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ESTIMATING SEISMIC HAZARD WITH SPARSE DATA: SEISMIC SOURCE MODEL AND SENSITIVITY OF A PSHA FOR PALMER STATION, ANTARCTICA

J. Feenstra, A. Hull, & F. Li
Golder Associates Inc., United States.

J. Fraser, M. Howard, & T. McMorran
Golder Associates (NZ) Ltd., Christchurch, New Zealand.

ABSTRACT

A site-specific probabilistic seismic hazard analysis (PSHA) has been used to develop ASCE 7-10 seismic design parameters for Palmer Station, Anvers Island, Antarctica. Seismic sources located within 200 km of Palmer Station include an active seafloor spreading centre, back-arc volcanism, and a potentially active subduction zone. Global earthquake catalogues, however, lack sufficient records to adequately characterize the seismic source zones for a site-specific PSHA. In this study, we augmented global earthquake catalogues with the results from temporary seismic networks to characterize the seismotectonics surrounding Palmer Station. Where there were insufficient earthquake data to develop stable earthquake activity rate estimates, several analogue regions were used for the site-specific seismic source model. The ASCE 7-10 maximum considered earthquake (MCE) 0.2-second (S_S) and 1-second (S_1) values are low at 0.17 and 0.06 g, respectively. The S_{MS} and S_{M1} values are about 20% lower when adjusted for the site-specific Site Class A condition at Palmer Station. The primary contributor to the MCE S_S hazard is the subduction zone intraslab seismic source, while the shallow crustal earthquakes contribute most to the S_1 spectral period. Mean earthquake ground motions developed in this study have significant uncertainties that reflect the lack of knowledge of long-term earthquake activity rates in Antarctica. A sensitivity analysis of the mean ground motions to uncertainty in the seismic source model and ground motion models (GMMs) used in this study indicates that the results are most sensitive to the uncertainty in the GMMs, particularly the GMMs for the subduction zone intraslab source zone.

1 INTRODUCTION

Seismic hazard analysis requires the development of a seismic source model for the region of interest based on the analysis and interpretation of geological, tectonic, and seismological information. Prior to the start of the International Geophysical Year in 1957, however, very little was known about the seismotectonics of Antarctica, which was thought to be largely aseismic (Richter 1958; Gutenberg and Richter 1954). During the last 50 years, the monitoring of earthquakes in Antarctica has steadily increased. A variety of geophysical methods have been employed to characterize the seismotectonics of Antarctica, particularly the Antarctic Peninsula and South Shetland Islands region (Fig. 1). This paper presents the results of a site-specific probabilistic seismic hazard analysis (PSHA) for Palmer Station, located on the southern side of Anvers Island, west of the main Antarctic Peninsula (Fig. 1). We attempt to overcome the sparse and relatively recent instrumental earthquake record for this part of Antarctica by integrating both global and campaign seismic data into the seismic source model developed for the PSHA. This paper describes the development and quantifications of the site-specific seismic source model, selected results and sensitivity of the site-specific PSHA, and discussion of the remaining uncertainties.

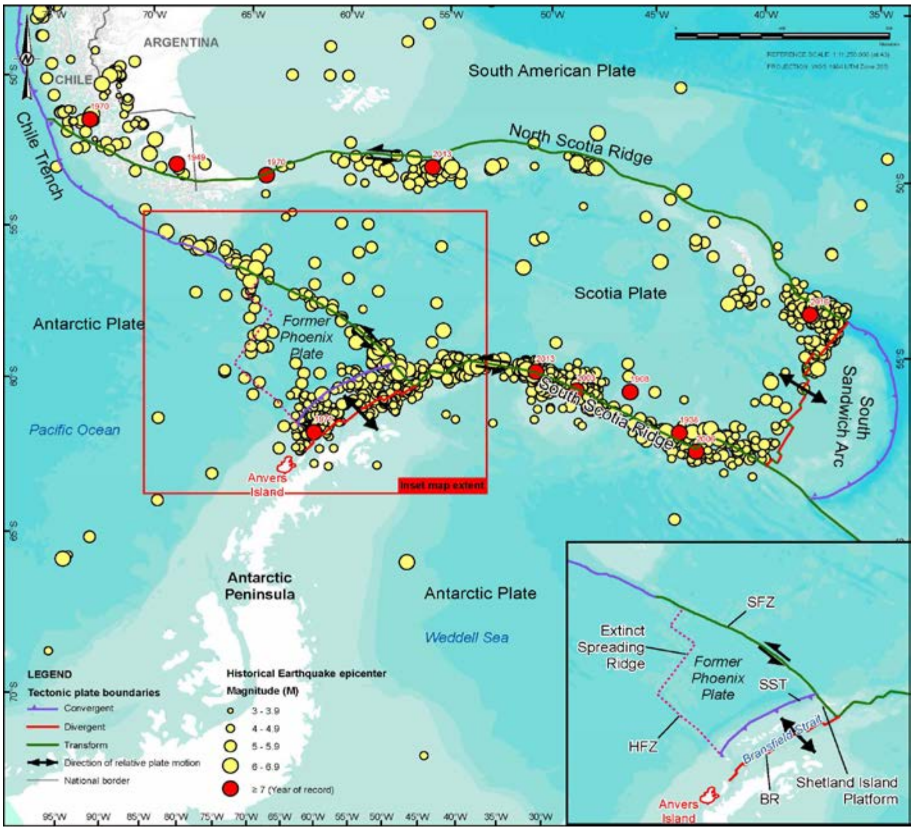

Figure 1. Regional plate tectonic map and historical earthquake epicentres (full catalogue) showing the northern part of the Antarctic Peninsula and southern tip of South America. HFZ - Hero Fracture Zone, SFZ - Shackleton Fracture Zone, BR - Bransfield Rift, SST - South Shetland Trench.

2 SITE-SPECIFIC SEISMIC SOURCE MODEL

The site-specific seismic source model developed for the Palmer Station site comprises three uniform area source zones, one subduction zone intraslab source, and one subduction zone interface source located within about 300 km of Palmer Station (Fig. 2). Seismogenic fault sources were not included in the model because current information indicates no evidence for discrete shallow crustal faults.

Different methods were used to estimate the earthquake recurrence parameters for the seismic sources developed for this study. Where there is a sufficient number of observed earthquakes to obtain a robust estimate on the recurrence parameters, the Weichert (1980) method was used to estimate earthquake recurrence. For most of the seismic sources in this region, however, there are insufficient data because of the low earthquake occurrence rate and/or the short duration and low density of the earthquake monitoring networks. For these seismic sources, analogue regions were identified based on similarity in tectonic and geological setting, and recurrence parameters were adopted from those analogue regions. Details of the characterization of the sources within the seismic source model are summarized below. Parameters used for the seismic sources in this study are listed in Table 2 at the end of this section.

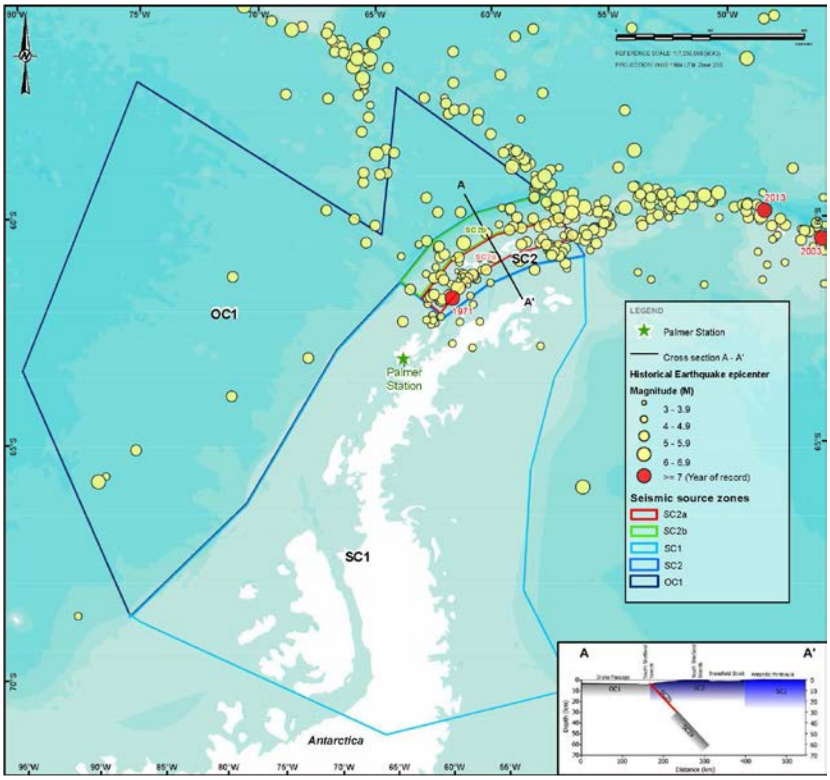

Figure 2. Historical earthquake epicentres (declustered catalogue) and seismic source zones used for site-specific seismic hazard analysis.

2.1 Project Earthquake Catalogue

A site-specific earthquake catalogue was developed to evaluate the spatial and temporal distribution of observed earthquakes for a wide region surrounding Palmer Station. Earthquakes within approximately 1000 km of Palmer Station obtained from global earthquake catalogues were combined to form the project catalogue. Due to distant global seismic station spacing of 20º or more and a detection threshold of approximately body wave magnitude (mb) 5 since the 1960s (Larter 2001), global earthquake catalogues are incomplete for lower magnitude earthquakes and lack sufficient records to adequately characterize seismic source zones for a PSHA. Global catalogues, therefore, were augmented with earthquakes identified by temporary seismic arrays (Robertson Maurice et al. 2003; Ibáñez et al. 1997) to develop the project catalogue.

After combining the individual earthquake catalogues, automatic and manual procedures were used to remove duplicate records. Earthquake magnitudes were then normalized to a common magnitude scale, moment magnitude (**M**), using the relationships of Storchak et al. (2012) for Ms[1] and mb to **M**, and for earthquakes with $M_L \geq 5$, we assume that M_L is equivalent to **M**. The resulting earthquake catalogue, referred to as the "full catalogue", includes about 2,205 event records of **M**≥3.0 from 1879 to October 2016 (Fig. 1). The full catalogue was then "declustered" to remove dependent events (foreshocks and aftershocks) using the algorithm proposed by Gardner and Knopoff (1974). The final declustered catalogue with **M**≥3.0 contains 942 records (Fig. 2).

2.2 Uniform Area Sources

Figure 2 shows the three uniform area source zones developed for this study. The source zone boundaries are based on approximate plate boundary locations and distribution of historical earthquakes (Fig. 1).

2.2.1 Shallow Crustal Source 1 (SC1)

Uniform area source zone SC1 incorporates shallow crustal earthquakes associated with the Antarctic Peninsula. The Antarctic Peninsula appears to have a very low rate of earthquake occurrence; however, the seismicity rate may be underestimated because of the wide seismic network station spacing and/or is suppressed by present-day ice loading (Reading 2002). Palmer Station is located within area source SC1.

We identified 13 earthquakes recorded within area source zone SC1, all of which are concentrated along the northern boundary of the source zone near the South Shetland Island region. Nine of the earthquakes identified in this source zone were located by temporary seismic arrays deployed in the late 1990s (Robertson Maurice et al. 2003). The majority of observed earthquakes occur between a depth of about 5 and 15 km below the ground surface (bgs), and range in magnitude from **M**4.7 to **M**5.1.

We considered there to be insufficient data to calculate reliable recurrence parameters for SC1. Therefore, we identified analogue regions as a way to estimate the recurrence parameters for SC1. Criteria for suitable analogue regions included extended continental margin type tectonic setting with low rates of observed seismicity. Analogue regions identified included the state of Florida in the United States, the northern Rocky Mountain fold and thrust belt of British Columbia, Canada, and the stable shallow crust of the southern Andes in South America. The recurrence parameters for these analogue regions were obtained from the 2014 USGS National Seismic Hazard Maps (USGS2014), the Fifth Generation Seismic Hazard Model for the 2015 National Building Code of Canada (NBCC2015), and the South America Risk Assessment (SARA) study performed by GEM (2016), respectively.

After estimating recurrence parameters based on these analogue regions and assuming a Gutenberg-Richter recurrence model (G-R model; Gutenberg and Richter 1954), the mean activity rate for minimum **M**5 is within 0.006 km^{-2} yr^{-1} of the worldwide rate estimated for stable cratonic regions (Fenton et al. 2006). We consider the recurrence parameters calculated from these analogue regions provide a reasonable range of activity rates and *b-values* for SC1.

2.2.2 Shallow Crustal Source 2 (SC2)

Uniform area source SC2 extends along the South Shetland trench parallel to the Antarctic Peninsula and includes the South Shetland Island platform and the Bransfield Strait. The South Shetland Island platform is considered to be the only tectonically active portion of the Antarctic continental margin (Taylor et al. 2008). At its closest, area source SC2 is located approximately 150 km northeast of Palmer Station.

[1] Ms is the surface wave magnitude; mb is the body wave magnitude; M_L is the local magnitude.

We identified 77 earthquakes within area source zone SC2 with magnitudes ranging from **M**3 to **M**7, and about 50 earthquakes with magnitudes ranging from **M**5 to **M**7. The majority of observed earthquakes occur at a depth of about 5 to 12 km bgs.

Earthquake records for SC2 were evaluated for temporal completeness and grouped in different magnitude intervals. Catalogue completeness was evaluated following the procedures of Mulargia and Tinti (1985). We considered there to be insufficient data to estimate the completeness periods for earthquakes with magnitudes greater than **M**6.0, so completeness periods from the global ISC catalogue (Storchak et al. 2012) were referred to for the remaining earthquakes. The reference years obtained in the catalogue completeness analysis for each magnitude interval are listed in Table 1.

The Weichert (1980) method was used to estimate the best fitting *b-value* and activity rate, as well as the lower and upper bound recurrence parameters for the assigned completeness periods. The lower and upper bound values equal the best-estimate plus and minus one standard deviation, respectively.

Table 1: Catalogue Completeness Years for Uniform Area Sources SC2 and OC1.

Magnitude (M)	**SC2 Year**	**OC1 Year**
5.0≤**M**< 5.5	1966	1967
5.5≤**M**< 6.0	1975	1979*
6.0≤**M**< 6.5	1960*	1960*
6.5≤**M**< 7.0	1960*	1918*
7.0≤**M**< 8.0	1917*	1917*

* Completeness period from global ISC catalogue (Storchak et al. 2012).

2.2.3 Oceanic Crustal Source (OC1)

Uniform area source OC1 encompasses oceanic crustal earthquakes to the northwest of the Antarctic Peninsula. The oceanic plate is thought to be capable of producing very large earthquakes with a recurrence interval of several hundred years, as indicated by the 1998 **M**8.1 earthquake that occurred in the Balleny Islands region (Reading 2007). At its closest, area source OC1 is located approximately 140 km northwest of Palmer Station.

We identified 15 earthquakes within area source zone OC1 with magnitudes ranging from **M**5 to **M**6.3 and occurring at a depth of about 5 to 12 km bgs. The completeness periods and earthquake recurrence parameters were estimated for OC1 following the procedure outlined above for area source SC2. The reference years obtained in the catalogue completeness analysis for each magnitude interval are listed in Table 1.

2.3 Subduction Zone Sources

Based on a literature review, active, albeit very slow, subduction may occur at the South Shetland Trench (e.g. Robertson Maurice et al. 2003; Ibáñez et al. 1997; Pelayo and Wiens 1989; Yegerova et al. 2011; Guidarelli and Panza 2006). Active subduction could produce interface and/or deep intraslab earthquakes. Some researchers, however, suggest that subduction ceased ca. 3 to 4 million years ago (e.g. Barker 1982; Galindo-Zaldivar et al. 1996; Gracia et al. 1996), and if so, present-day subduction interface earthquakes are absent or very infrequent. To account for the possibility that subduction at the trench is either (1) occurring very slowly or (2) ceased, a simplified subduction zone interface seismic source zone with a 10% probability of activity was included in the seismic source model. Because intraslab events can occur in both active and inactive subduction zone slabs, and because instrumental earthquakes have been located in the subducting slab (Robertson Maurice et al. 2003; Ibáñez et al. 1997; Pelayo and Wiens 1989), the subduction zone intraslab seismic source is included with a 100% probability of activity.

2.3.1 Subduction Zone Intraslab Source (SC2a)

The subduction zone intraslab source (SC2a) is modelled as a 25º southeast-dipping plane from 30 km to 65 km depth. The geometry of the subducted slab is based on seismic, gravity, and magnetic models of the lithospheric structure of the Antarctic Peninsula and continental margin (e.g. Robertson Maurice et al. 2003; Pelayo and Wiens 1989; Yegerova et al. 2011; Grad et al. 2993; Grad et al. 2002). Assuming that the north western boundary of area source SC2 coincides with the South Shetland Trench, the surface trace of the trench to a depth of 30 km and 65 km (dip angle of 25º) is used to model the upper and lower traces of SC2a, respectively. The seismogenic thickness of the slab is approximately 5 to 10 km based on the results of Yegerova et al. (2011). At its closest, SC2a is located approximately 150 km northeast of Palmer Station.

We considered there to be insufficient data to estimate the recurrence parameters for SC2a based on observed intraslab earthquakes. Based on a review of available literature, we considered the Cascadia subduction zone (CSZ) of western North America to be an appropriate analogue to the South Shetland subduction zone (Larter 2001; Robertson Maurice et al. 2003; Yegerova et al. 2011). The lithosphere of the Juan de Fuca plate subducts slowly, similar to the lithosphere in the South Shetland Islands region, and the seismicity distribution of Cascadia is similar to that observed in the South Shetland Island region (Robertson Maurice et al. 2003).

Both the USGS2014 and the NBCC2015 models provide estimates of activity rates for CSZ deep intraslab seismic sources and indicate similar earthquake recurrence in the CSZ intraslab. Earthquake activity rates decrease relatively slowly from **M**5.0 to about **M**7.2, then decrease at a much higher rate for **M**7.2 and greater magnitude earthquakes. The recurrence curve estimated here for SC2a closely resembles those from the USGS2014 and the NBCC2015 models.

2.3.2 Subduction Zone Interface Source (SC2b)

Similar to the intraslab source, SC2b is modelled as a 25º southeast-dipping plane from 5 to 30 km depth. At its closest, SC2b is located approximately 160 km north of Palmer Station. We considered there to be insufficient data to estimate the recurrence parameters for SC2b based on the observed seismicity. Due to a lack of knowledge of the earthquake activity rate for this subduction zone interface, we adopted the average global *b-value* for the G-R relation (1.0) and assumed an 80:20 combination of pure characteristic and exponential earthquake recurrence behaviour. Assuming that the rate of convergence across the South Shetland Trench is comparable to the spreading rate observed in the Bransfield Strait—approximately 10 mm/yr (GEM-SARA 2016), —and because very little is known about the ratio of plate coupling at the trench, we estimated that about half of the convergence could be accommodated at the subduction interface, for an average annual slip rate of 5 mm/yr.

2.4 Fault Mechanism

The fault mechanism was estimated for the uniform area sources based on the expected faulting style associated with the tectonic regime. The faulting mechanisms for the uniform area sources were assumed to be a weighted combination of reverse, normal, and strike-slip. For SC1 and OC1, a higher weight was given to the reverse faulting mechanism because of the compressional stress field in these regions. A higher weight was given to the normal faulting mechanism for the SC2 source because the spreading centre occurs in this seismic source zone.

2.5 Maximum Earthquake Magnitudes

The maximum earthquake magnitude of the uniform shallow crustal area sources—SC1 and SC2—is based on the typical maximum magnitude for shallow continental crust—**M**7.5. The maximum magnitude of the oceanic crustal area source (OC1) was assumed to be **M**8.1 based on the 1998 **M**8.1 earthquake that occurred in the Balleny Islands region (Reading 2007).

The maximum magnitude of the intraslab source was assumed to be **M**7.5 based on typical subduction zone intraslab sources used in other PSHA studies. The maximum magnitude for the interface source was estimated using the empirical earthquake-magnitude scaling equation of Strasser et al. (2010) that was determined by Stirling and Goded (2012) to be the most suitable magnitude scaling relation for subduction interface megathrust events. Using a full trench length of 450 km, a seismogenic depth of 30 km (Yegerova et al. 2011), and a dip of 25º degrees (Robertson Maurice et al. 2003; Pelayo and Wiens 1989; Yegerova et al. 2011; Grad et al. 1993; Grad et al. 2002), the maximum magnitude of the interface source is estimated to be **M**8.25.

2.6 Seismogenic Depth

To capture the full range of uncertainty in the seismogenic depth, we modelled the seismogenic thickness of the crust as indicated in Table 2. The depth alternatives were selected based on observed seismicity, average continental and oceanic crustal thickness, typical crustal thickness of spreading centres, and crustal thicknesses reported in the literature (e.g. Grad et al. 1993; Grad et al. 2002).

The maximum seismogenic depth of the intraslab source is approximately 65 km (Robertson Maurice et al. 2003; Pelayo and Wiens 1989; Yegerova et al. 2011). The minimum seismogenic depth of the intraslab and maximum seismogenic depth of the interface source (30 km) is estimated from joint geophysical and petrological profiles of Yegerova et al. (2011) that show the interpreted maximum depth of brittle continental crust overriding the subducting oceanic plate.

Table 2: Recurrence Parameters for Seismic Source Zones.

Source Zone Name	Dist. to Site (km)	Min. Mag[1]	Max Mag, L-P-U[2]	Recurrence Model						Fault Type[4]	Min Depth (km)	Max Depth (km),
				Preferred		Lower Bound		Upper Bound				
				b-value	AR[3]	*b-value*	AR	*b-value*	AR			
SC1	5	5	7.2-7.5-7.8	0.85	2.5 e-2	1.0	1e-2	0.7	4e-2	R-SS-N (0.6-0.2-0.2)	5	12-15-25
SC2	147	5	7.2-7.5-7.8	1.0	0.9	1.16	0.68	0.85	1.2	N-SS-R (0.5-0.3-0.2)	5	8-12-20
OC1	139	5	8.1	0.98	2.5 e-1	N/A	N/A	N/A	N/A	R-SS-N (0.6-0.2-0.2)	5	10-12-15
SC2a – low[5]	146	5	7.2	0.5	0.2	0.6	0.1	0.4	0.3	Intra-slab	30	65
SC2a – high[5]	146	7.2	7.5	0.8	5e-4	0.8	2e-4	0.8	1e-3	Intra-slab	30	65

SC2b	159	5	7.95-8.25-8.55	1	5[6]	N/A	N/A	N/A	N/A	Inter-face	5	30

N/A = not applicable.

1. The earthquake magnitude is in moment magnitude scale (**M**).
2. The lower (L) and upper (U) bounds are both weighted 0.2. The preferred (P) value is weighted 0.6.
3. AR is the activity rate in events per year at the minimum earthquake magnitude.
4. Fault type is indicated as follows: (SS) strike slip; (R) reverse; (N) normal. Weighting for each fault type provided in parentheses below fault type.
5. "Low" and "high" source zone names indicate recurrence models for low magnitude range and high magnitude range, respectively.
6. Slip rate in mm/yr provided for area source SC2b.

2.7 Ground Motion Models (GMMs)

Four Next Generation Attenuation (NGA-West2) GMMs were used to model earthquake ground motion attenuation for the crustal uniform area sources: Abrahamson et al. (2014), Boore et al. (2014), Campbell and Bozorgnia (2014), and Chiou and Youngs (2014). These GMMs are applicable to plate boundary regions such as western Antarctica. For shallow crustal area sources SC1 and SC2, the four NGA-West2 GMMs were given equal weights in the seismic hazard model. In addition to the four NGA-West2 GMMs, the Atkinson-Boore (2006) GMM was also employed for the oceanic crustal area source (OC1) since this GMM was developed to simulate expected ground motions for various site conditions for earthquakes in stable craton regions and since there are no GMMs developed and published in well-recognized journals specifically for oceanic crustal regions. For OC1, the Atkinson-Boore (2006) GMM was weighted 0.5 and the four NGA-West2 GMMs were each weighted 0.125.

For the subduction zone intraslab source, we used BCHydro (2012), Zhao et al. (2006), and Atkinson and Boore (2003, worldwide) GMMs. These GMMs were developed for earthquake ground motion prediction at the surface for earthquakes occurring deep within subduction zones and were recommended by Stewart et al. (2013, 2015) for global subduction zones. BCHydro (2012) was developed with the most up-to-date strong motion recordings, it was therefore preferred and weighted 0.5, while Zhao et al. (2006) was weighted 0.3 and Atkinson and Boore (2003, worldwide) was weighted 0.2.

For the subduction zone interface source, only BCHydro (2012) and Zhao et al. (2006) GMMs were used in this analysis as Atkinson and Boore (2003, worldwide) is considered to underpredict the rate of attenuation for subduction interface sources, particularly for large magnitude earthquakes (Stewart et al. 2013; 2015). The two GMMs were equally weighted in this study.

3 SITE-SPECIFIC SEISMIC HAZARD ANALYSIS

The site-specific seismic hazard for Palmer Station was calculated for the maximum considered earthquake (MCE) with a reference site condition of $V_{S,30}$ of 760 m/s (corresponding to a soil Site Class B/C boundary in ASCE 7-10 [2013]) and return period of 2,475 years. Spectral accelerations (5%-damped) were calculated based on procedures described by Cornell (1968) and McGuire (1976, 2004). The MCE uniform hazard acceleration response spectrum (5%-damped) was then modified using ASCE 7-10 amplification factors to estimate the soil-modified MCE acceleration response spectrum for the site-specific soil condition—Site Class A. Logic tree analyses were used to account for epistemic uncertainties in the location, magnitude, and mechanisms of future earthquakes.

The site-specific PSHA results indicate mean 0.2 second (S_S), 1.0 second (S_1), and horizontal peak ground acceleration (PGA) values for the Palmer Station MCE of 0.17 g, 0.06 g, and 0.08 g, respectively. For Site Class A and a return period of 2,475 years, the mean 0.2 second, 1.0 second, and horizontal PGA values are

0.14 g, 0.05 g, and 0.06 g, respectively. These acceleration values indicate a very low seismic hazard for the Palmer Station site. Hazard deaggregation by seismic source indicates that the dominant contributor to seismic hazard at spectral periods from PGA to about 0.5 seconds is the subduction zone intraslab source (SC2a). At a spectral period of 1 second, the dominant contributor to the seismic hazard is uniform area source SC2.

The sensitivity of the mean ground motions to uncertainty in both the seismic source model and GMMs was assessed and depicted as tornado plots in Figure 3. The sensitivity was assessed by selecting a node of the logic tree, giving one branch a weight of unity and the others a weight of zero, calculating the mean hazard and then repeating the process for all branches at the same node. Each point in Figure 3 represents a 2,475-year return period spectral acceleration calculated for a logic tree branch. The broader the scatter between the points for the same node, the higher the sensitivity of ground motions to the associated input uncertainty. As anticipated, ground motions are very sensitive to the uncertainty in GMMs, particularly the intraslab GMMs. The ground motions are also relatively sensitive to the recurrence parameters and depth of the uniform area source zones.

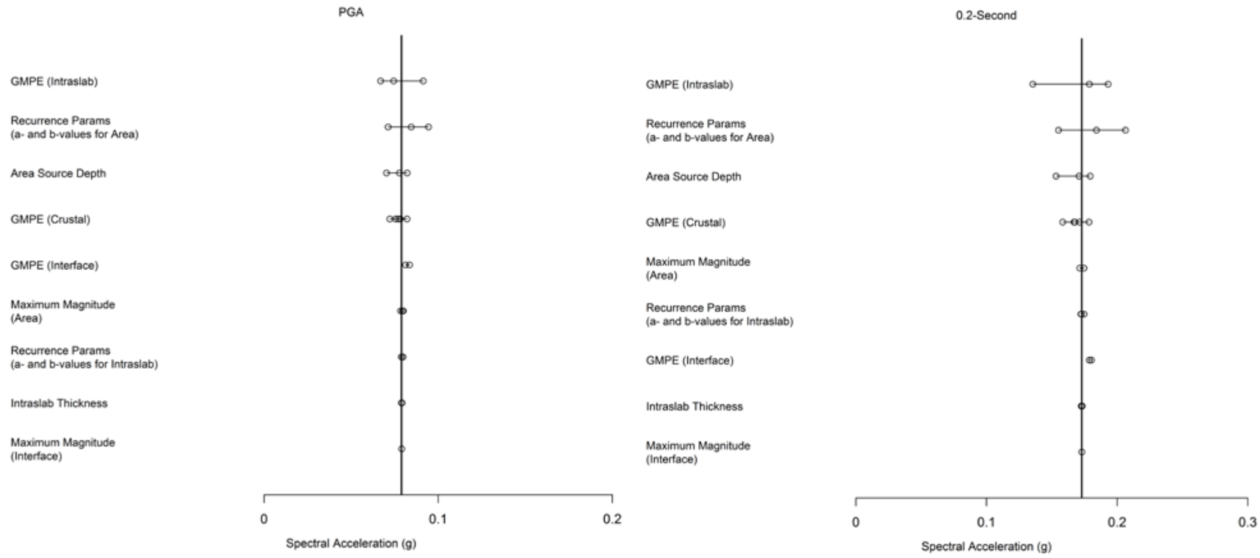

Figure 3 Tornado plots for 2,475-year return period PGA and 0.2 second spectral accelerations.

4 SUMMARY AND CONCLUSIONS

The pattern and occurrence of historical earthquakes and longer-term regional tectonics in the region within about 300 km of Palmer Station are used to develop a site-specific seismic source model. The source model has three uniform area seismic source zones, one subduction zone intraslab seismic source, and one subduction zone interface seismic source. Area source zone boundaries were defined based on the location of transform faults and the distribution of historical earthquake epicentres. To overcome the sparse global earthquake records, global earthquake catalogues were augmented with earthquake data from temporary seismic arrays. Where the combined earthquake catalogue was still insufficient to develop stable earthquake activity rate estimates, analogue regions were used to develop the seismic source model.

Site-specific earthquake ground motions were estimated for the Palmer Station site for two site soil conditions: the MCE ($V_{S,30}$ = 760 m/s) and the soil Site Class A ($V_{S,30}$ = 1500 m/s). The PSHA results indicate that the 5%-damped, mean horizontal PGA values for Site Class A for a return period of 2,475 years is about 0.06 g. The dominant contributor to seismic hazard at spectral periods from PGA to 0.5 seconds is the subduction zone intraslab source (SC2a) located approximately 150 km north of Palmer Station. At a spectral period of 1 second, the dominant contributor to the seismic hazard is uniform area source SC2, located approximately 150 km northeast of the site. The major contribution from the subduction zone intraslab source—SC2a—is expected at short periods because (1) the seismicity of the intraslab source is much higher than that of the shallow crustal source SC1 directly underlying the site, and (2) although the seismicity of the intraslab source is similar to that of the shallow crustal source SC2, an intraslab earthquake of a similar magnitude and distance to a crustal earthquake results in higher ground motions at the site of interest. Sensitivity analyses indicate that the mean ground motions are most sensitive to the uncertainty in the subduction zone intraslab GMMs.

Overall, the calculated PGA and spectral acceleration values indicate a low seismic hazard, although there are significant uncertainties associated with the mean earthquake ground motions. The uncertainty reflects a lack of knowledge of the long-term earthquake activity rates in Antarctica.

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