investigations in Alaska and the Aleutians, with the region's relatively frequent, large earthquakes, may provide key insights that will improve seismic hazard assessment in general.

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