Seismic Hazard Assessment for Guam and the Northern Mariana Islands

By Charles S. Mueller, Kathleen M. Haller, Nicholas Luco, Mark D. Petersen, and Arthur D. Frankel

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Abbreviations Used in This Report

0.2sSA	0.2-second response spectral acceleration for 5 percent critical damping
1.0sSA	1.0-second response spectral acceleration for 5 percent critical damping
a, b	earthquake rate parameters
cm/yr	centimeter per year
E	east
EVC	Engdahl-Villaseñor Centennial
g	gravitational acceleration
ISC	International Seismological Centre
km	kilometer
km ²	square kilometer
m	meter
mm/yr	millimeter per year
m/s	meter per second
M_w	moment magnitude
N	north
NGA	Next Generation Attenuation
PDE	Preliminary Determination of Epicenters
PGA	peak ground acceleration
USGS	U.S. Geological Survey
Vs30	30-meter average shear-wave velocity

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Abstract

We present the results of a new probabilistic seismic hazard assessment for Guam and the Northern Mariana Islands. The Mariana island arc has formed in response to northwestward subduction of the Pacific plate beneath the Philippine Sea plate, and this process controls seismic activity in the region. Historical seismicity, the Mariana megathrust, and two crustal faults on Guam were modeled as seismic sources, and ground motions were estimated by using published relations for a firm-rock site condition. Maps of peak ground acceleration, 0.2-second spectral acceleration for 5 percent critical damping, and 1.0-second spectral acceleration for 5 percent critical damping were computed for exceedance probabilities of 2 percent and 10 percent in 50 years.

For 2 percent probability of exceedance in 50 years, probabilistic peak ground acceleration is 0.94 gravitational acceleration at Guam and 0.57 gravitational acceleration at Saipan, 0.2-second spectral acceleration is 2.86 gravitational acceleration at Guam and 1.75 gravitational acceleration at Saipan, and 1.0-second spectral acceleration is 0.61 gravitational acceleration at Guam and 0.37 gravitational acceleration at Saipan.

For 10 percent probability of exceedance in 50 years, probabilistic peak ground acceleration is 0.49 gravitational acceleration at Guam and 0.29 gravitational acceleration at Saipan, 0.2-second spectral acceleration is 1.43 gravitational acceleration at Guam and 0.83 gravitational acceleration at Saipan, and 1.0-second spectral acceleration is 0.30 gravitational acceleration at Guam and 0.18 gravitational acceleration at Saipan.

The dominant hazard source at the islands is upper Benioff-zone seismicity (depth 40–160 kilometers). The large probabilistic ground motions reflect the strong concentrations of this activity below the arc, especially near Guam.

Introduction

In this report we present new probabilistic seismic hazard maps for Guam and the Northern Mariana Islands (fig. 1). These two United States territories, together composing the Mariana Islands group, lie in the western North Pacific Ocean along the Mariana arc about three quarters of the distance from Hawaii to the Philippines and halfway between Japan and New Guinea. Guam (13.5°N, 144.8°E) is the largest island in the Mariana chain with an area of 550 square kilometers (km²); its 2011 population was 180,000 (CIA World Factbook, 2011). The 14 Northern Mariana Islands extend 800 kilometers (km) north from Guam along the arc to Farallon de Pajaros island (20.5°N, 144.9°E). The northernmost islands are largely uninhabited owing to ongoing volcanic threats and only the three largest southern islands, Rota (14.2°N, 145.2°E), Tinian (15.0°N, 145.6°E), and Saipan (15.2°N, 145.8°E), support substantial populations. The total area of the Northern Mariana Islands is 460 km² and the 2011 population was 50,000 (CIA World Factbook, 2011).

Figure 1. Geographic and tectonic setting of the Mariana Islands region. The Pacific plate subducts west-northwestward beneath Guam at 6.3 cm/yr and the back-arc Mariana trough opens at 4.7 cm/yr full rate (Sella and others, 2002). Structural elements are generalized from Karig and others (1978). [m, meter; cm/yr, centimeters per year]

The east-convex Mariana trench-arc system has formed in response to northwestward subduction of the Pacific tectonic plate beneath the Philippine Sea plate (fig 1). Repetti (1939), Earthquake Engineering Research Institute (1995), and U.S. Geological Survey (2012a) reviewed the history of damaging earthquakes in the Mariana Islands during the past two centuries. Destructive earthquakes struck in 1825 (Modified Mercalli Intensity VIII), 1834 (VIII), 1849 (IX), 1862 (VII), 1892 (VIII), 1902 (IX), 1903 (VII), 1909 (VIII), 1936 (VIII), 1970 (V), 1975 (VII), 1978 (VII), and 1993 (IX), but only the most recent large events have been well recorded and studied. Aspects of historical seismicity in the region are summarized in figures 2 and 3 in the main report and in table A1 and figure A1 in the appendix.

In modeling the seismic hazard of the region it is important to recognize that no great—or even very large—thrust earthquake has ever been associated with the Mariana plate boundary. On the basis of its seismic history and tectonic expression, the Mariana megathrust is commonly categorized as the weakly coupled, “aseismic” end-member in global subduction-zone classifications (Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980; Zhang and Lay, 1992).

Little is known about large earthquakes of 1902 (moment magnitude (M_w) 7.5) and 1914 (body-wave magnitude 7.9).

On 05 April 1990, an M_w 7.4 earthquake occurred just east of the Mariana trench near 15.2°N and 147.6°E. Although not destructive, it is noteworthy as the largest shallow earthquake ever recorded in the region. This event was studied by Yoshida and others (1992) and Zhang and Lay (1992). Yoshida and others (1992) interpreted a normal-faulting mechanism with slip on a west-dipping plane within the outer-rise region of the subducting Pacific plate in response to gravitational slab-pull forces.

On 08 August 1993, an M_w 7.8 (surface-wave magnitude (M_s) 8.1) earthquake occurred about 60 km south-southeast of Agana, the capital city of Guam, near 13.0°N and 144.8°E at a depth of 60–70 km. The largest earthquake ever recorded in the region, it caused considerable damage on Guam, especially to long-period structures. Earthquake Engineering Research Institute (1995) described its effects and estimated peak ground accelerations (PGA) of 0.15 to 0.25 gravitational acceleration (g) on Guam; there were no strong-motion recordings. This earthquake was clearly associated with the subducting Pacific plate, but initially neither aftershock patterns nor seismic or tsunami modeling could distinguish between alternative interface or inslab mechanisms (Tanioka and others, 1995). Campos and others (1996) interpreted it as an interface event, with important implications for then-current ideas about seismic coupling (see also Scholz and Campos, 1995). Harada and Ishibashi (2008), after making a joint relocation of a large Mariana seismicity dataset, determined that the 1993 earthquake ruptured along a subhorizontal fault plane deep within the subducting Pacific slab; this result contradicted the Campos and others (1996) interpretation.

Large earthquakes on 28 March 2000 and 28 September 2007 (M_w 7.6 and M_w 7.5, respectively) occurred north of 22°N within the Benioff zone at depths greater than 100 km.

In fact, the largest modern (1976–2011) Mariana earthquakes with likely shallow thrust mechanisms appear to be 06 June 1993 M_w 6.4 and 14 August 2002 M_w 6.5 events (Global CMT Project, 2011). Regardless, the recent great 2004 Sumatra-Andaman and 2011 Tohoku-Oki earthquakes have called the traditional subduction-zone classifications into question, with the implication that any major subduction zone—even Mariana—may be capable of a great

megathrust earthquake (Stein and Okal, 2007). To accommodate this idea in the hazard model we supplement the limited Mariana seismic history with data from other Pacific-region subduction zones.

We present probabilistic seismic hazard maps for the Mariana Islands region for PGA, 0.2-second spectral acceleration for 5 percent critical damping (0.2sSA), and 1.0-second spectral acceleration for 5 percent critical damping (0.1sSA) for exceedance probabilities of 2 percent and 10 percent in 50 years (corresponding to ground-motion return times of approximately 2,500 and 500 years, respectively). Shallow seismicity, Benioff-zone seismicity, the Mariana megathrust fault, and two crustal faults on Guam are modeled as seismic sources. Appropriate published ground-motion relations for a firm-rock site condition are used for each source. The probabilistic seismic-hazard methodology developed by the U.S. Geological Survey (USGS) for the United States national seismic hazard maps (Frankel and others, 1996; Frankel and others, 2000; Frankel and others, 2002; Petersen and others, 2008) is adapted for the Mariana case. As with other USGS seismic hazard maps, these are intended to inform building codes and other structural-design guidelines as well as earthquake mitigation and response plans (Leyendecker and others, 2000).

Seismic and Tectonic Setting of Guam and the Northern Mariana Islands

Seismicity in the region is primarily controlled by active convergence between two purely oceanic tectonic plates: the Pacific plate subducts northwestward beneath the Philippine Sea plate at the Mariana trench (Karig, 1971; Karig and others, 1978; Hussong and Uyeda, 1981; Ranken and others, 1984). The Mariana volcanic arc lies west of the trench, and the back-arc Mariana trough lies west of the arc (fig. 1). The east-convex plate boundary changes strike orientation from north-northwest at the latitude of the northernmost Mariana Islands (about 20°N) to east-northeast southwest of Guam. In a global analysis of space geodesy data (primarily global positioning system data), Sella and others (2002) found a velocity for the Pacific plate relative to Guam (relative subduction velocity) of 6.3 centimeters per year (cm/yr) at an azimuth of 285 degrees. They also derived an extension rate across the Mariana trough of 4.7 cm/yr (full rate, at the latitude of Guam), in rough agreement with geologic rates (Hussong and Uyeda, 1981). An older analysis of earthquake slip-vector data constrained by global plate-motion models (Seno and others, 1993) gave a relative Pacific plate–Philippine plate velocity near 20°N of about 4 cm/yr, which diminished southwestward along the plate boundary to about 2 cm/yr southwest of Guam. South of 13°N the volcanic arc is truncated by a series of east-west-trending fractures (Karig and others, 1978; Ranken and others, 1984). Hengesh (1994) argued that the oblique component of convergence implied by the changing plate-boundary geometry south of Guam should be partitioned onto such transcurrent structures in a manner similar to strain partitioning near Sumatra, Puerto Rico, and the western Aleutians.

The configuration of the subducting plate changes markedly along the boundary (Ranken and others, 1984; Tanioka and others, 1995). North of 15°N the Benioff zone dips steeply (it is essentially vertical below 200–250 km) and deep earthquakes occur down to 700 km, whereas west of 143°E, southwest of Guam, no earthquakes deeper than 200 km have been recorded. Selected focal mechanisms from 1976 to 2011 (Global CMT Project, 2011) are plotted in figure 2. The declustered earthquake catalog developed for this project (described below in the Gridded Historical Seismicity section) is mapped in figure 3. (Seismicity is plotted in several cross-section views in appendix figure A1.)

A

Global CMT 1976-2011: $M_w \geq 6$, depth ≤ 40 kilometers

Figure 2. Focal-mechanisms (Global CMT Project, 2011): A) earthquakes 1976–2011 with $M_w \geq 6$ and depth 0–40 km; B) earthquakes 1976–2011 with $M_w \geq 6$ and depth 41–200 km; C) earthquakes 1990–2011 with $5.5 \leq M_w < 6$ and depth 0–40 km. Earthquakes are denoted by month, day, year (MMDDYY). (See fig. 1 for explanation of geographic and tectonic features.) [CMT, Centroid Moment Tensor; <, Less than; $\leq$, less than or equal to; M_w , moment magnitude; d, depth; $\geq$, greater than or equal to; km, kilometer]—Continued

BGlobal CMT 1976-2011: $M_w \geq 6$, $40 < \text{depth} \leq 200$ kilometers

Figure 2. Focal-mechanisms (Global CMT Project, 2011): A) earthquakes 1976–2011 with $M_w \geq 6$ and depth 0–40 km; B) earthquakes 1976–2011 with $M_w \geq 6$ and depth 41–200 km; C) earthquakes 1990–2011 with $5.5 \leq M_w < 6$ and depth 0–40 km. Earthquakes are denoted by month, day, year (MMDDYY). (See fig. 1 for explanation of geographic and tectonic features.) [CMT, Centroid Moment Tensor; <, Less than; $\leq$, less than or equal to; M_w , moment magnitude; d, depth; $\geq$, greater than or equal to; km, kilometer]—Continued

CGlobal CMT 1990-2011: $5.5 \leq M_w < 6.0$, depth ≤ 40 kilometers

Figure 2. Focal-mechanisms (Global CMT Project, 2011): A) earthquakes 1976–2011 with $M_w \geq 6$ and depth 0–40 km; B) earthquakes 1976–2011 with $M_w \geq 6$ and depth 41–200 km; C) earthquakes 1990–2011 with $5.5 \leq M_w < 6$ and depth 0–40 km. Earthquakes are denoted by month, day, year (MMDDYY). (See fig. 1 for explanation of geographic and tectonic features.) [CMT, Centroid Moment Tensor; <, Less than; $\leq$, less than or equal to; M_w , moment magnitude; d, depth; $\geq$, greater than or equal to; km, kilometer]—Continued

Figure 3. Declustered seismicity catalog: earthquakes 1964–2011 with $M_w \geq 4.5$ (stars, color-coded by depth). Megathrust zone and outer-rise zone boundaries are plotted as dashed and dotted lines, respectively. (The three source catalogs are mapped in fig. A2.) [M_w , moment magnitude; $\geq$, greater than or equal to; m, meter; d, depth]

The Mariana islands are formed of volcanic rocks and calcareous sedimentary rocks of Tertiary and Quaternary age. Guam consists of volcanic mountains in the south and low-lying coralline-limestone marine terraces in the north. There is evidence of crustal faulting all along the arc, both in sea-floor images (for example, Hussong and Uyeda, 1981) and from onshore reconnaissance (Tracey and others, 1964). Hengesh (1994) reported long-term tilting and displacement of a prominent late Holocene bench that is preserved across Guam and faulting of other young features (see also Earthquake Engineering Research Institute, 1995). He speculated that the shape of the island itself might be controlled by one or more young faults.

As noted above, no great earthquake has ever been associated with the Mariana megathrust interface. In the taxonomy of global subduction systems proposed by Uyeda and Kanamori (1979), weak plate coupling and low seismic activity on the interface correlate with extension in the overriding plate, active back-arc spreading, old subducting lithosphere, and a steep Benioff zone. The Mariana system shows a predominance of extensional structural features (for example, high-angle normal faults) in the shallow fore-arc and little evidence of sediment accretion at the inner trench wall; both observations are consistent with weak coupling in the subduction zone (Hussong and Uyeda, 1981).

Methodology and Hazard Model

The U.S. Geological Survey probabilistic seismic hazard methodology is based on specific fault sources with geologically or geophysically derived slip-rate or recurrence information and on gridded and smoothed historical (background) seismicity. Earthquake rates are generalized using truncated exponential (Gutenberg-Richter) frequency-magnitude distributions with regionally determined b values and maximum magnitudes (that is, truncated $N_m = 10^{a-bm}$, where parameters a and b specify N_m , the rate of earthquakes of magnitude m). Magnitude ranges are adjusted in the model to avoid double counting hazard from different types of sources. Uncertainties in sources and ground-motion attenuation relations are accommodated by using logic trees. Modeled earthquakes are assumed to occur randomly in time; the probabilistic ground motions presented here represent mean, time-independent seismic hazard.

Specific sources in the Mariana seismic hazard model include faulting on the subduction megathrust west of the Mariana trench, normal faulting on two crustal faults on Guam that we judge to be active, and gridded and smoothed historical seismicity using earthquakes from 1964 to 2011, larger than M_w 4.5, that are divided into eight depth ranges down to 700 km. Lacking magnitude or recurrence information, we do not model the Mariana trough boundary faults, the east-west-trending fractures that truncate the southern arc, or other crustal faults as specific sources; their hazard is accounted for by background seismicity. Alternative ground-motion predictions for a uniform firm-rock site condition (30-meter (m) average shear-wave velocity (V_{s30}) = 760 meters per second (m/s)) are used. M.D. Petersen and others (written commun., 2012) made a seismic-hazard assessment for American Samoa incorporating new ground-motion estimates for oceanic paths, and we adopt some of their results. With a site grid spacing of 0.1 degree in latitude and longitude, we compute hazard curves for approximately 17,000 sites within the area mapped in figure 1.

Gridded Historical Seismicity

A uniform moment-magnitude-based seismicity catalog is constructed for the Mariana region from three global source catalogs. The Engdahl-Villaseñor Centennial (EVC) catalog is a compilation of large 20th-century earthquakes, many relocated, with completeness levels of about M_w 5.5 since 1964 and M_w 6.5 since 1900 (Engdahl and Villaseñor, 2002). The U.S. Geological Survey Preliminary Determination of Epicenters catalog (PDE) lists earthquakes since 1973 with variable completeness levels (U.S. Geological Survey, 2012b). The International Seismological Centre global catalog (ISC) lists earthquakes since 1900 with variable completeness levels (International Seismological Centre, 2011). We use catalog search parameters: $1900 \leq \text{year} \leq 2011$, $8 \leq \text{lat}^\circ\text{N} \leq 24$, $138 \leq \text{lon}^\circ\text{E} \leq 152$, depth = all, and magnitude ≥ 3.8 . Listed magnitudes of various types are converted to M_w following Utsu (2002) and Sipkin (2003), and a preferred M_w is determined for each entry. The three source catalogs (appendix fig. A2) are concatenated and sorted chronologically. Duplicates and dependent events are identified and removed following Mueller and others (1997): duplicates are deleted using the source-catalog preference order $\text{EVC} > \text{PDE} > \text{ISC}$, and aftershocks and foreshocks are deleted (to insure the statistical independence of the final catalog) by using the algorithm of Gardner and Knopoff (1974). The final declustered catalog (fig. 3) includes 4,164 main shocks with $M_w \geq 4$ (144 EVC, 2,859 PDE, 1,161 ISC), and we judge it to be complete to M_w 4.5–5.0 since 1964. Most earthquakes deeper than about 40 km are associated with the Benioff zone of the subducting Pacific plate (appendix fig. A1). Appendix A1 lists earthquakes in the declustered catalog with $M_w \geq 6$.

For the hazard calculation the declustered catalog is divided into eight subcatalogs by depth: 0–40 km, 41–80, 81–120, 121–160, 161–200, 201–300, 301–500, and 501–700. To accommodate regional differences in b values or maximum magnitudes the 0–40-km (shallow) subcatalog is further divided into three tectonic zones: megathrust, outer-rise, and shallow-other. The megathrust zone boundary (dashed line in fig. 3) corresponds with the surface used to model the Mariana megathrust fault (described below). The outer-rise zone boundary (dotted line in fig. 3) extends about 100 km oceanward from the Mariana trench axis. The shallow-other zone includes the remaining shallow seismicity (not megathrust or outer-rise). Completeness levels and b values are derived from statistical analysis of each subcatalog. Figure 4A shows the result for shallow megathrust seismicity (all shallow earthquakes within the megathrust zone, regardless of mechanism). Binned incremental annual earthquake rates (dots, plotted in the center of each 0.5-magnitude-unit bin) are determined for the listed completeness levels. A b value of 1.06 (solid line) is derived from a maximum-likelihood fit (Weichert, 1980) to the rates of earthquakes with $M_w \geq 5.0$. Figure 4B shows the result for shallow seismicity outside the megathrust zone (combined outer-rise and shallow-other). A b value of 1.07 (dashed line) is derived from the rates of earthquakes with $M_w \geq 4.5$; $b = 1.06$ (solid line) is used in the hazard model for simplicity and consistency with the megathrust-zone result. Figure 4C shows the result for seismicity in the 40–200-km depth range. A b value of 1.124 (dashed line) is derived from the rates of earthquakes with $M_w \geq 5.0$, but the fit underestimates the historical rates of large earthquakes. For simplicity $b = 1.06$ (solid line) is again used in the hazard model; in our judgment it fits the rates of large earthquakes better without seriously violating the other rates. For seismicity in the 200–700-km depth range, $b = 0.80$ provides a good fit to the rates of earthquakes with $M_w \geq 5.0$ (not shown).

Figure 4. Seismicity rates and exponential-model fits for variable completeness (Weichert, 1980). Data (dots) are incremental annual earthquake rates in 0.5-magnitude-unit bins. A) Depth 0–40 km, inside megathrust zone: fit gives $b = 1.06$ (solid line). B) Depth 0–40 km, outside megathrust zone: fit gives $b = 1.07$ (dashed line), but $b = 1.06$ (solid line) is used in the hazard calculation. C) Depth 40–200 km: fit gives $b = 1.124$, but $b = 1.06$ (solid line) is used in the hazard calculation. Completeness levels are listed on each graph. The megathrust zone boundary is mapped in figure 3. [Eqks/yr, earthquakes per year; M_w , moment magnitude; b , earthquake rate parameter; km, kilometer; s, since; $<$, less than; d, depth; $\leq$, less than or equal to]—Continued

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A 0.1° -latitude $\times$ 0.1° -longitude grid was superimposed on the study region and a seismic activity rate, incremental 10^a (for a bin size of 0.1 magnitude unit), was computed for each grid cell considering catalog completeness (Weichert, 1980; Frankel and others, 2000). Separate 10^a grids were made for the shallow megathrust, shallow outer-rise, shallow-other, and the seven 41–700-km subcatalogs. Following Frankel and others (1996, 2000) gridded 10^a values were spatially smoothed using a two-dimensional Gaussian function with a 50-km correlation distance for the three shallow grids and a 30-km correlation distance for the seven deeper grids. The 10^a grids were used to compute the hazard contribution from seismicity for the epicentral distance range 0–200 km. The historical seismicity source models are summarized in table 1.

Table 1. Historical earthquakes and seismicity hazard models.

[km, kilometer; b , parameter in earthquake rate model; $M_{\min}$, minimum magnitude; $M_{\max}$, maximum magnitude; M_w , moment magnitude, %, percent]

Depth range (km)	Largest observed (M_w)		Model parameters			
	1900–2011	1964–2011	b	$M_{\min}$ (M_w)	$M_{\max}$ (M_w)	Fix depth (km)
0–40 megathrust	7.3 (1940)	6.5 (2002)	1.06	5.0	7.0	20
0–40 outer-rise	7.4 (1990)		1.06	5.0	7.5 (80%) 8.2 (20%) *	20
0–40 other	7.5 (1902)	6.9 (2007,2010)	1.06	5.0	7.5	20
41–80	7.8 (1993)		1.06	5.0	8.2	60
81–120	8.2 (1914)	7.6 (2000)	1.06			100
121–160	6.8 (1912,1957)	6.6 (2005)	1.06			140
161–200	7.0 (1931)	6.9 (1953)	1.06			180
201–300	7.5 (2007)		0.80	5.0	8.0	250
301–500	7.1 (1905)	6.5 (2001)	0.80			400
501–700	7.1 (1995)		0.80			600

* $M_{\max}$ from American Samoa hazard study (M.D. Petersen and others, written commun., 2012)

For shallow seismicity we use three ground-motion prediction equations from the Next Generation Attenuation (NGA) project (Power and others, 2008) and one equation from Zhao and others (2006). The Next Generation Attenuation relations are essentially empirical, based largely on strong-motion data from crustal earthquakes in California, Taiwan, and Turkey. They are intended to predict ground motions “for shallow crustal earthquakes in the western United States and similar active tectonic regions” (Power and others, 2008). We use them with half weight overall, equally partitioned (weight 0.167 each) between the relations of Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008). Each is applied with weights 0.5 for strike-slip faulting and 0.5 for normal faulting in recognition of the evidence for extensional crustal deformation in the region. Zhao and others (2006) developed ground-motion relations from a large Japanese dataset supplemented by data from the western

United States for crustal earthquakes. M.D. Petersen and others (written commun., 2012) collected and processed a set of ground-motion data from the Pacific Basin, and they made a performance evaluation of three published ground-motion relations. They preferred the Zhao and others (2006) predictions, and used them exclusively in their seismic-hazard model for American Samoa. They noted that all earthquakes between 10 and 200 km depth had similar ground-motion characteristics. We use the Zhao and others (2006) interface ground-motion relation with half weight overall. No extra epistemic uncertainty is added for the shallow-seismicity ground motions. All equations account explicitly for the firm-rock site condition ($V_{s30} = 760$ m/s) applied here.

For deeper seismicity (depth 41–700 km, primarily Benioff-zone seismicity) we use Zhao and others (2006) inslab ground-motion relations exclusively. We partition these relations into the as-published equation with 70 percent weight and into an equation adjusted for regional differences (Pacific compared with global) with 30 percent weight (M.D. Petersen and others, written commun., 2012). In this case we include 25 percent additional epistemic uncertainty to account for ground-motion modeling variability (M.D. Petersen and others, written commun., 2012).

Mariana Megathrust

It is not known whether very large earthquakes can occur on the Mariana subduction megathrust or, if they do, what their rates and sizes are. The evidence for weak seismic coupling precludes estimating seismic activity rates directly from plate-motion data. Instead we assume an exponential frequency-magnitude distribution, extrapolate the rates of historical earthquakes associated with the megathrust, and judge that the implied rates for large earthquakes seem reasonable given the incomplete Mariana seismic history. The limited history also complicates direct estimates of maximum magnitudes. We consider two maximum magnitudes for the megathrust, one based on the local history and one from consideration of other subduction zones.

The megathrust is modeled as a west-dipping surface extending from latitude 23°N to about 11.5°N . The up-dip (eastern) edge is defined as the trace of the Mariana Trench and the down-dip (western) edge is defined as a 40-km depth contour estimated from spatial patterns of west-dipping seismicity; seismicity and the megathrust zone boundary are shown in figure 3. The megathrust boundary in figure 3 closely matches the updip and 40-km depth contours on the megathrust surface derived by Hayes and others (2012). Some support for fixing the downdip edge of the megathrust at 40 km comes from the recent great megathrust earthquakes in Chile (2010 Maule, M_w 8.8) and Japan (2011 Tohoku-oki, M_w 9.0): seismic and geodetic datasets show that primary coseismic slip in both cases occurred at depths shallower than about 35–40 km (for example, Hayes, 2011; Lorito and others, 2011; Ozawa and others, 2011; Pollitz and others, 2011; Wei and others, 2011). These earthquakes may or may not be very good Mariana analogs; the rationale for the comparison is simply that they are among the best-recorded and best-studied of all Pacific megathrust earthquakes, with among the best-determined slip distributions. Perhaps better support for the 40-km choice comes from considering the depths of historical earthquakes located along the northward-adjacent Izu-Bonin megathrust (local Mariana data are insufficient): populations of thrust-mechanism events (Hayes and others, 2012) show clear maxima in the 15–35-km depth range and a sharp decline at greater depths.

From the shallow seismicity within the megathrust boundary (all earthquakes, regardless of mechanism) we determine a b value of 1.06 (fig. 4A) and a rate that gives a M_w 8 or greater earthquake about every 450 years. The megathrust is modeled with spatially floating earthquakes following a truncated exponential frequency-magnitude distribution, extending from M_w 7 (the maximum magnitude for the shallow megathrust background seismicity; see table 1) to a maximum magnitude. Two values of maximum magnitude are applied in a logic tree: M_w 8 (weight 0.8) is based on the local Mariana seismic history, and M_w 9 (weight 0.2) acknowledges the possibility of a great earthquake on the megathrust.

Following M.D. Petersen and others (written commun., 2012) we use the subduction interface ground-motion relations of Zhao and others (2006) for the distance range 0–1,000 km. Twenty-five percent additional epistemic uncertainty is again added to account for ground-motion modeling uncertainty.

Crustal Faults on Guam

Tracey and others (1964), Hengesh (1994), and Earthquake Engineering Research Institute (1995) present evidence that some young geomorphic relationships on Guam are controlled by crustal faults. Earthquake Engineering Research Institute (1995; their fig. 2-5) shows several on-island faults and emphasizes that even a moderate earthquake on one of them could pose a substantial seismic threat. We have reviewed the work of Tracey and others (1964), and in our judgment two onshore faults merit inclusion in the seismic hazard model (fig. 5).

Figure 5. Guam with historical seismicity (used in the hazard calculation) and generalized traces of Adelup and Tamuning-Yigo faults (black lines). Filled circle, Agana, the capital city of Guam. [km, kilometer; ≈, approximately; mm/yr, millimeters per year; d, depth; <, less than; >, greater than]

The Cocos fault is shown on figure 25 of Tracey's report, but not on their 1:50,000-scale geologic map. In our judgment faulting is not required to produce the geologic relationships at the south end of the volcanic terrain of southern Guam, and, lacking clear geologic evidence to support the existence of this fault, we do not consider it as a potential source. The Cabras and Talofoto faults lie entirely within the Tertiary volcanic section. Although that is insufficient evidence on its own to preclude them from being potentially active, the absence of through-going topographic expression along the Cabras fault, and the observation that younger Tertiary and Quaternary-Tertiary deposits are unfaulted along the Talofoto fault zone suggest little post-Tertiary activity. Even though Tracey and others (1964) suggest that faulting on the Talofoto fault zone is synchronous with faulting on the Adelup fault to the north (see below), we see little evidence to support young movement on either the Cabras or Talofoto faults.

The Adelup (or Adelup-Pago) fault is an important structure. According to Tracey and others (1964) this fault extends across the narrow waist of the island and forms the structural boundary between the northern and southern parts of the island. As shown on their geologic map, the Adelup fault juxtaposes Quaternary-Tertiary limestones of the northern part of the island against volcanic terrain to the south; clearly it has had an extended history of movement. Two lines of evidence suggest young displacement. First, the broad limestone platform that forms the northern part of the island has a regional dip to the southwest of about 5 meters per kilometer. There does not seem to be any substantial east-west tilting, and the limestone deposits south of the Adelup fault do not share this regional dip. Thus, differential movement is probably accommodated along the Adelup fault. Second, the fault coincides with a topographic escarpment across the Quaternary-Tertiary Agana argillaceous facies and reef facies of the Mariana Limestone south of Pago Bay, on the east side of the island. The scarp is about 80 m high on the Agana argillaceous facies, whereas the scarp on the reef facies is more subdued and may be only 40–60 m high. The Adelup fault is likely characterized by low slip rates on the basis of a late-Holocene bench that is offset several feet (Earthquake Engineering Research Institute, 1995) and on the amount of offset suggested by the topographic expression of the fault in the older limestone. We believe from the evidence of surface rupture, however, that it is capable of generating earthquakes of at least M_w 6.5. Geologic relations suggest that it is probably a high-angle normal fault dipping to the northeast.

The Tamuning-Yigo fault zone (and the Santa Rosa horst at its north end), characterized by a topographic scarp indicating Quaternary displacement, should also be considered as a potential source. The fault is at least 25 km long, although Tracey and others (1964) note that the northeastern part is not well expressed. In our judgment the topographic and geologic evidence is consistent with a maximum earthquake of at least M_w 6.5. Tracey and others (1964) report that the Tamuning-Yigo fault zone is a high-angle, down-to-the-northwest fault with maximum relief of about 60 m.

A lack of ages for offset landforms or deposits considerably limits our ability to determine slip rates. For both the Adelup and Tamuning-Yigo faults, the age of the Mariana Limestone is critical. Tracy and others (1964) assign it a Quaternary-Tertiary age. If we assume an age of 1.6 mega-annum (the Quaternary-Tertiary boundary) the resulting slip rates are very small, less than about 0.05 millimeters per year (mm/yr). Preserving a topographic scarp is difficult at these rates in a tropical environment. If we assume an age of 0.5 mega-annum for the reef deposits (middle Quaternary) as reported by Earthquake Engineering Research Institute (1995), we get slip rates of 0.2 and 0.1 mm/yr for the Adelup and Tamuning-Yigo faults, respectively. This rate for the Adelup fault is supported by the several-foot offset of the late-

Holocene beach (Earthquake Engineering Research Institute, 1995). We believe that the Tamuning-Yigo fault zone is less active than the Adelup fault, so the relative difference in slip rates seems appropriate.

Figure 5 shows the island of Guam with the modeled (generalized) fault traces and background seismicity. The Adelup fault is modeled as a 10-km-long, northeast-dipping normal fault producing characteristic M_w 6.5 earthquakes. The slip rate of 0.2 mm/yr and an average displacement of 0.44 m (Wells and Coppersmith, 1994), imply a recurrence time of about 2,200 years. The Tamuning-Yigo fault is modeled as a 25-km-long, northwest-dipping normal fault producing characteristic M_w 6.5 earthquakes. The slip rate of 0.1 mm/yr and an average displacement of 0.44 m (Wells and Coppersmith, 1994), imply a recurrence time of about 4,400 years.

For the crustal faults we use Next Generation Attenuation ground-motion relations for normal faulting with full weight, equally partitioned (weight 0.333 each) between the relations of Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008), for the distance range 0–200 km.

Results and Discussion

Hazard maps of probabilistic peak ground acceleration (PGA), 0.2-second spectral acceleration for 5 percent critical damping (0.2sSA), and 1.0-second spectral acceleration for 5 percent critical damping (1.0sSA) for all modeled sources are presented in figures 6, 7, and 8, respectively. The “A” and “B” panels in each figure show maps for 2 percent and 10 percent probability of exceedance in 50 years (approximately 2,500- and 500-year return times, respectively). Probabilistic ground motions at Guam (Agana) and Saipan are summarized in table 2. Figures 9, 10, and 11 show hazard curves for Guam and Saipan with contributions from individual sources for PGA, 0.2sSA, and 1.0sSA, respectively. At both locations the dominant hazard source for all structural periods and all probability levels considered is the upper Benioff-zone seismicity. As the Pacific plate subducts westward, concentrations of Benioff-zone earthquakes trade off with depth and distance from the islands, with the result that seismicity at different depths can dominate the hazard at different locations. Figures 9–11 show that 41–80-km seismicity controls the hazard at Guam, whereas 81–120-km seismicity dominates at Saipan. These results can be further understood by considering appendix figure A3, which compares PGA hazard maps (2 percent probability of exceedance in 50 years) for individual seismic sources. Overall, the probabilistic ground motions are large, reflecting the high rates of activity and relative proximity of the Benioff-zone sources (especially at Guam), as well as their large maximum magnitudes (table 1). The shallow (0–40 km) seismicity is more diffuse and its hazard contribution is smaller. Owing to its distance from the islands and relatively small modeled activity rate, the Mariana megathrust is a minor contributor, even at 1.0-second period. (Note that the two megathrust hazard curves in figures 9–11 are not scaled by the 0.8 and 0.2 weights used in the final model.) Owing to their small slip rates, the two crustal faults are not major contributors, even at Agana. Both faults may be capable of larger earthquakes, however, and more complex hazard models might be warranted in other applications.

Table 2. Probabilistic ground motions (*g*) at Guam and Saipan.

[g, gravitational acceleration; %, percent; yr, year; PGA, peak ground acceleration; 0.2sSA, 0.2-second spectral acceleration for 5 percent damping; 1.0sSA, 1.0-second spectral acceleration for 5 percent damping]

Parameter	Guam (Agana)		Saipan	
	2% in 50 yr	10% in 50 yr	2% in 50 yr	10% in 50 yr
PGA	0.94	0.49	0.57	0.29
0.2sSA	2.86	1.43	1.75	0.83
1.0sSA	0.61	0.30	0.37	0.18

Figure 6. Probabilistic peak ground acceleration for all modeled sources for exceedance probabilities of A) 2 percent in 50 years and B) 10 percent in 50 years. [PGA, peak ground acceleration; %g, percent of gravitational acceleration; %, percent; y, year]—Continued

Figure 6. Probabilistic peak ground acceleration for all modeled sources for exceedance probabilities of A) 2 percent in 50 years and B) 10 percent in 50 years. [PGA, peak ground acceleration; %g, percent of gravitational acceleration; %, percent; y, year]

Figure 7. Probabilistic 0.2-second spectral acceleration (5 percent damping) for all modeled sources for exceedance probabilities of A) 2 percent in 50 years and B) 10 percent in 50 years. [0.2sSA, 0.2-second spectral acceleration; %g, percent of gravitational acceleration; %, percent; y, year]—Continued

B

0.2sSA(%g), 10 percent probability of exceedance in 50 years (all sources)

Figure 7. Probabilistic 0.2-second spectral acceleration (5 percent damping) for all modeled sources for exceedance probabilities of A) 2 percent in 50 years and B) 10 percent in 50 years. [0.2sSA, 0.2-second spectral acceleration; %g, percent of gravitational acceleration; %, percent; y, year]

Figure 8. Probabilistic 1.0-second spectral acceleration (5 percent damping) for all modeled sources for exceedance probabilities of A) 2 percent in 50 years and B) 10 percent in 50 years. [0.1sSA, 0.1-second spectral acceleration; %g, percent of gravitational acceleration; %, percent; y, year]—Continued

B

1.0sSA(%g), 10 percent probability of exceedance in 50 years (all sources)

Figure 8. Probabilistic 1.0-second spectral acceleration (5 percent damping) for all modeled sources for exceedance probabilities of A) 2 percent in 50 years and B) 10 percent in 50 years. [0.1sSA, 0.1-second spectral acceleration; %g, percent of gravitational acceleration; %, percent; y, year]

Figure 9. Peak ground acceleration hazard curves showing contributions by sources for Guam (top) and Saipan (bottom). [PGA, peak ground acceleration; Exceedance/yr, exceedance per year; g, gravitational acceleration; km, kilometer; M_w , moment magnitude; N, North; E, east]

Figure 10. Hazard curves (0.2-second spectral acceleration) showing contributions by sources for Guam (top) and Saipan (bottom). [0.2sSA, 0.2-second spectral acceleration; Exceedance/yr, exceedance per year; g, gravitational acceleration; km, kilometer; M_w , moment magnitude; N, North; E, east]

Figure 11. Hazard curves (1.0-second spectral acceleration) showing contributions by sources for Guam (top) and Saipan (bottom). [0.1sSA, 0.1-second spectral acceleration; Exceedance/yr, exceedance per year; g, gravitational acceleration; km, kilometer; M_w , moment magnitude; N, North; E, east]

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Appendix. Supplementary Data Supporting Mariana Islands Seismic Hazard Analysis

Earthquakes from the declustered catalog 1900–2011 with $M_w \geq 6$.

7.5	146.000	18.000	0	1902	09	22	01	46	0.	EVCABE 7.5MwP&S
7.1	143.000	22.000	450	1905	07	11	15	37	30.	EVCUTS 7.2mBAbE1
6.8	144.500	12.000	50	1909	12	09	23	28	48.	EVCG&R 6.8MsAN2
6.8	146.000	14.000	130	1912	10	26	09	00	36.	EVCG&R 7.0mBAbE1
7.0	145.500	14.500	0	1913	05	18	02	08	53.	EVCISS 7.0MsAN1
8.2	143.000	22.000	110	1914	11	24	11	53	30.	EVCG&R 7.9mBAbE1
6.2	148.000	18.000	35	1921	02	10	23	53	45.	ISC
6.6	143.000	22.000	35	1922	07	11	14	13	0.	EVCUTS 6.6MjUTSU
6.2	144.000	13.000	35	1924	01	30	04	47	43.	ISC
6.2	141.500	12.000	35	1925	07	17	03	13	53.	ISC
6.0	142.000	14.000	35	1925	07	17	22	31	04.	ISC
6.0	145.000	23.000	35	1926	04	22	23	47	52.	ISC
6.0	141.000	13.000	35	1927	07	17	08	48	33.	ISC
6.0	141.000	11.000	35	1928	02	13	05	33	37.	ISC
6.0	143.500	21.500	200	1928	12	19	15	15	50.	ISC
6.2	144.000	12.000	35	1929	01	17	22	28	42.	ISC
6.8	145.686	18.761	35	1929	03	10	14	34	34.9	EVCEHB 6.8UKG&R
6.2	147.000	14.000	35	1929	05	01	07	38	41.	ISC
6.2	141.000	11.000	35	1929	12	31	01	03	57.	ISC
6.2	146.500	18.500	190	1930	01	26	12	20	30.	ISC
7.0	146.570	18.351	35	1930	10	24	20	15	12.9	EVCEHB 7.0MsABE1
7.1	144.803	10.778	35	1931	01	28	21	24	10.9	EVCEHB 7.1MsABE1
7.0	145.489	19.152	172	1931	09	09	20	38	28.4	EVCEHB 7.1mBAbE1
6.5	146.000	17.000	520	1931	10	29	08	39	18.	ISC
6.2	147.000	17.000	100	1931	11	03	02	35	55.	ISC
6.0	148.000	20.000	130	1932	01	05	11	22	25.	ISC
6.0	146.000	13.500	90	1932	02	13	19	12	30.	ISC
6.8	147.460	15.733	35	1932	03	19	10	59	43.4	EVCEHB 6.8UKG&R
6.5	142.500	23.000	140	1932	09	02	12	56	30.	ISC
6.0	146.500	16.500	170	1932	11	03	19	42	53.	ISC
6.5	143.500	22.000	280	1932	12	26	22	31	06.	ISC
6.2	145.500	22.000	200	1933	05	21	21	54	05.	ISC
6.0	139.000	11.000	35	1933	07	18	19	05	22.	ISC
6.0	146.000	18.000	70	1933	11	07	06	39	58.	ISC
6.5	145.000	18.500	570	1934	02	04	03	10	45.	ISC
7.2	144.067	22.878	35	1934	02	24	06	23	46.8	EVCEHB 7.2MwP&S
6.5	146.000	18.000	210	1934	10	21	17	53	44.	ISC

6.0	147.000	18.500	35	1934	12	25	06	27	20.	ISC
6.0	146.000	19.000	200	1935	07	29	04	12	49.	ISC
6.9	141.705	12.322	35	1935	10	18	11	05	27.1	EVCEHB 6.9MsABE1
6.5	143.500	21.500	270	1935	12	14	12	47	29.	ISC
6.8	145.414	13.203	35	1936	10	29	18	38	50.3	EVCEHB 6.8UKPAS
6.2	147.000	17.500	170	1936	11	12	02	15	58.	ISC
6.2	145.750	19.250	190	1937	05	05	21	15	39.	ISC
6.5	145.500	19.000	120	1937	08	08	10	12	03.	ISC
6.2	146.000	20.500	140	1937	09	12	11	54	53.	ISC
6.2	143.500	12.000	90	1939	11	09	16	06	20.	ISC
7.3	148.218	17.244	31	1940	01	17	01	14	58.7	EVCEHB 7.3mBABE1
6.0	146.000	18.000	150	1940	08	15	21	23	28.	ISC
7.3	147.527	18.140	35	1940	12	28	16	37	46.6	EVCEHB 7.3mBABE1
6.2	146.000	15.500	35	1941	07	26	20	11	19.	ISC
6.8	148.008	14.548	49	1942	06	14	03	09	58.0	EVCEHB 7.0mBABE1
7.0	140.101	9.123	35	1942	06	18	09	31	00.9	EVCEHB 7.0MsABE1
6.8	142.000	9.500	0	1943	03	15	04	47	56.	EVCG&R 6.8UKG&R
6.7	146.000	19.000	170	1943	04	09	08	48	59.	EVCG&R 6.9mBABE1
6.9	143.000	13.000	110	1944	08	15	11	47	40.	EVCG&R 6.9UKG&R
6.8	146.500	14.500	60	1944	12	04	20	34	34.	EVCG&R 6.8UKG&R
7.0	146.500	17.500	120	1945	07	15	05	35	13.	EVCG&R 7.1mBABE1
6.9	145.500	21.500	0	1947	06	13	20	24	49.	EVCG&R 6.9MsABE1
6.8	142.500	22.000	240	1948	12	15	19	11	28.	EVCG&R 6.8UKG&R
6.6	148.000	16.000	50	1949	07	02	19	57	13.	EVCG&R 6.6MsABE1
6.8	147.600	16.400	191	1949	07	25	03	50	41.	EVCISS 6.8UKPAS
7.0	143.500	13.000	90	1950	05	25	18	35	07.	EVCG&R 7.1mBABE1
6.7	146.000	18.500	64	1953	02	14	21	48	16.	EVCISS 6.7MsROTHE
6.9	145.600	17.800	192	1953	07	26	16	53	20.	EVCISS 6.9MsROTHE
6.8	145.006	18.819	380	1956	02	01	13	41	52.6	EVCEHB 7.0mBABE1
6.7	144.267	21.776	107	1957	05	21	01	12	04.8	EVCEHB 6.9mBABE3
6.8	143.910	13.090	151	1957	06	10	03	13	17.	EVCISS 6.8UKPAS
6.8	146.090	13.430	0	1959	01	13	01	15	27.	EVCISS 6.8UKPAS
6.9	145.066	19.134	693	1962	03	07	11	01	06.2	EVCEHB 6.9MwHRV
6.3	144.637	11.719	33	1964	07	04	10	49	30.5	EVCEHB 6.0mbISC
6.5	146.309	20.764	44	1966	02	10	14	21	12.6	EVCEHB 6.5UKPAS
6.4	146.347	13.832	18	1966	05	20	09	14	44.3	EVCEHB 6.4UKPAS
7.1	139.641	11.302	50	1966	06	07	13	59	37.8	EVCEHB 7.1UKB&D
6.3	145.949	22.141	12	1966	10	27	14	21	03.7	EVCEHB 6.0mbISC
6.5	140.840	12.189	71	1967	08	26	00	36	48.1	EVCEHB 6.1mbISC
6.2	143.107	21.594	306	1969	08	15	08	41	54.8	EVCEHB 6.2MwHRV
6.2	143.857	12.169	37	1970	03	04	03	30	37.7	EVCEHB 6.2MsUSCGS
6.1	145.370	18.583	621	1970	05	10	20	05	18.8	EVCEHB 6.1MwHRV
6.4	147.702	17.705	59	1970	09	01	05	11	19.9	EVCEHB 6.4MsUSCGS

6.3	142.549	11.857	16	1971	10	23	22	33	31.	EVCEHB 6.3MsNEIS
6.4	142.442	11.900	33	1971	10	24	01	37	32.2	EVCEHB 6.4MsNEIS
6.0	144.274	12.616	71	1974	03	24	04	21	06.4	EVCEHB 5.8mbISC
7.0	144.813	13.851	108	1975	11	01	01	17	34.7	EVCEHB 7.1mBABE3
6.6	145.970	10.532	13	1975	11	30	13	32	33.7	EVCEHB 6.6UKPAS
6.4	145.448	18.814	216	1977	05	24	10	23	25.7	EVCEHB 6.4MwHRV
6.2	143.215	11.829	15	1977	09	17	05	23	28.9	EVCEHB 6.2MwHRV
6.7	145.437	19.015	241	1979	05	13	06	26	08.2	EVCEHB 6.7MwHRV
7.0	145.409	18.521	583	1979	10	17	05	43	02.8	EVCEHB 7.0MwHRV
6.0	145.522	16.578	316	1981	06	07	21	40	37.2	EVCEHB 6.0MwHRV
6.3	143.546	22.315	114	1982	02	27	16	16	54.3	EVCEHB 6.3MwHRV
6.1	144.974	13.867	109	1983	02	13	06	35	31.5	EVCEHB 6.1MwHRV
6.0	140.983	10.561	39	1983	02	14	00	23	21.2	EVCEHB 6.0MwHRV
6.3	145.854	18.120	159	1983	09	14	11	25	02.3	EVCEHB 6.3MwHRV
6.1	145.372	13.876	104	1984	09	22	18	10	37.4	EVCEHB 6.1MwHRV
6.0	143.334	22.609	121	1984	12	04	07	43	23.1	PDE
6.0	144.314	12.314	28	1985	05	31	07	24	34.9	EVCEHB 6.0MwHRV
6.0	140.277	11.157	27	1985	08	11	00	19	03.5	EVCEHB 6.0MwHRV
6.6	146.368	19.366	51	1986	09	16	18	20	19.6	EVCEHB 6.6MwHRV
6.1	147.003	18.796	26	1987	04	14	02	08	15.6	EVCEHB 6.1MwHRV
6.3	145.894	18.501	126	1988	05	04	23	47	04.2	EVCEHB 6.3MwHRV
6.3	145.767	17.466	164	1989	12	23	11	24	04.4	EVCEHB 6.3MwHRV
7.4	147.596	15.150	18	1990	04	05	21	12	38.3	EVCEHB 7.4MwHRV
6.0	144.807	14.068	155	1991	02	10	14	15	21.2	EVCEHB 6.0MwHRV
6.0	145.654	18.541	195	1991	10	26	02	27	33.3	EVCEHB 6.0MwHRV
6.2	145.786	18.368	154	1993	01	18	01	18	08.0	EVCEHB 6.2MwHRV
6.4	146.630	15.782	29	1993	06	06	13	23	24.9	EVCEHB 6.4MwHRV
7.8	144.838	12.983	62	1993	08	08	08	34	26.7	EVCEHB 7.8MwHRV
6.0	145.699	13.173	27	1993	08	11	14	17	40.2	EVCEHB 6.0MwHRV
6.3	145.421	18.506	222	1994	12	30	15	12	27.0	EVCEHB 6.3MwHRV
6.2	142.748	21.744	271	1995	04	08	17	45	14.5	EVCEHB 6.2MwHRV
7.1	145.279	18.814	598	1995	08	23	07	06	04.4	EVCEHB 7.1MwHRV
6.5	145.780	17.368	151	1996	06	09	01	12	18.8	EVCEHB 6.5MwHRV
6.5	144.992	13.991	101	1997	04	23	19	44	29.9	EVCEHB 6.5MwHRV
6.0	144.798	13.208	29	1997	05	09	09	06	39.0	EVCEHB 6.0MwHRV
6.3	148.202	17.099	19	1998	08	30	01	48	08.4	EVCEHB 6.3MwHRV
6.0	143.209	11.858	12	1998	09	22	01	16	57.5	EVCEHB 6.0MwHRV
6.0	144.720	12.867	48	1999	12	19	00	48	38.3	EVCEHB 6.0MwHRV
6.2	144.808	13.831	114	2000	02	26	08	11	47.9	EVCEHB 6.2MwHRV
7.6	143.711	22.232	105	2000	03	28	11	00	20.7	EVCEHB 7.6MwHRV
6.0	147.568	17.444	14	2000	05	02	15	03	33.0	EVCEHB 6.0MwHRV
6.0	139.240	11.375	19	2000	05	26	00	30	04.7	EVCEHB 6.0MwHRV
6.2	144.856	11.748	15	2000	12	19	13	11	46.0	EVCEHB 6.2MwHRV

6.0	147.073	18.799	34	2001	06	15	06	17	46.9	EVCEHB 6.0MwHRV
6.5	143.040	21.632	303	2001	07	03	13	10	45.3	EVCEHB 6.5MwHRV
7.0	145.051	12.724	43	2001	10	12	15	02	19.4	EVCEHB 7.0MwHRV
7.1	144.619	13.088	85	2002	04	26	16	06	07.	PDE 7.10mwGS
6.1	140.690	10.985	33	2002	06	10	22	48	36.2	PDE 6.10mwGS
6.5	146.199	14.101	30	2002	08	14	13	57	52.1	PDE 6.50mwHRV
6.0	143.246	22.321	101	2003	11	11	18	48	23.7	PDE 6.00mwGS
6.0	146.993	14.546	7	2004	10	04	19	20	34.9	PDE 6.00mwHRV
6.60	140.842	10.934	24	2005	01	16	20	17	52.7	PDE 6.60mwGS
6.30	144.715	14.080	158	2005	02	02	02	30	25.9	PDE 6.30mwHRV
6.60	145.867	16.011	142	2005	02	05	03	34	25.7	PDE 6.60mwHRV
6.00	145.801	20.134	48	2005	08	13	07	36	52.7	PDE 6.00mwHRV
6.10	140.995	12.232	22	2005	12	20	05	51	12.5	PDE 6.10mwGS
6.30	146.180	20.821	40	2006	02	14	15	27	23.3	PDE 6.30mwHRV
6.60	144.705	20.980	20	2007	01	30	21	37	44.3	PDE 6.60mwGCMT
7.50	142.668	22.013	260	2007	09	28	13	38	57.8	PDE 7.50mwGCMT
6.90	145.718	10.454	14	2007	09	30	02	08	30.1	PDE 6.90mwGS
6.10	147.148	18.730	20	2007	10	06	12	38	49.1	PDE 6.10mwGCMT
7.20	145.388	18.900	207	2007	10	31	03	30	15.9	PDE 7.20mwGS
6.80	143.181	12.516	76	2008	05	09	21	51	29.7	PDE 6.80mwGCMT
6.10	144.703	19.335	457	2010	03	08	09	47	11.6	PDE-W 6.10mwGS
6.30	145.999	11.143	13	2010	07	10	11	43	32.7	PDE-W 6.30mwUCMT
6.90	141.476	12.484	10	2010	08	13	21	19	33.0	PDE-W 6.90mwUCMT

Figure A1. Four seismicity cross-sections across the Mariana plate boundary. In the north (A, B) the Benioff zone dips steeply and earthquakes occur down to about 700 kilometers. Southwestward (C, D) the Benioff zone dips more shallowly and very deep earthquakes have not been observed. (See fig. 1 in text for explanation of geographic and tectonic features.—Continued

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Figure A2. Maps of earthquakes from three sources: A, Engdahl-Villaseñor Centennial catalog (Engdahl and Villaseñor, 2002); B, International Seismological Centre catalog (International Seismological Centre, 2011); and C, Preliminary Determination of Epicenters catalog (U.S. Geological Survey, 2012b). (See fig. 1 for explanation of geographic and tectonic features; see fig. 3 for map of final declustered catalog used in the hazard analysis.)—Continued

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Figure A3. Maps of probabilistic peak ground acceleration for 2 percent probability of exceedance in 50 years showing hazard from individual sources: A, all modeled sources (same as fig. 6A); B, 0–40-km-deep seismicity, 50 percent Next Generation Attenuation + 50 percent Zhao-crustal attenuation [$0.5\text{-nga} + 0.5\text{-zhaoC}$]; C, 41–80-km-deep seismicity, 70 percent Zhao-inslab as-published + 30 percent Zhao-inslab Pacific-adjusted attenuation plus epistemic [$0.7\text{-zhaoIS} + 0.3\text{-zhaoIS}' + \text{epistemic}$]; D, 81–120-km-deep seismicity, same attenuation as C; E, 121–160-km-deep seismicity, same attenuation as C; F, 161–700-km-deep seismicity, same attenuation as C; G, megathrust with 80 percent $\text{MW}_{\text{max}}=8$ + 20 percent $\text{MW}_{\text{max}}=9$, Zhao interface attenuation plus epistemic [$0.8\text{-M}_{\text{max}}8 + 0.2\text{-M}_{\text{max}}9, \text{zhaoIF} + \text{epistemic}$]; H, Guam crustal faults, Next Generation Attenuation plus epistemic [$\text{nga} + \text{epistemic}$] (note change in scale). [PGA, peak ground acceleration; %g, percent of gravitational acceleration; 02px50, 2 percent probability of exceedance in 50 years; km, kilometer; MW_{max} , maximum moment magnitude]—Continued

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Figure A3. Maps of probabilistic peak ground acceleration for 2 percent probability of exceedance in 50 years showing hazard from individual sources: A, all modeled sources (same as fig. 6A); B, 0–40-km-deep seismicity, 50 percent Next Generation Attenuation + 50 percent Zhao-crustal attenuation [$0.5 \times \text{nga} + 0.5 \times \text{zhaoC}$]; C, 41–80-km-deep seismicity, 70 percent Zhao-inslab as-published + 30 percent Zhao-inslab Pacific-adjusted attenuation plus epistemic [$0.7 \times \text{zhaoIS} + 0.3 \times \text{zhaoIS}' + \text{epistemic}$]; D, 81–120-km-deep seismicity, same attenuation as C; E, 121–160-km-deep seismicity, same attenuation as C; F, 161–700-km-deep seismicity, same attenuation as C; G, megathrust with 80 percent $\text{MW}_{\text{max}}=8$ + 20 percent $\text{MW}_{\text{max}}=9$, Zhao interface attenuation plus epistemic [$0.8 \times \text{M}_{\text{max}}8 + 0.2 \times \text{M}_{\text{max}}9, \text{zhaoIF} + \text{epistemic}$]; H, Guam crustal faults, Next Generation Attenuation plus epistemic [$\text{nga} + \text{epistemic}$] (note change in scale). [PGA, peak ground acceleration; %g, percent of gravitational acceleration; 02px50, 2 percent probability of exceedance in 50 years; km, kilometer; MW_{max} , maximum moment magnitude]—Continued

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