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Abstract

The b value, a measure of the relative number of large and small earthquakes, for the Cascadia subduction zone off the coast of southern British Columbia is low (0.44-0.74) when compared to other seismic zones in Canada and to global averages (0.65-1.1.0). The hazard for this region is dominated by in-slab earthquakes, or those that occur within the subducting slab rather than at the slab interface. It has not been known whether the low b value is a characteristic of in-slab earthquakes or whether Cascadia is truly anomalous. This study evaluates in-slab earthquakes worldwide and finds that on average the b values are comparable to those for other types of earthquakes and suggests that Cascadia is unusual. These results are based on earthquakes of magnitude 5.5 or greater obtained from a global database, which has sufficient information to separate in-slab events from slab interface and shallow crustal earthquakes in the same subduction zone. Regional databases would be useful for extending the magnitude range studied but generally do not have the resolution required to reliably separate the events. We compare the b values and magnitude 7 recurrence intervals to physical properties of the subduction zones, such as age, dip angle and rate of subduction and find no obvious correlations.

Introduction

To be robust and reliable, seismic hazard estimates of a region must take into account earthquakes from all sources that may affect the region. However, in the initial stages it makes sense to treat each source zone separately before combining them since the b values, recurrence rates and ground motions associated with them may be different. For example, three principal types of earthquakes typically occur within subduction zones: slab interface earthquakes, in-slab earthquakes (or those that occur within the subducting slab) and shallow crustal earthquakes. This paper focuses on in-slab earthquakes, about which less is known relative to the other types but which make significant contributions to the seismic hazard. The occurrence of the 2001 (magnitude 6.8) Nisqually earthquake refocused attention on the potential hazard from in-slab earthquakes in southern British Columbia and the northwestern United States where attention has been focused on the potential for the occurrence of a megathrust (slab interface) earthquake. For more discussion of the Nisqually earthquake, see Kao et al (2008) and references therein.

The b value, a measure of the relative number of small and large earthquakes, for the Cascadia subduction zone off the coast of British Columbia is anomalously low. Globally, b values for most seismic zones range from 0.65 to 1.1 and lower values are generally interpreted to mean higher seismic hazard. Adams and Halchuk, (2002) obtained a value of 0.49 for earthquakes within the subducting slab of the Juan de Fuca plate. Bolton (2003) calculated b values in the range of 0.63-0.74 for the same region with the exact value being a function of which catalog was used and whether historical earthquakes were included. She also commented that much of the difference between the results of these two studies could be attributed to the choices of upper and lower magnitude bounds and noted that the b value for the Georgia Strait-Puget Sound region dominated by in-slab earthquakes is lower than that of the west coast of Vancouver Island where the seismicity is dominated by shallower earthquakes. What has not been clear is whether the region as a whole is anomalous or whether the b values for in-slab earthquakes, which dominate the seismic hazard for this region, are in general lower than for other types of earthquakes.

The intent of this paper is not to study any particular region in detail but to calculate b values and magnitude recurrence intervals for in-slab earthquakes worldwide to provide a global context for individual zones that may be of interest. We find that on average their b values are not significantly different from those for other types of earthquakes indicating that the low b value for Cascadia is unusual. A comparison of b values with subduction zone properties such as age, dip angle and rate of subduction did not show any obvious correlations. The same is generally true for recurrence rates.

Data

We analyze data from in-slab earthquakes in thirty-nine subduction zones (Table 1). We define the subduction zone boundaries as those used by Astiz et al (1988) for a global study of intermediate depth (i.e. 40-200 km) earthquakes. The boundaries are based on physical characteristics of the subduction zones.

The Global Centroid Moment Tensor Project (GCMT, 2011) catalog was searched for events with depths of 20 km or greater and predominantly normal focal mechanisms from 1977 through 2010. The data set includes events with both pure normal and oblique normal mechanisms or, in other words, those where normal slip comprises at least one third of the total slip. Restricting both the depth and focal mechanism helps separate the in-slab events from both the slab interface and shallow crustal earthquakes that occur within the same subduction zones as in-slab earthquakes are characterized by intermediate depths and predominantly normal mechanisms. Comparing the number of events in the GCMT (2011) to those catalogued by United States Geological Survey (USGS, 2011), which is complete to lower magnitudes, suggests that the GCMT catalog is complete for magnitude 5.5 and greater since 1977.

A drawback to using global catalogs is that the magnitude range is more restricted than in most regional catalogs and, in the case of moment tensor catalogs, may cover a relatively short time period. If the overall rate of seismicity is low the resulting data set can be rather sparse. However, most regional catalogs do not have adequate resolution to separate the in-slab from the slab interface earthquakes. An advantage to using the GCMT catalog is that all earthquakes have been processed in a uniform manner whereas there may be significant differences from one regional catalog to another.

Calculations

Using the method outlined by Weichert (1980) magnitude recurrence curves were calculated for in-slab earthquakes in each of the subduction zones. This technique employs the maximum likelihood method of curve fitting and expresses the slope of the line as β, which can be converted to be more commonly used "b" value by $\beta = b \ln 10$.

In simple terms, a higher b or β value indicates that there are a higher number of smaller earthquakes for every larger one. Low b values are generally interpreted to be indicators of high seismic hazard levels. On a global scale, b values are typically in the range of 0.65-1.10. However, it has not been known whether the values specifically for in-slab earthquakes are similar. The results of this study, which looks at b values specifically for in-slab earthquakes globally, suggest that they are.

For this study the "best estimate" of maximum magnitude is defined as 0.2 magnitude units greater than the largest known in-slab earthquake within the subduction zone. Sensitivity tests suggest that the choice has little or no effect on the outcome unless unrealistically large values are selected for maximum magnitude. The largest event is taken to be whichever is largest of the earthquakes extracted from the GCMT (2011) catalog for this analysis and those listed in Astiz et al (1988) many of which predate the establishment of the GCMT catalog. For the upper and lower bound curves the minimum estimate of maximum magnitude is that of the largest known earthquake and the maximum is 8.5. Tests show that the choice of the upper bound has little if any effect on the outcome. Note that the GCMT (2011) magnitudes are all M_W. Some of the magnitudes for the earlier events in Astiz et al (1988) are m_B, which we treat as being equal to M_W. This assumption may not be true in all cases but is not of great consequence because we are using maximum magnitude solely to set limits for the calculations. Note that m_B is a broader band magnitude scale than the m_b scale more commonly used at the present. The magnitudes of all earthquakes used in the analysis are M_W's calculated directly from the waveforms. That is, they are not converted from other magnitude types.

We calculated the b value and magnitude 7.0 recurrence interval for each subduction zone (Table 2, Figures 2-37). Because the subduction zones are not of equal size the recurrence rates have also been normalized to recurrence intervals per 100 km along the trench and per 100 km (length) x 20 km (depth) patches for comparison purposes. These numbers are somewhat arbitrary but not inappropriate for a magnitude 7 earthquake and they assume that the seismicity is uniform throughout the subducting slab. This assumption is likely reasonable in terms of seismicity along the length of the trench but may not be valid in terms of seismicity with depth. However, we emphasize that these dimensions are being used for comparison purposes only.

Discussion

As seen in Table 2 and Figure 1, b values for in-slab earthquakes are within the range for all earthquakes worldwide. The values determined in this study range from 0.347 to 2.374 but all except a few outliers lie between 0.65 and 1.0. The b value obtained for the entire data set is 0.933 ± 0.02. There are three zones (Greater Antilles, Rivera and Sulawesi) for which we had insufficient data to perform the calculations. The magnitude recurrence curves for individual subduction zones are shown in Figures 2-37.

We look more closely at those zones where the b value is greater than 1.5 or less than 0.5 and note that many of them were calculated from small data sets and may not be as reliable as the results for other zones. The highest value, 2.374, is for northern Taiwan. It was calculated from only eight events and has an uncertainty of 0.85, which allows for the possibility of a b value in the more normal range. The Scotia zone has a b value of 1.906 ± 0.37 determined from twenty-seven events. The data set is large enough to suggest that the high b value is valid. Southern Chile also has a high b value, 1.625, but as for Taiwan this was derived from s small data set (five events) and has a relatively high uncertainty (0.74).

At the other extreme is the Juan de Fuca (Cascadia) zone with a b value of 0.42. Although derived from only four events and with an uncertainty of 0.43, the value is very similar to the 0.48 obtained from regional data (Adams and Halchuk, 2002) but lower than the 0.63-0.74 of Bolton (2003) who also used regional data. We do not that the results of all three studies overlap if the standard deviations are taken into account. The Lesser Antilles also has an anomalously low b value, 0.347, but was derived from only three events and has an uncertainty of 0.41. Of the five most extreme b values, four were derived from very small data sets and without corroborating evidence extreme caution should be used when making assumptions about the seismic hazard from in-slab earthquakes in these regions.

The recurrence rates for magnitude 7 earthquakes vary by several orders of magnitude even when normalized to account for the fact that the subduction zones are not all of equal size. The highest rates on the order of at least one magnitude 7 or greater earthquake every decade occur for the Altiplano, Northern Chile, Peru, Izu-Bonin and Tonga. These subduction zones also have the highest recurrence rates when normalized to 100 km lengths along the trench and to 100 km x 20 km patches. The lowest recurrence rates of one every thousand years or greater are for the Southern Chile, Burma and Scotia subduction zones but we note that the first two are based on very small data sets and are therefore not well constrained. When normalized to fault area, Kermadec also has a low recurrence rate, suggesting that the seismicity in that subduction zone is not evenly distributed.

We evaluate the b values and normalized recurrence rates to each other and to several physical properties of the subduction zone (age, dip angle of the subducting plate at intermediate depths, convergence rate and convergence rate normal to the trench axis) and find no obvious correlations (Figures 38-46). The values for the physical properties are as summarized by Astiz et al (1988) based on the references cited therein.

Despite the limited magnitude range, the b values determined from the global data set appear to be relatively stable. A comparison of b values calculated using data through 2001 (Bent, 2002), done in response to the 2001 Nisqually and El Salvador in-slab earthquakes, and those using data through 2010 (an approximate increase of 25% in the size of the data set) show that for the most part there is little difference (Table 3). The subduction zones where the changes were more significant were those with very small data sets where there was a large relative increase in the number of events from 2001 to 2010 and/or where the largest event in the subduction zone occurred during that time period. The comparison suggests that the global data set does provide reasonable estimates of b values although caution should be used in the interpretation for any regions where the data are sparse.

Conclusions

Using data from the GCMT (2011) catalog b values and magnitude 7 recurrence rates have been calculated for in-slab earthquakes for thirty-six subduction zones. Three other zones were considered but had insufficient data. On average, the b values for in-slab earthquakes are comparable to those from all types of earthquakes indicating that the low value for the Cascadia subduction zone, obtained from regional data and corroborated in this study, is truly anomalous. While data from regional catalogs with sufficient resolution to separate in-slab from other subduction zone earthquakes would be useful in extending the magnitude range and providing an independent verification of the results from this study, a comparison of the b values using the GCMT catalog through 2001 and through 2010 show that the results are generally stable.

Acknowledgments

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Table 1
Subduction Zones*

Zone	Mmax**	Lat min (º)	Lat max (º)	Lon min (º)	Lon max (º)
Colombia	7.2 (G)	2.5	11.1	-80	-70
Ecuador	7.5 (A)	-4	2.5	-85	-70
Peru	8.2 (G)	-14	-4	-85	-65
Altiplano	7.6 (A)	-21	-14	-80	-60
N. Chile	7.7 (A)	-30	-21	-80	-60
Cent. Chile	7.5 (A)	-37.5	-30	-80	-60
S. Chile	7.5 (A)	-45	-37.5	-80	-60
Scotia	7.6 (A)	-60	-50	-40	-20
Rivera	?	17	22	-110	-102.8
Mexico	7.7 (A)	12.2	20	-102.8	-94.9
C. America	7.7 (G)	8	20	-94.9	-80
Gr. Antilles	7.0 (A)	13	20	-77.4	-65.9
Ls. Antilles	7.5 (A)	11.7	20	-65.9	-55
Juan de Fuca	7.1 (A)	41	52	-132	-118
Alaska	7.3 (A)	50	66	-163	-140
Aleutians	7.4 (A)	50	60	165	-163
Kamchatka	7.8 (A)	50	60	155	165
Kuriles	7.7 (G)	45	55	140	155
NE Japan	7.5 (A)	37	47	128	140
Izu-Bonin	7.9 (A)	20	37	135	150
Marianas	7.4 (G)	10	20	140	150
Ryukyu	8.1 (A)	22	37	125	133
N. Taiwan	7.6 (A)	22	29	119	125
Luzon	7.2 (G)	15	21	117	125
Philippines	7.7 (G)	-3	15	120	130
Sulawesi	7.8 (A)	-3	0	130	133

Burma	7.4 (A)	17	30	90	100
Andaman	7.5 (G)	2	17	90	100
Sunda	7.3 (A)	-8	2	95	108
Java	8.3 (G)	-12	-3	108	122
Timor	7.8 (A)	-12	-3	122	136
New Guinea	7.3 (A)	-10	0	136	148
New Britain	7.2 (A)	-10	-3	148	153
New Ireland	7.3 (A)	-8	-1	153	156
Solomon	7.3 (A)	-12	-7	156	165
New Hebrides	7.9 (A)	-25	-10	165	176
Tonga	8.0 (G)	-32	-10	176	-170
Kermadec	7.1 (G)	-38	-32	175	-175
New Zealand	7.1 (A)	-45	-38	170	180

* subduction zones as defined by Astiz et al (1988)
**maximum magnitude for intermediate depth earthquakes; A = Astiz et al (1988) and G = GCMT (2011); the larger of the two is used

Table 2
Summary of b Values and Recurrence Rates

Sub. Zone	Events	Beta	±	b	±	Age	Dip	Len.	Depth	Rate	VN	Magnitude 7.0 Recurrence		
						(m.y.)	(deg)	(km)	(km)	(cm/y)	(cm/y)	(p.a.)	(100km)	(100kmx20km)
Alaska	13	1.60	0.58	0.696	0.25	45	45	2000	160	7.2	6.3	0.01630	0.000815	0.000102
Aleutians	21	2.40	0.57	1.043	0.25	60	63	3000	280	8.0	6.9	0.01160	0.000387	0.000028
Altiplano	92	2.02	0.23	0.878	0.10	50	28	750	300	9.2	8.3	0.10000	0.013333	0.000889
Andaman	23	2.36	0.53	1.026	0.23	55	50	1000	100	6.3	4.5	0.01310	0.001310	0.000262
Burma	4	2.84	1.48	1.234	0.64		60	900	200	6.0	2.1	0.00116	0.000129	0.000013
C. America	85	2.15	0.25	0.932	0.11	40	60	1500	280	8.0	7.8	0.07310	0.004873	0.000348
Cent. Chile	25	2.15	0.48	0.935	0.21	35	10	600	200	9.1	8.6	0.02000	0.003333	0.000333
Columbia	12	1.24	0.58	0.538	0.25	20	35	800	250	7.9	6.2	0.02000	0.002500	0.000200
Ecuador	22	1.47	0.41	0.639	0.18	20	30	600	200	8.0	7.9	0.04160	0.006933	0.000693
Gr. Antilles						125	75	300	180	0.2	0.2	-		
Izu-Bonin	104	1.69	0.19	0.736	0.08	135	45	1000	560	6.5	6.0	0.19000	0.019000	0.000679
Java	76	2.30	0.27	0.999	0.12	135	60	1700	650	7.7	7.5	0.06000	0.003529	0.000109
Juan de Fuca	4	0.97	0.99	0.420	0.43	10	22	500	100	3.8	3.1	0.00631	0.001262	0.000252
Kamchatka	13	1.92	0.59	0.835	0.25	90	50	450	540	8.8	8.8	0.01630	0.003622	0.000134
Kermadec	11	2.89	0.93	1.254	0.41	100	70	600	600	7.2	7.1	0.00213	0.000355	0.000012
Kuriles	34	1.71	0.34	0.744	0.15	97.5	47.5	1000	612.5	9.1	8.7	0.05310	0.005310	0.000173
Ls. Antilles	3	0.80	0.94	0.347	0.41	80	65	800	250	2.0	1.5	0.01160	0.001450	0.000116
Luzon	19	1.44	0.48	0.626	0.21	28	60	500	640	7.3	5.2	0.02531	0.005062	0.000158
Marianas	50	1.98	0.32	0.860	0.14	150	80	750	640	4.1	3.7	0.04630	0.006173	0.000193
Mexico	29	1.46	0.34	0.635	0.15	30	15	900	200	7.0	6.9	0.06310	0.007011	0.000701

N. Chile	152	2.18	0.19	0.946	0.08	40	30	720	300	9.3	9.1	0.12000	0.016667	0.001111
N. Taiwan	8	5.47	1.96	2.374	0.85	65	70	120	300	6.0	5.6	?		
NE Japan	9	1.62	0.67	0.705	0.29	100	40	900	580	9.4	8.0	0.01400	0.001556	0.000054
New Britain	42	2.56	0.43	1.111	0.19	30	60	500	200	9.2	9.2	0.01400	0.002800	0.000280
New Guinea	33	1.88	0.40	0.816	0.17	30	55	550	200	3.3	3.3	0.03163	0.005751	0.000575
New Hebrides	67	2.08	0.27	0.904	0.12	65	70	1500	320	10.0	9.9	0.07000	0.004667	0.000292
New Ireland	29	2.26	0.47	0.982	0.20	30	75	400	550	10.1	10.1	0.01630	0.004075	0.000148
New Zealand	7	1.72	0.87	0.748	0.38	90	67	500	350	5.0	4.8	0.00570	0.001140	0.000065
Peru	62	1.53	0.22	0.666	0.10	35	8	1000	220	8.7	8.3	0.14000	0.014000	0.001273
Philippines	124	2.31	0.22	1.002	0.10	55	60	1500	640	8.3	6.4	0.09000	0.006000	0.000188
Rivera						6	10	300	90	2.3	2.1	-		
Ryukyu	34	2.24	0.40	0.972	0.17	45	65	1000	220	5.6	5.5	0.03000	0.003000	0.000273
S. Chile	5	3.74	1.69	1.625	0.74	20	27	1250	160	9.0	8.6	0.00040	0.000032	0.000004
Scotia	27	4.39	0.85	1.906	0.37	70	70	500	200	5.4	4.4	0.00083	0.000166	0.000017
Soloman	24	2.79	0.60	1.214	0.26	60	50	1000	200	10.0	7.7	0.00700	0.000700	0.000070
Sulawesi						60	62	350	190			-		
Sunda	21	2.67	0.62	1.159	0.27	80	47	1500	300	7.0	6.3	0.00700	0.000467	0.000031
Timor	77	2.03	0.25	0.881	0.11	90	70	1100	690	7.8	7.7	0.08310	0.007555	0.000219
Tonga	526	2.25	0.10	0.978	0.04	100	55	1500	650	9.2	9.1	0.43100	0.028733	0.000884

Note: age, dip, trench length, depth, rate of subduction and rate normal to trench axis (VN) are those stated in Astiz et al (1988); when a range of values is given, we use the mean; the magnitude 7 recurrence rates are given for the subduction zone as a whole, and normalized per 100 km length along the trench and per 100 km x 20 km area. The subduction zones are shown in Figure 1.

Table 3
Comparison of 2001 and 2010 b Values

	2001		2010			
Zone	**n eqs**	**b**	**n eqs**	**b**	**Δb**	**Comments**
Alaska	13	0.696	13	0.696	0.000	
Aleutians	15	1.075	21	1.043	-0.033	
Altiplano	66	0.843	92	0.878	0.035	M7.8 2005
Andamans	14	1.313	23	1.026	-0.287	M7.5 2009
Burma	3	0.927	4	1.234	0.307	
Central America	65	0.894	85	0.932	-0.038	
Central Chile	17	0.804	25	0.935	0.131	
Colombia	9	0.373	12	0.538	0.165	
Ecuador	16	0.714	22	0.639	-0.075	
Izu-Bonin	84	0.735	104	0.736	0.001	
Japan	6	0.667	9	0.705	0.038	
Java	64	0.987	76	0.999	0.012	
Juan de Fuca	3	0.523	4	0.420	-0.103	
Kamchatka	8	1.760	13	0.835	-0.935	M6.9 2003, M6.8 2004
Kermadec	8	0.998	13	1.254	0.219	
Kuriles	25	0.971	34	0.744	-0.227	M7.7 2008
Lesser Antilles	2	1.759	3	0.347	-1.412	M7.4 2007
Luzon	16	0.465	19	0.626	0.161	
Marianas	42	0.886	50	0.860	-0.260	
Mexico	21	0.488	29	0.635	0.191	
New Britain	34	1.190	42	1.111	-0.079	
New Guinea	22	0.741	33	0.816	0.075	
New Hebrides	51	0.885	67	0.904	0.019	
New Ireland	21	0.968	29	0.982	0.014	
New Zealand	6	0.540	7	0.748	0.208	
Northern Chile	101	0.899	152	0.946	0.047	
Peru	48	0.711	62	0.666	-0.045	
Philippines	94	1.238	124	1.002	-0.236	
Ryukyu	28	0.890	34	0.972	0.082	
Scotia	18	2.041	27	1.906	-0.135	
Solomon Islands	16	1.206	24	1.214	0.008	
Southern Chile	3	1.121	5	1.625	0.504	
Sunda	12	1.333	21	1.159	-0.174	M7.3 2004
Taiwan	7	2.139	8	2.374	0.235	
Timor	49	0.817	77	0.881	0.064	
Tonga	397	0.943	526	0.978	0.035	
Greater Antilles	0		1			
Rivera	0		0			
Sulawesi	0		0			

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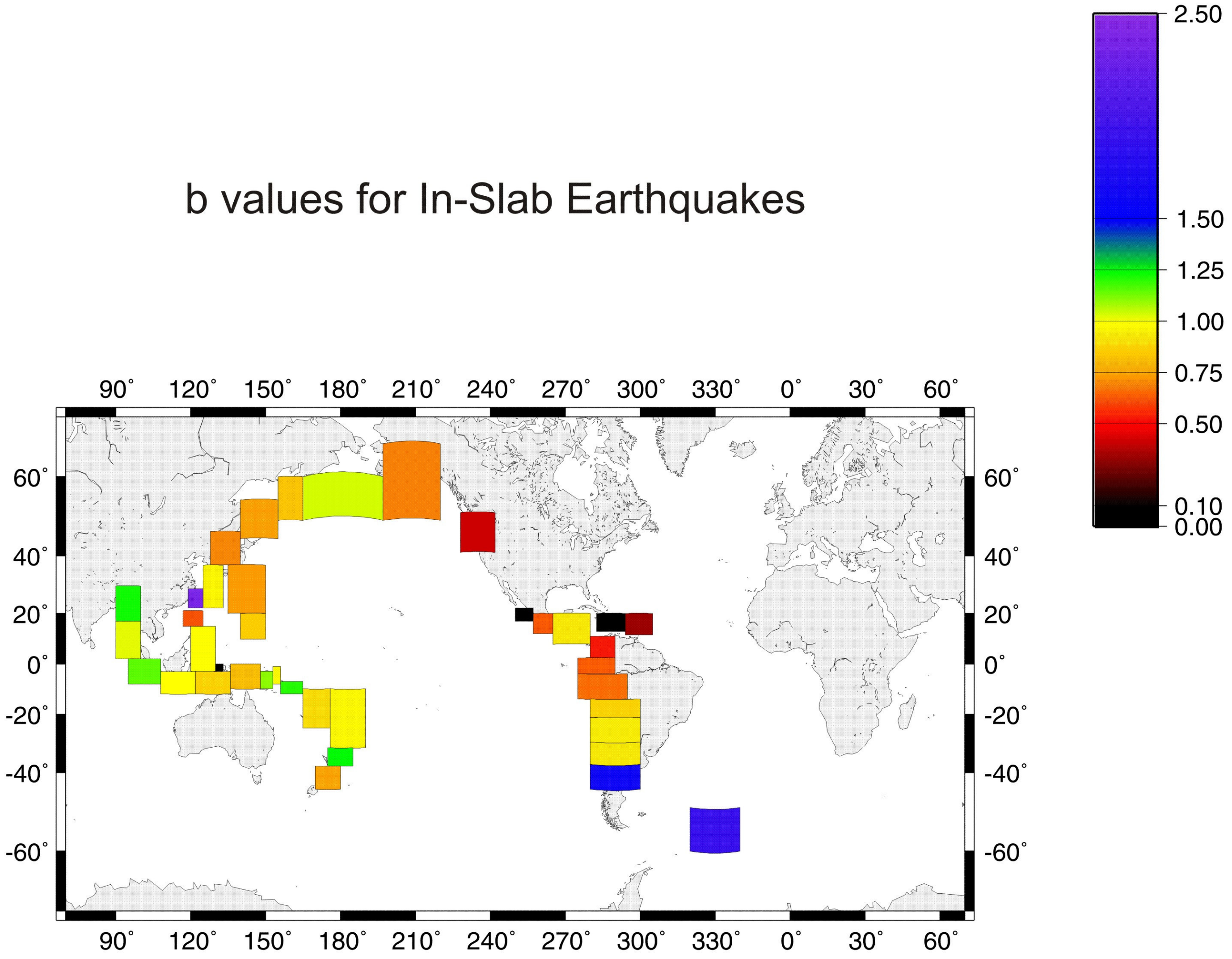

Figure 1: b values for in-slab earthquakes in subduction zones defined in Table 1. We used a b value of 0.0 (black) to indicate that there were insufficient data to determine a b value.

Figure 2: Magnitude recurrence curve for the Alaska subduction zone showing moment magnitude M_W plotted against the cumulative rate of in-slab earthquakes per year. M_X is the best estimate of maximum M_W and is chosen on criteria discussed in the text.

Figures 3-37: Magnitude recurrence curves for the remaining subduction zones. Same format as Figure 2. Subduction zones plotted in alphabetical order.

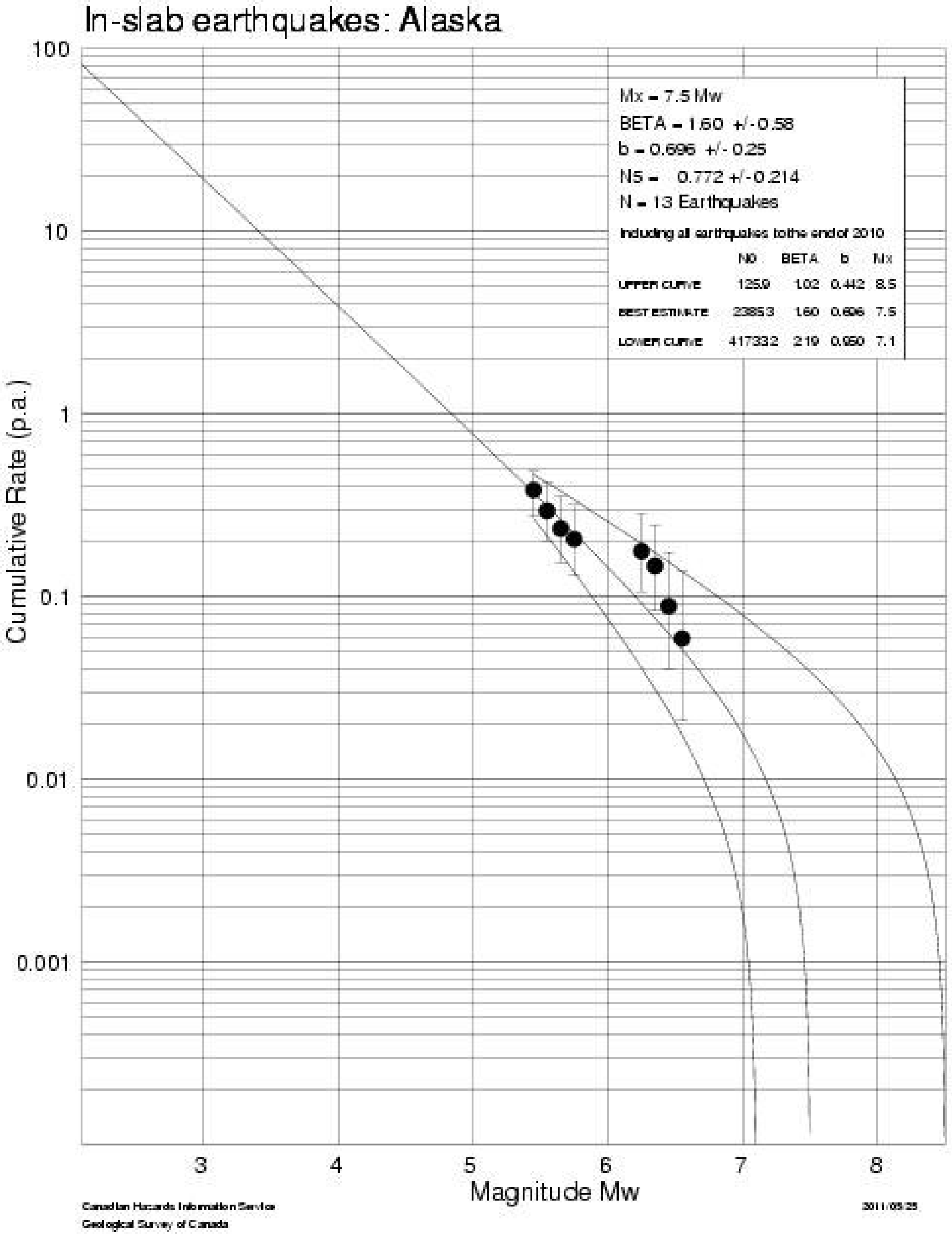
In-slab earthquakes: Alaska
Mx = 7.5 Mw
BETA = 1.60 +/- 0.58
b = 0.696 +/- 0.25
N5 = 0.772 +/- 0.214
N = 13 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 125.9 1.02 0.442 8.5
BEST ESTIMATE 2385.3 1.60 0.696 7.5
LOWER CURVE 41733.2 2.19 0.950 7.1
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 2.

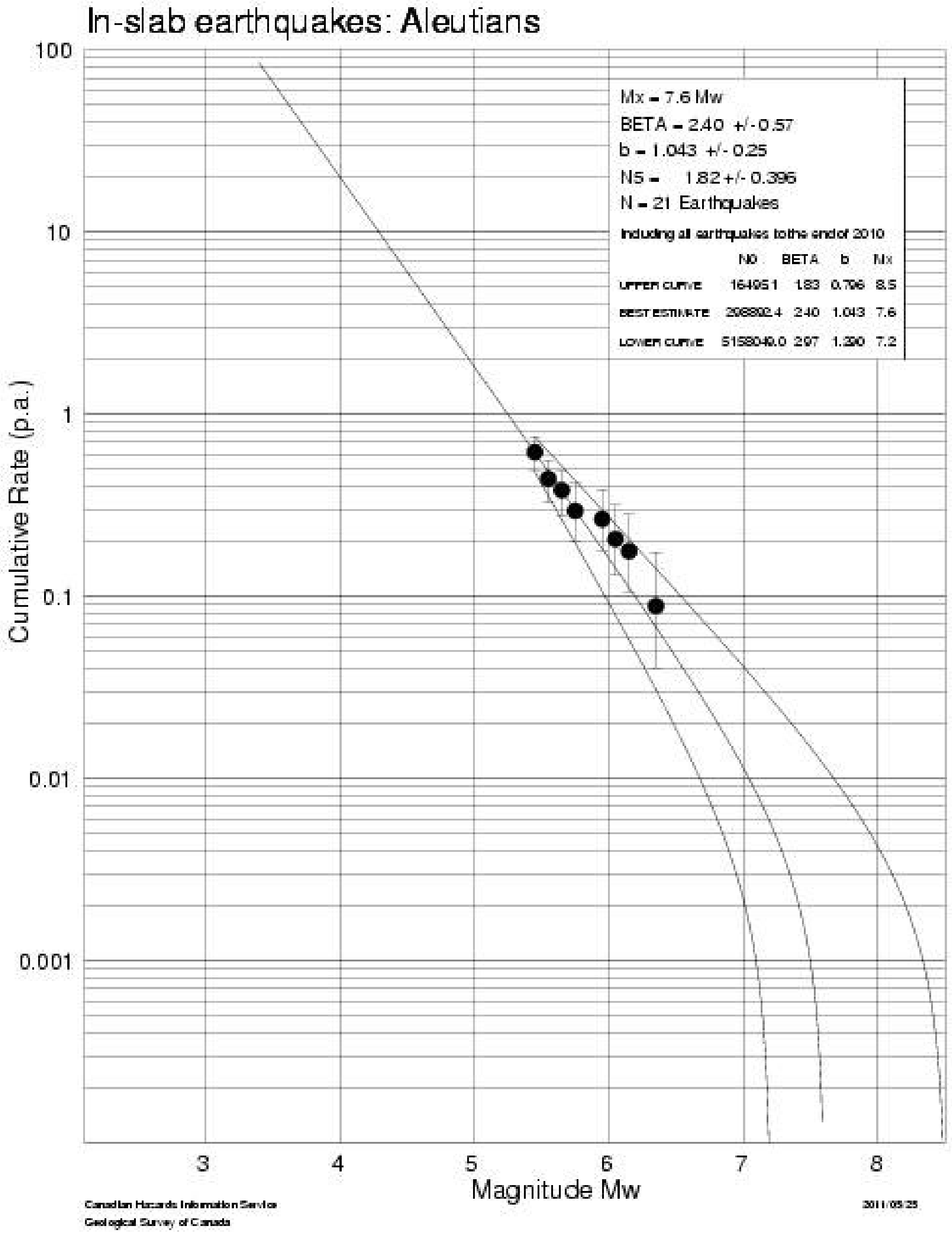
In-slab earthquakes: Aleutians
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Mx = 7.6 Mw
BETA = 2.40 +/- 0.57
b = 1.043 +/- 0.25
N5 = 1.82 +/- 0.396
N = 21 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 164951 1.83 0.796 8.5
BEST ESTIMATE 298892.4 2.40 1.043 7.6
LOWER CURVE 5158049.0 2.97 1.290 7.2
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 3

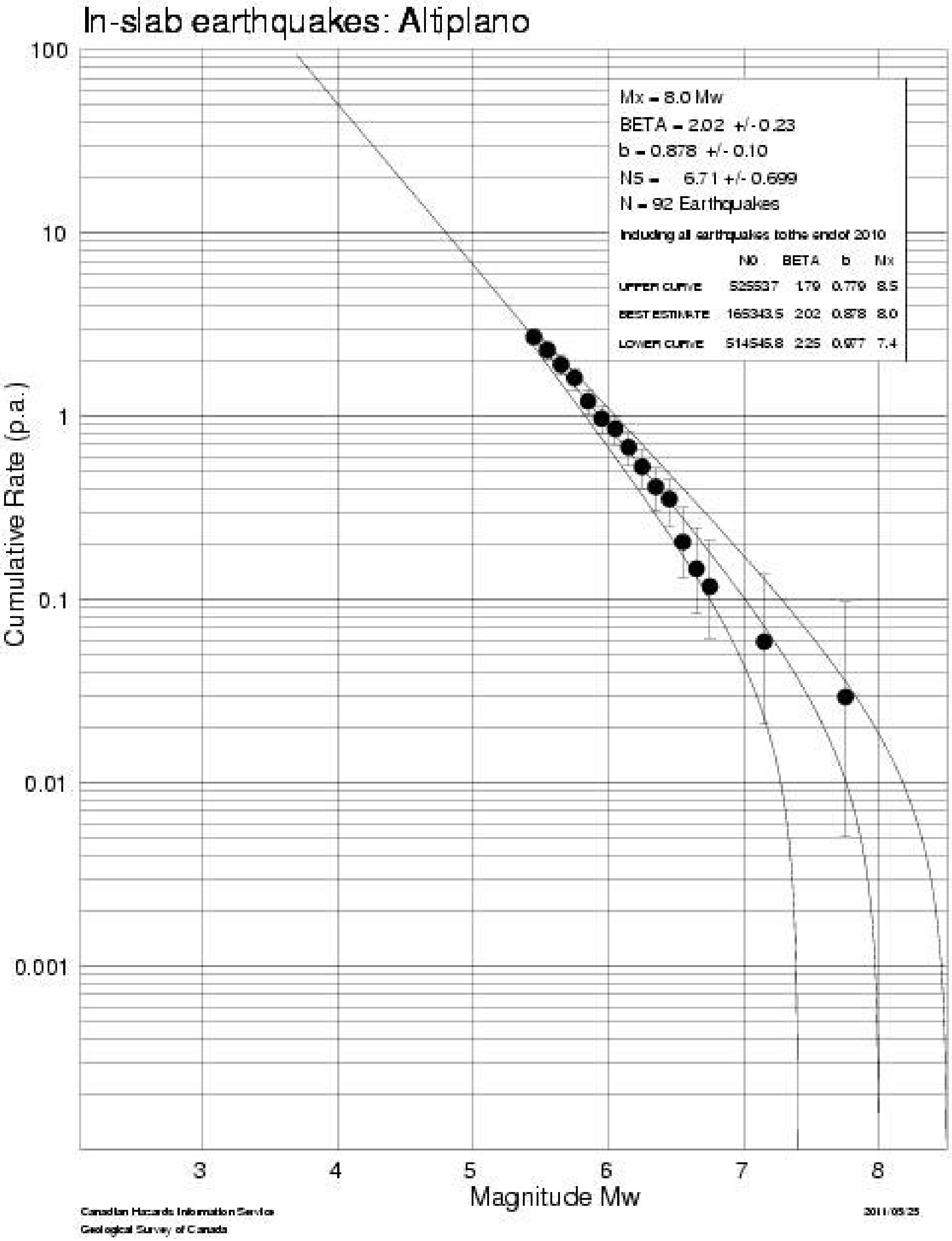
In-slab earthquakes: Altiplano
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Mx = 8.0 Mw
BETA = 2.02 +/- 0.23
b = 0.878 +/- 0.10
N5 = 6.71 +/- 0.699
N = 92 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 525537 1.79 0.779 8.5
BEST ESTIMATE 165343.5 2.02 0.878 8.0
LOWER CURVE 514546.8 2.25 0.977 7.4
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 4

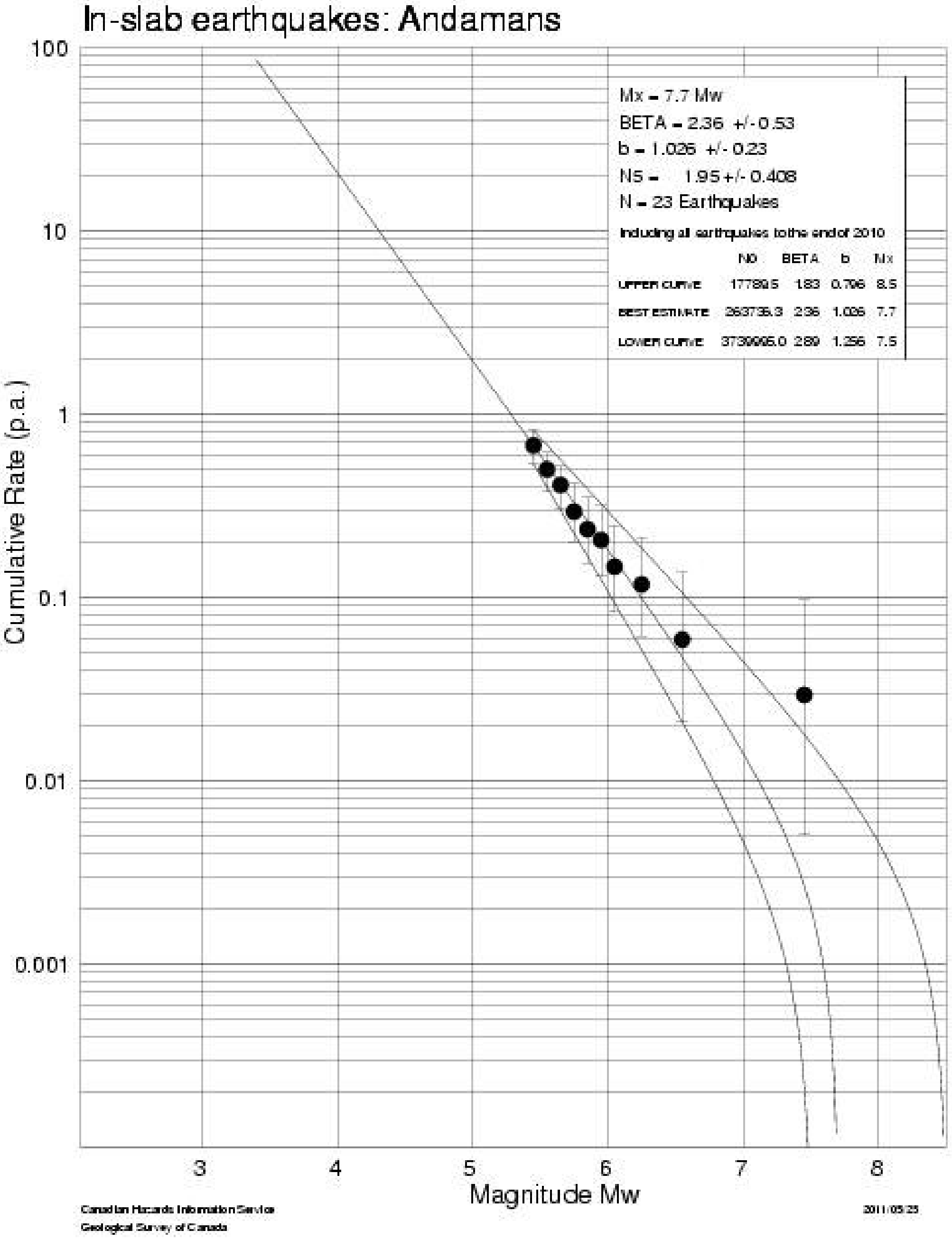
In-slab earthquakes: Andamans
Mx = 7.7 Mw
BETA = 2.36 +/- 0.53
b = 1.026 +/- 0.23
N5 = 1.95 +/- 0.408
N = 23 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 177789.5 1.83 0.796 8.5
BEST ESTIMATE 263735.3 2.36 1.026 7.7
LOWER CURVE 3739995.0 2.89 1.256 7.5
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 5

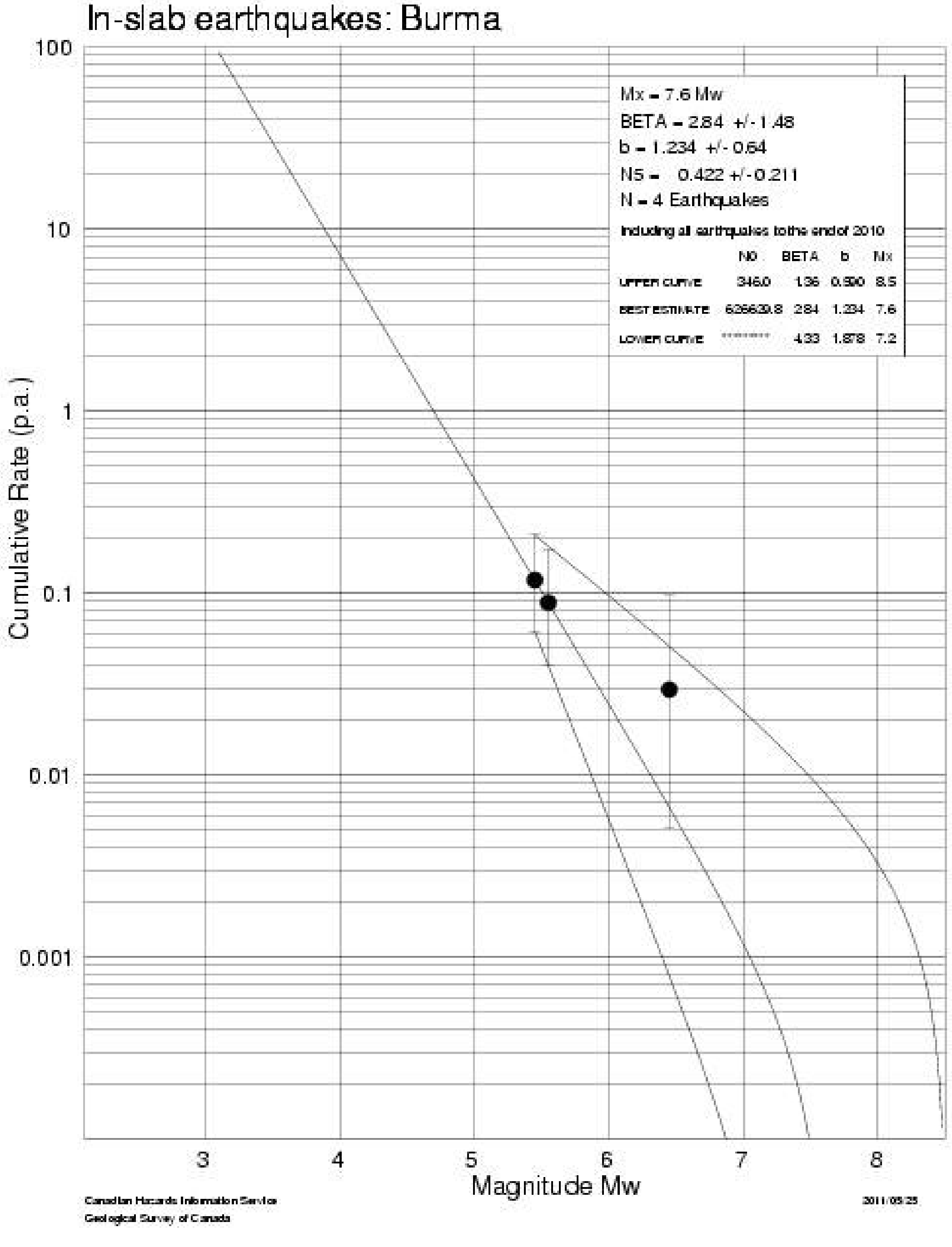
In-slab earthquakes: Burma
Mx = 7.6 Mw
BETA = 2.84 +/- 1.48
b = 1.234 +/- 0.64
N5 = 0.422 +/- 0.211
N = 4 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 346.0 1.36 0.590 8.5
BEST ESTIMATE 626629.8 2.84 1.234 7.6
LOWER CURVE ******** 4.33 1.878 7.2
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 6

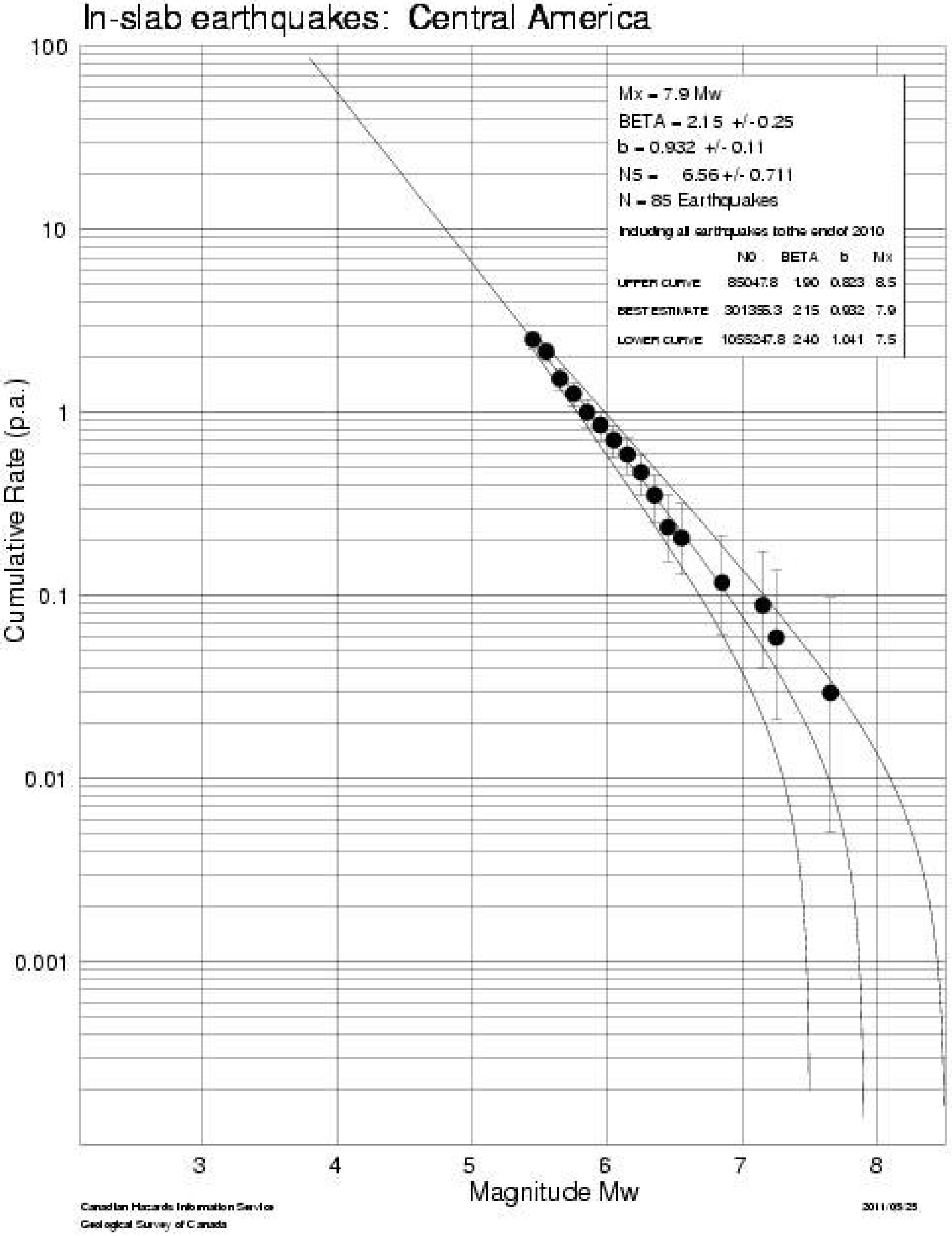
In-slab earthquakes: Central America
Mx = 7.9 Mw
BETA = 2.15 +/- 0.25
b = 0.932 +/- 0.11
N5 = 6.56 +/- 0.711
N = 85 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 85047.8 1.90 0.823 8.5
BEST ESTIMATE 301355.3 2.15 0.932 7.9
LOWER CURVE 1055247.8 2.40 1.041 7.5
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 7

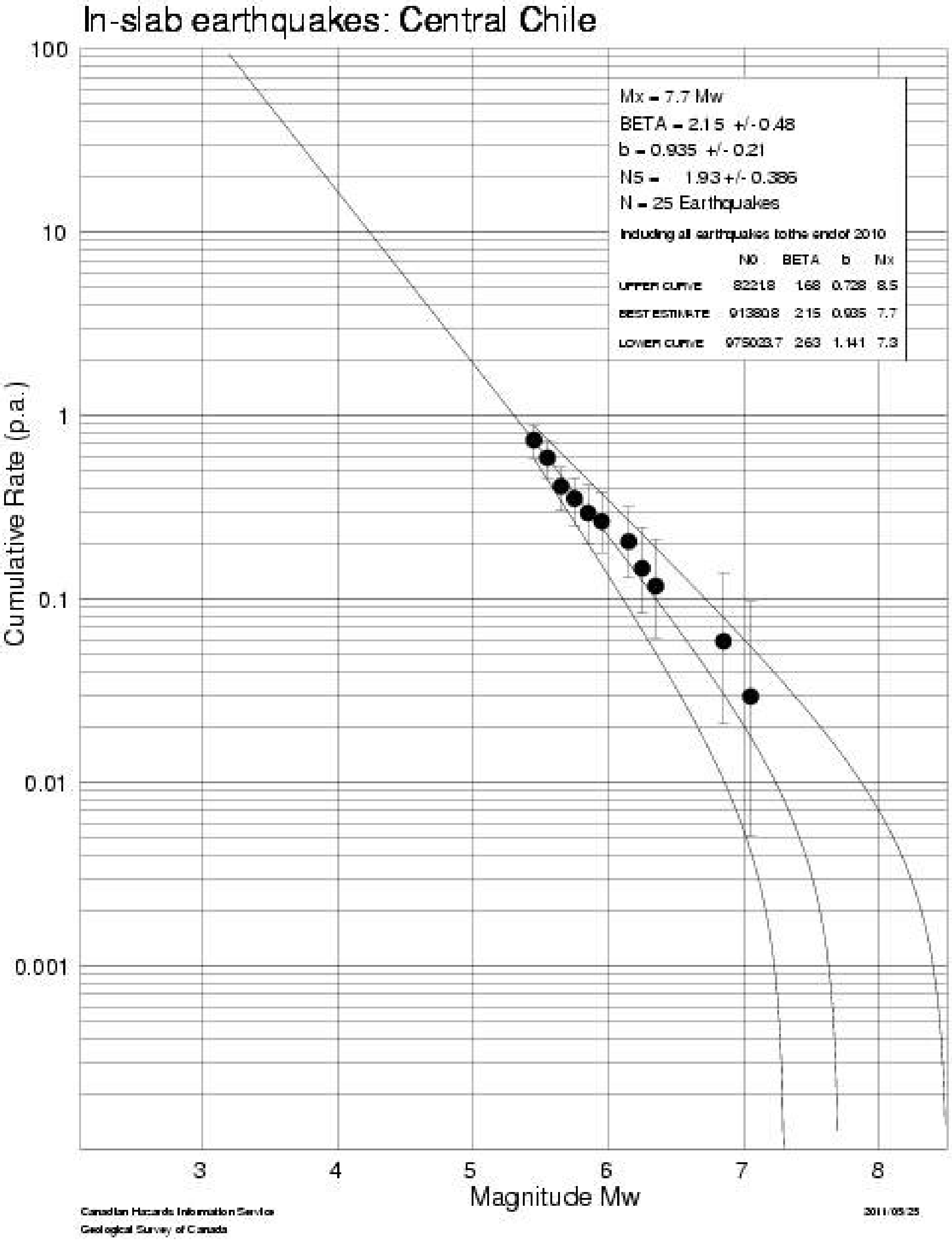
In-slab earthquakes: Central Chile
Mx = 7.7 Mw
BETA = 2.15 +/- 0.48
b = 0.935 +/- 0.21
N5 = 1.93 +/- 0.386
N = 25 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 82218 1.68 0.728 8.5
BEST ESTIMATE 913808 2.15 0.935 7.7
LOWER CURVE 9790023.7 2.63 1.141 7.3
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 8

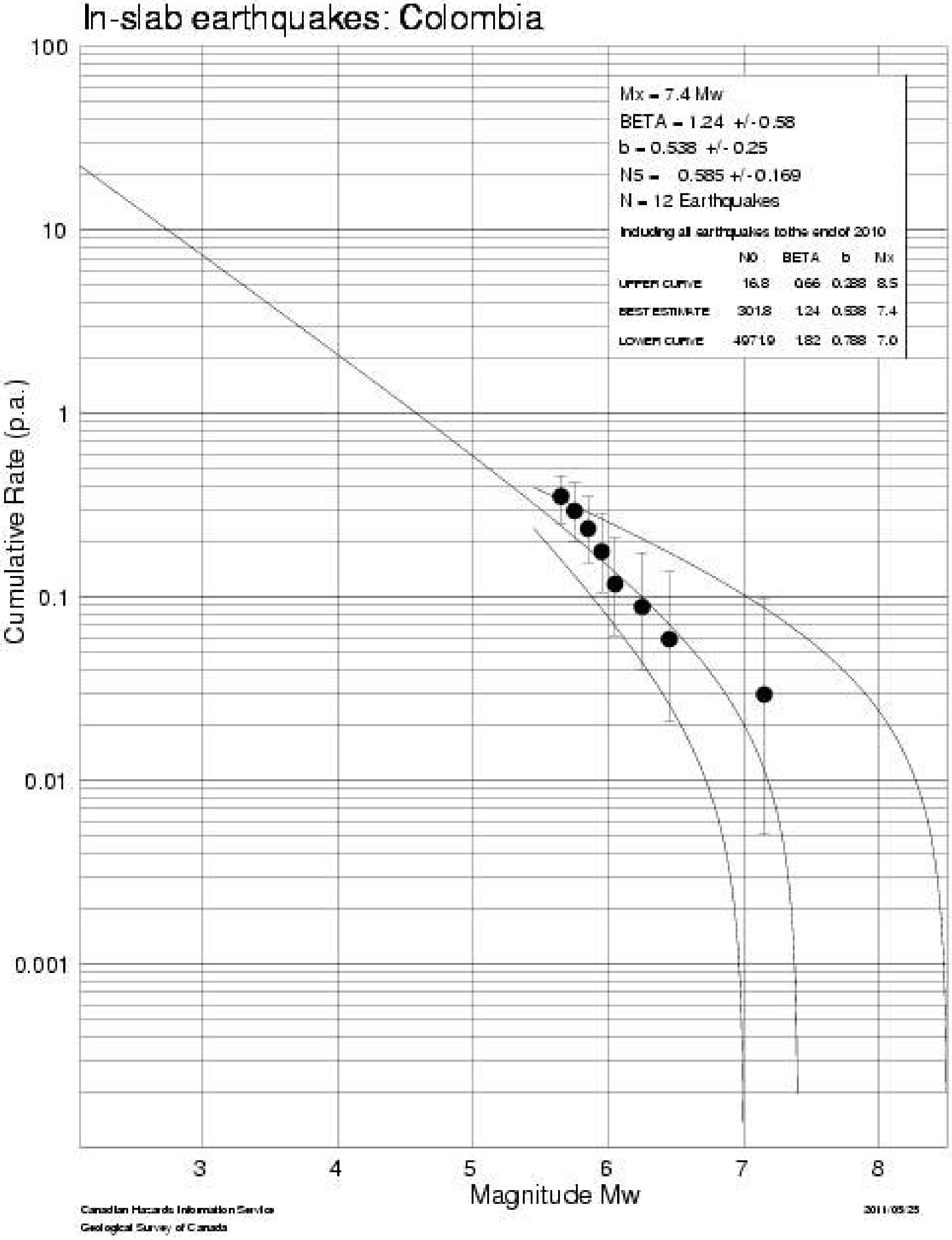
In-slab earthquakes: Colombia
Mx = 7.4 Mw
BETA = 1.24 +/- 0.58
b = 0.538 +/- 0.25
N5 = 0.585 +/- 0.169
N = 12 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 16.8 0.66 0.288 8.5
BEST ESTIMATE 301.8 1.24 0.538 7.4
LOWER CURVE 4971.9 1.82 0.788 7.0
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 9

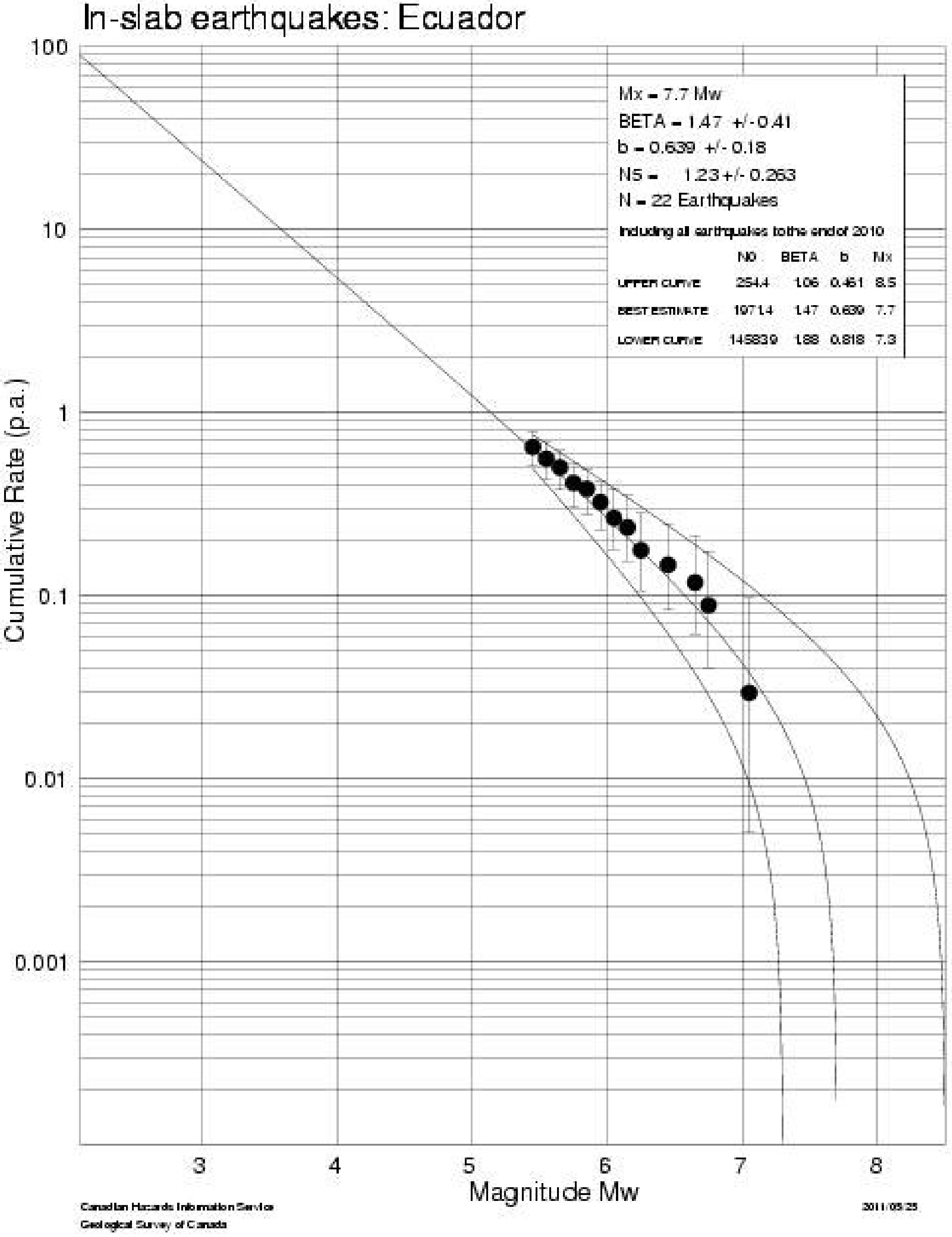
In-slab earthquakes: Ecuador
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Mx = 7.7 Mw
BETA = 1.47 +/- 0.41
b = 0.639 +/- 0.18
N5 = 1.23+/- 0.263
N = 22 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 254.4 1.06 0.461 8.5
BEST ESTIMATE 1971.4 1.47 0.639 7.7
LOWER CURVE 145839 1.88 0.818 7.3
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 10

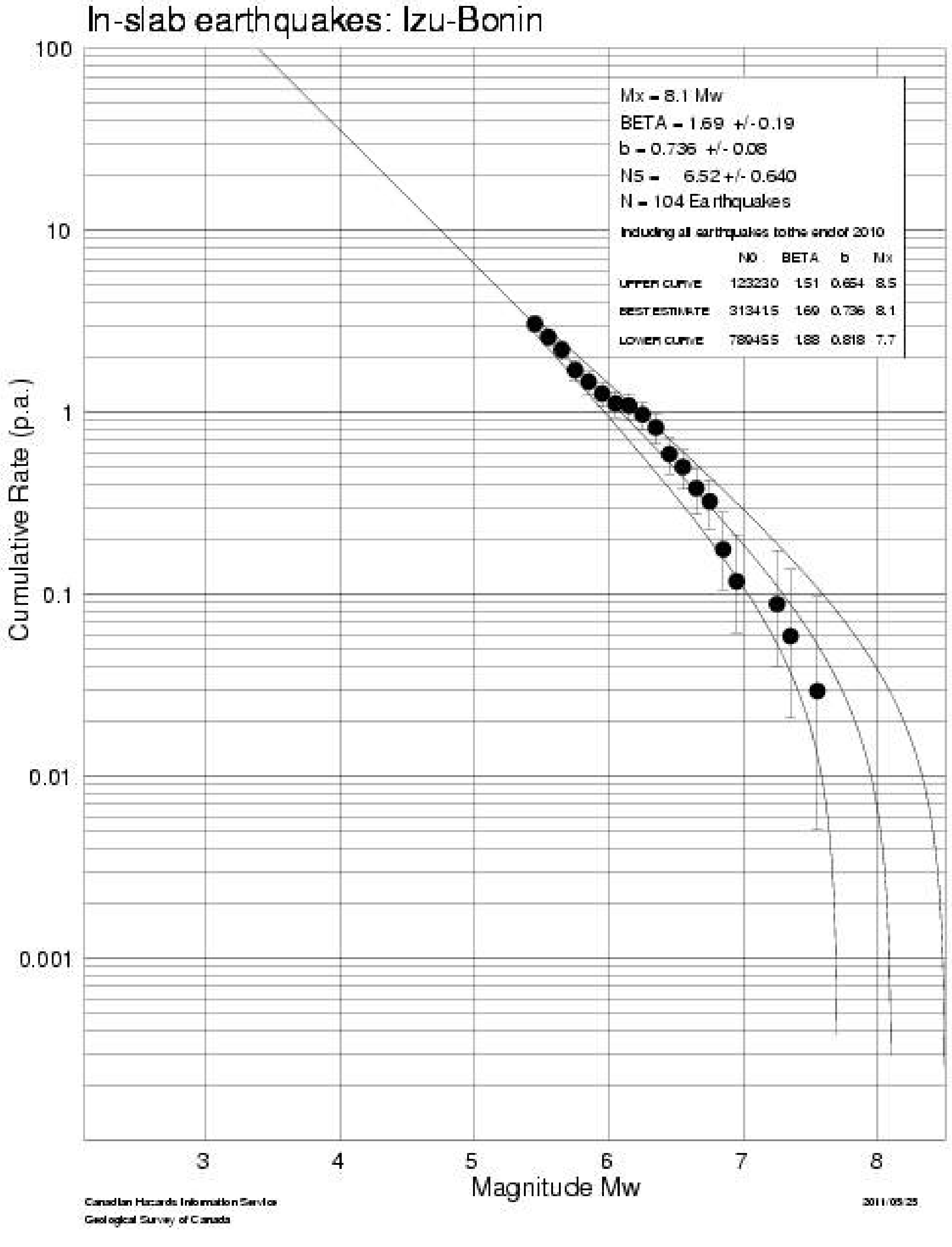
In-slab earthquakes: Izu-Bonin
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
Magnitude Mw
3
4
5
6
7
8
Mx = 8.1 Mw
BETA = 1.69 +/- 0.19
b = 0.736 +/- 0.08
N5 = 6.52 +/- 0.640
N = 104 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 123230 1.51 0.654 8.5
BEST ESTIMATE 313415 1.69 0.736 8.1
LOWER CURVE 789455 1.88 0.818 7.7
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 11

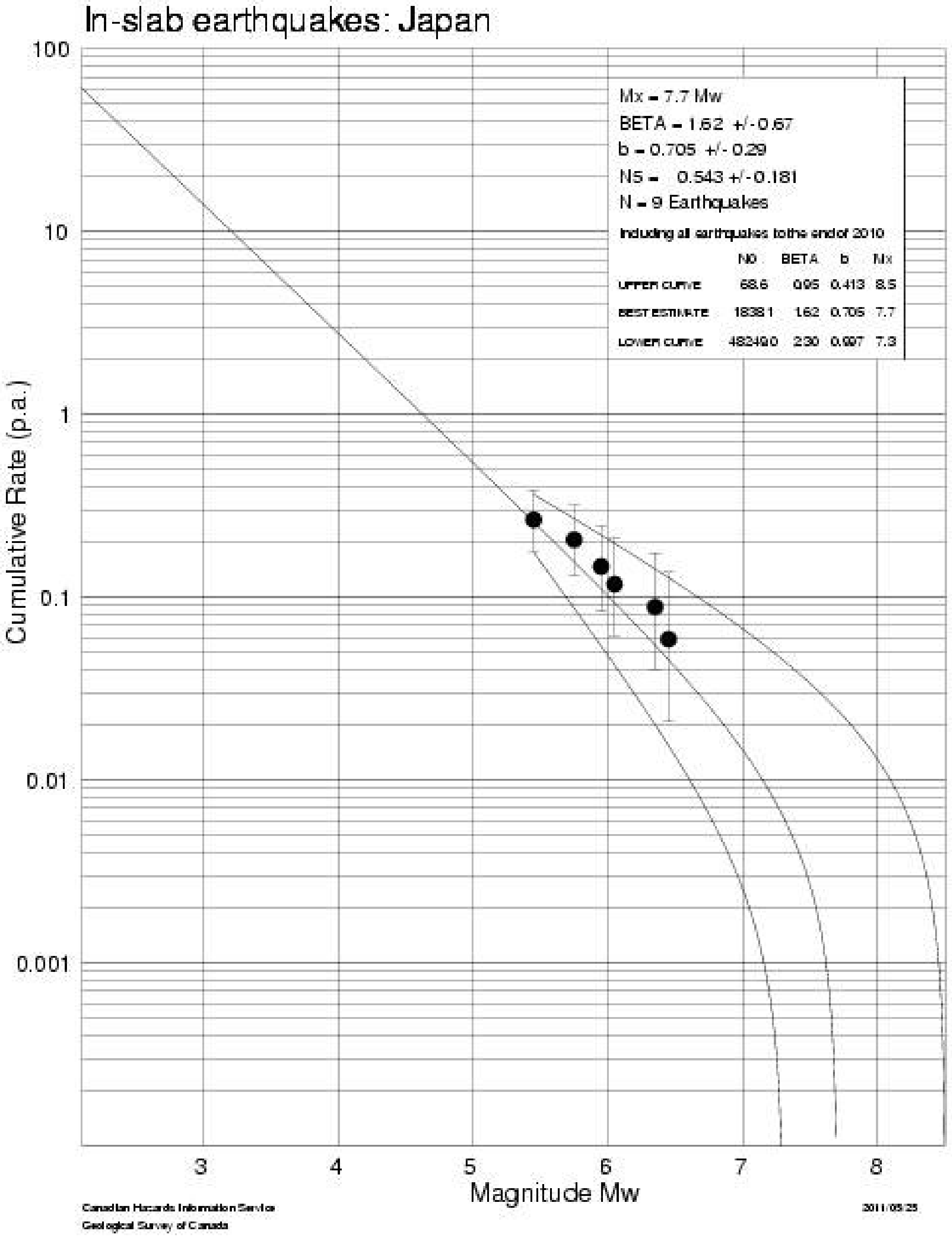
In-slab earthquakes: Japan
Mx = 7.7 Mw
BETA = 1.62 +/- 0.67
b = 0.705 +/- 0.29
N5 = 0.543 +/- 0.181
N = 9 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 68.6 0.95 0.413 8.5
BEST ESTIMATE 1838.1 1.62 0.705 7.7
LOWER CURVE 48249.0 2.30 0.997 7.3
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 12

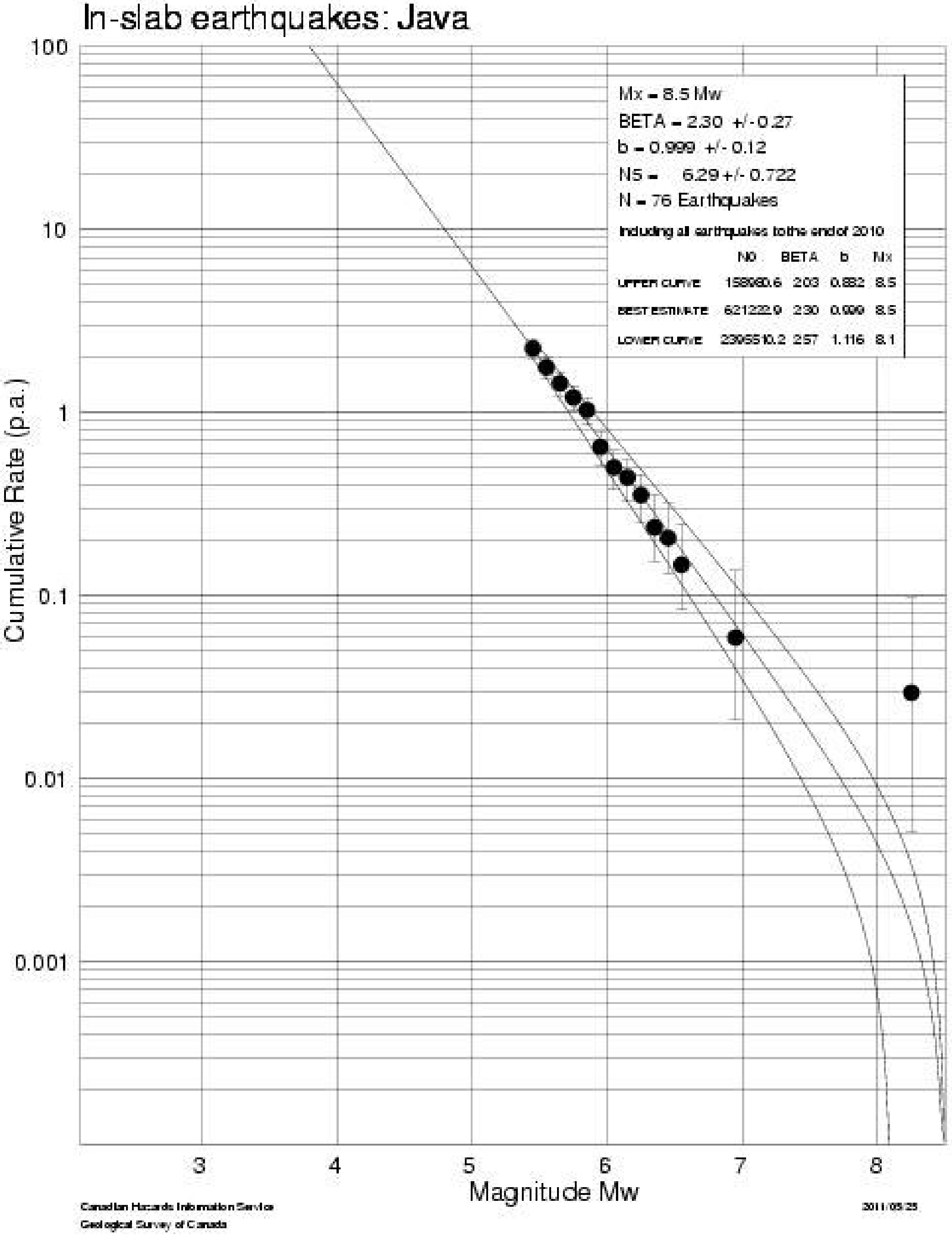
In-slab earthquakes: Java
Mx = 8.5 Mw
BETA = 2.30 +/- 0.27
b = 0.999 +/- 0.12
N5 = 6.29 +/- 0.722
N = 76 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 158960.6 2.03 0.882 8.5
BEST ESTIMATE 621222.9 2.30 0.999 8.5
LOWER CURVE 2395510.2 2.57 1.116 8.1
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 13

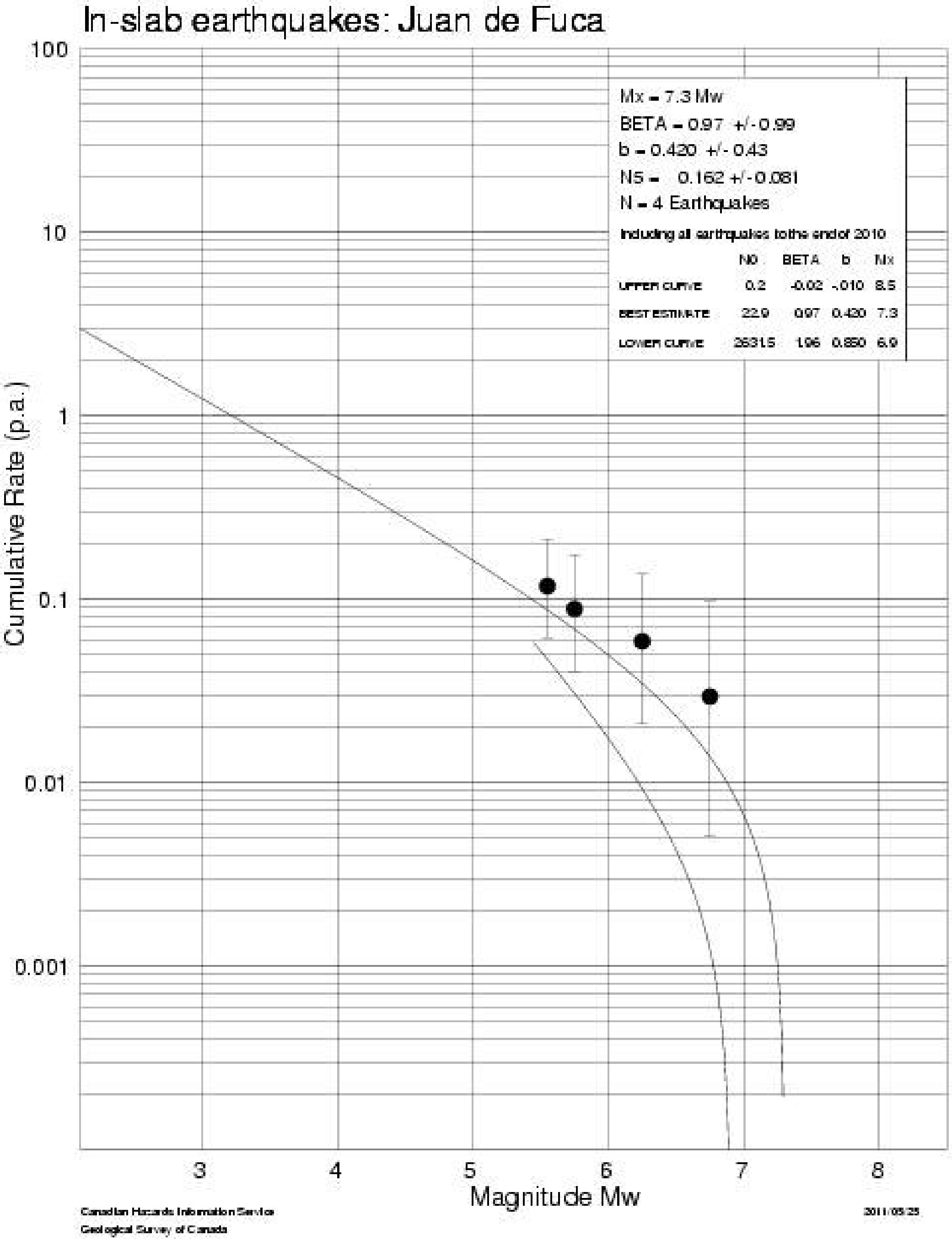
In-slab earthquakes: Juan de Fuca
Mx = 7.3 Mw
BETA = 0.97 +/- 0.99
b = 0.420 +/- 0.43
N5 = 0.162 +/- 0.081
N = 4 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 0.2 -0.02 -.010 8.5
BEST ESTIMATE 22.9 0.97 0.420 7.3
LOWER CURVE 26315 1.96 0.850 6.9
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 14

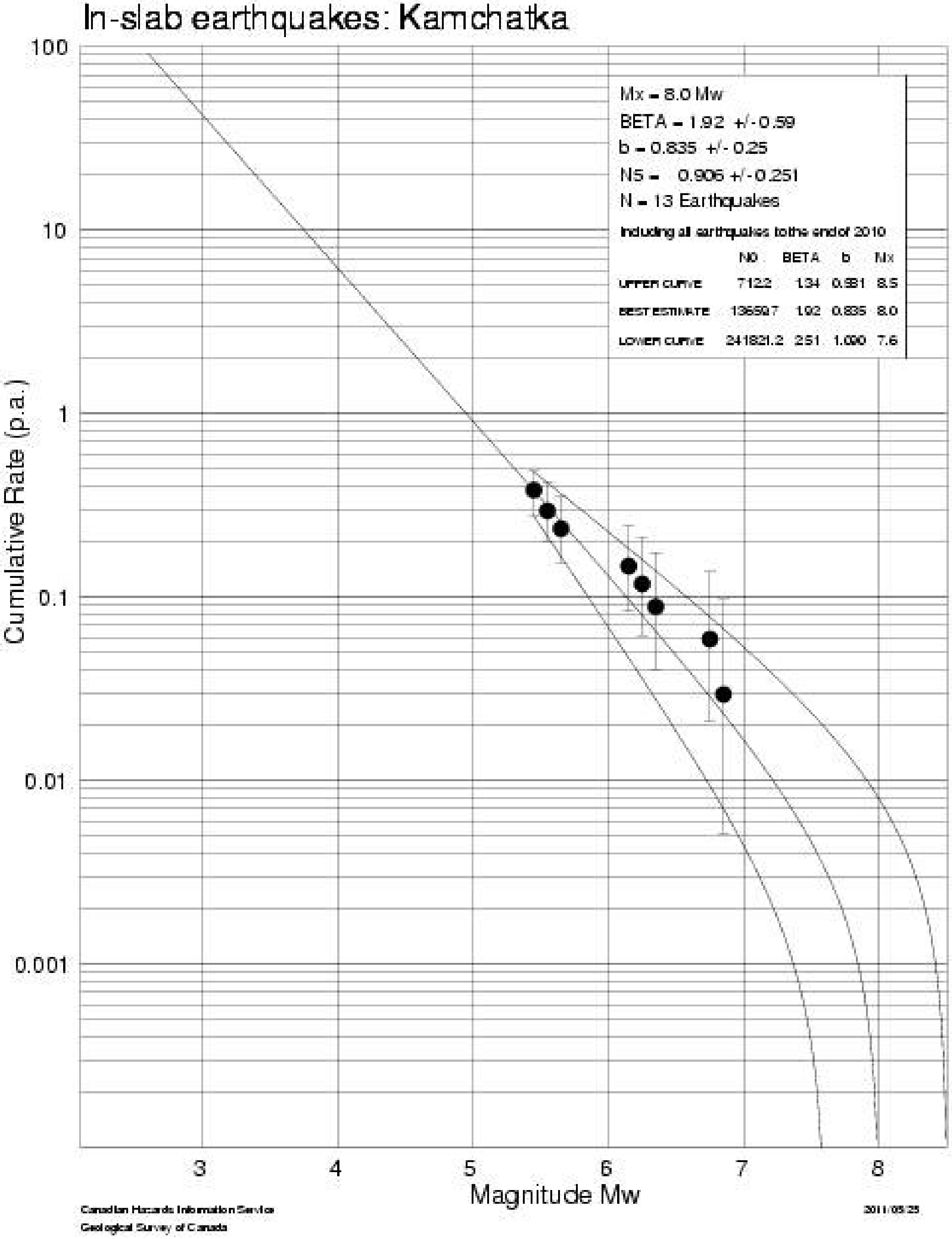
In-slab earthquakes: Kamchatka
Mx = 8.0 Mw
BETA = 1.92 +/- 0.59
b = 0.835 +/- 0.25
N5 = 0.906 +/- 0.251
N = 13 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 712.2 1.34 0.581 8.5
BEST ESTIMATE 1365.97 1.92 0.835 8.0
LOWER CURVE 241821.2 2.51 1.090 7.6
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 15

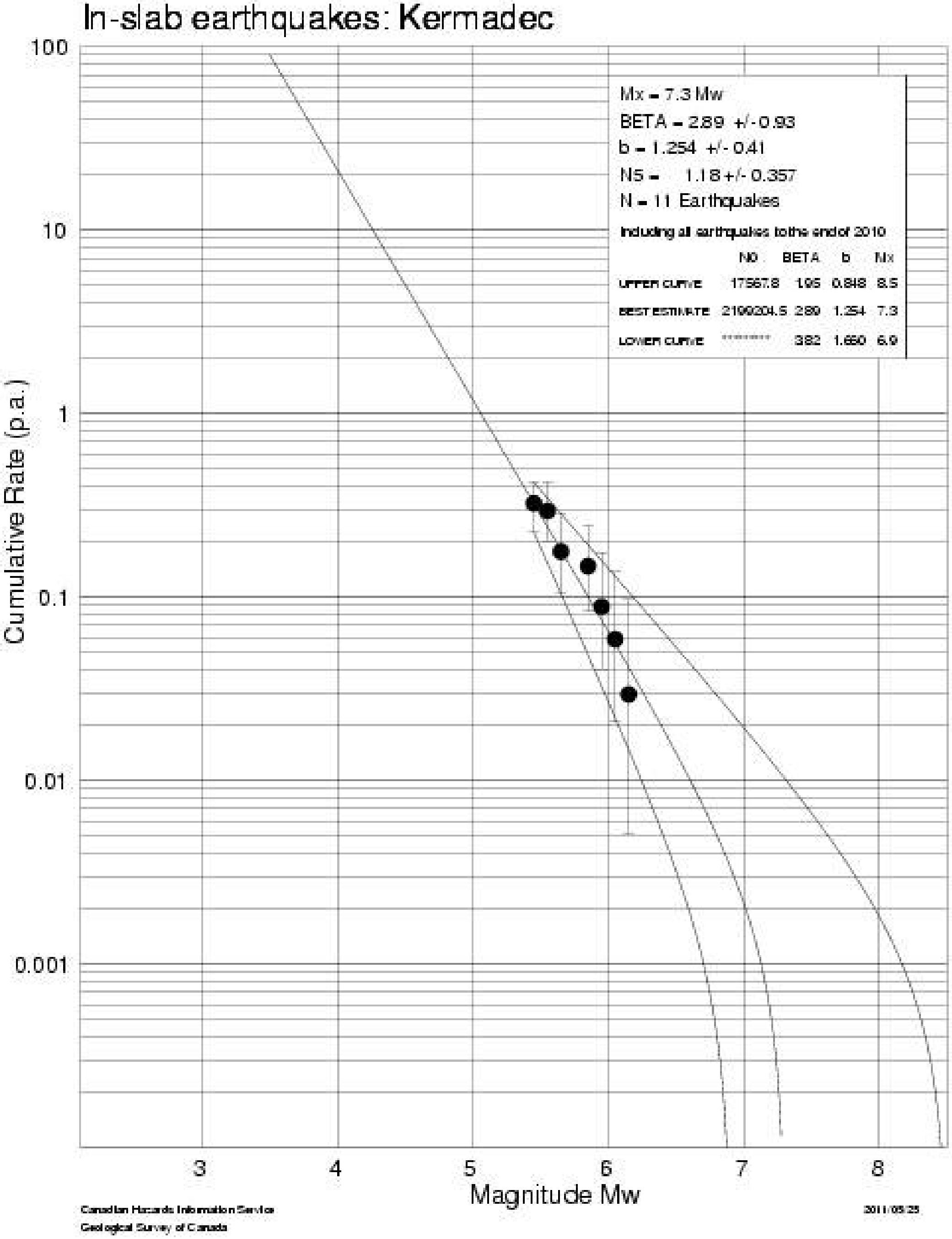
In-slab earthquakes: Kermadec
Mx = 7.3 Mw
BETA = 2.89 +/- 0.93
b = 1.254 +/- 0.41
N5 = 1.18 +/- 0.357
N = 11 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 17567.8 1.95 0.848 8.5
BEST ESTIMATE 2199204.5 2.89 1.254 7.3
LOWER CURVE ********* 3.82 1.660 6.9
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 16

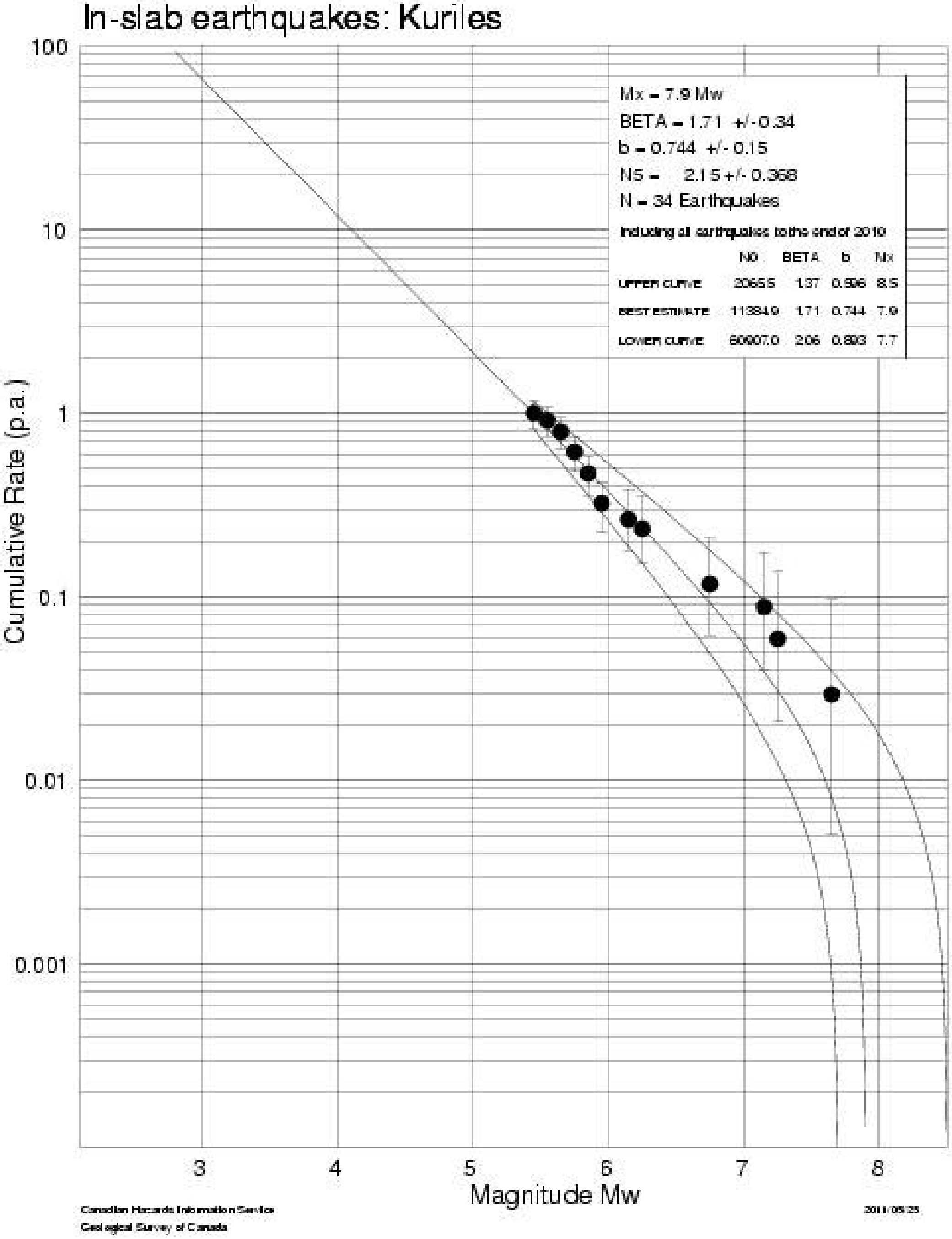
In-slab earthquakes: Kuriles
Mx = 7.9 Mw
BETA = 1.71 +/- 0.34
b = 0.744 +/- 0.15
N5 = 2.15 +/- 0.368
N = 34 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 20655 1.37 0.596 8.5
BEST ESTIMATE 11384.9 1.71 0.744 7.9
LOWER CURVE 60907.0 2.06 0.893 7.7
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
Magnitude Mw
3
4
5
6
7
8
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 17

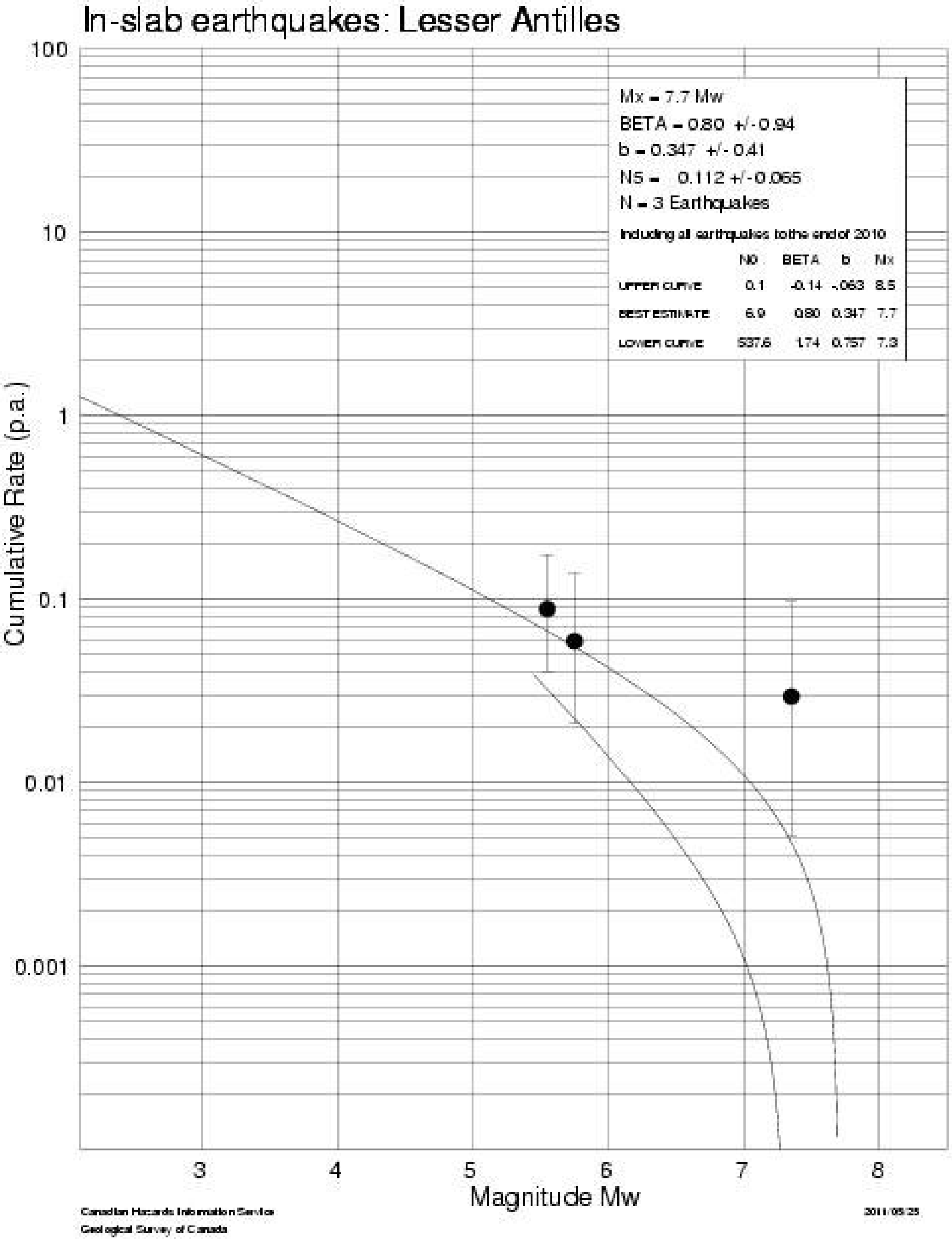
In-slab earthquakes: Lesser Antilles
Mx = 7.7 Mw
BETA = 0.80 +/- 0.94
b = 0.347 +/- 0.41
N5 = 0.112 +/- 0.065
N = 3 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 0.1 -0.14 -.063 8.5
BEST ESTIMATE 6.9 0.80 0.347 7.7
LOWER CURVE 537.6 1.74 0.757 7.3
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 18

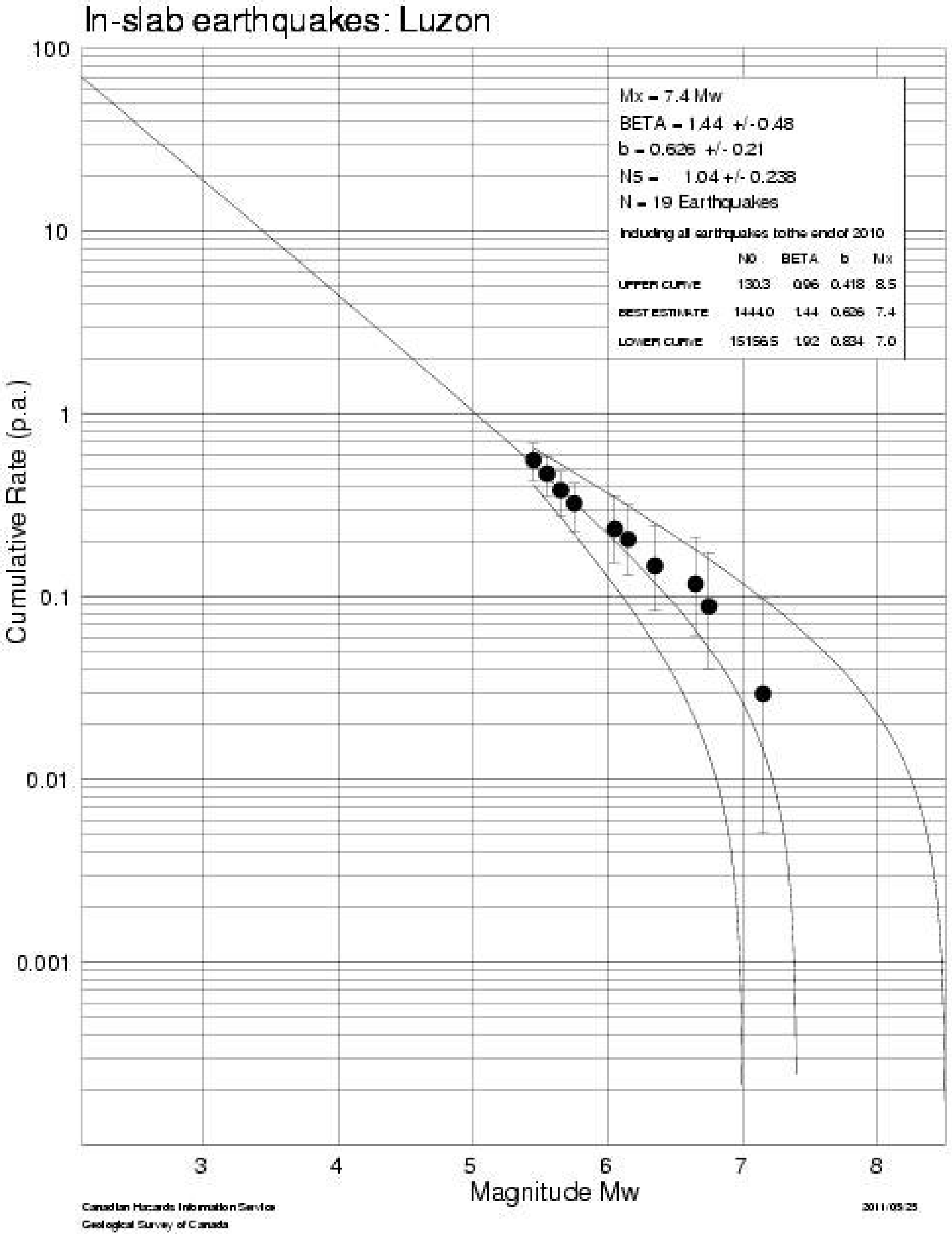
In-slab earthquakes: Luzon
Mx = 7.4 Mw
BETA = 1.44 +/- 0.48
b = 0.626 +/- 0.21
N5 = 1.04 +/- 0.238
N = 19 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 130.3 0.96 0.418 8.5
BEST ESTIMATE 1444.0 1.44 0.626 7.4
LOWER CURVE 15156.5 1.92 0.834 7.0
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 19

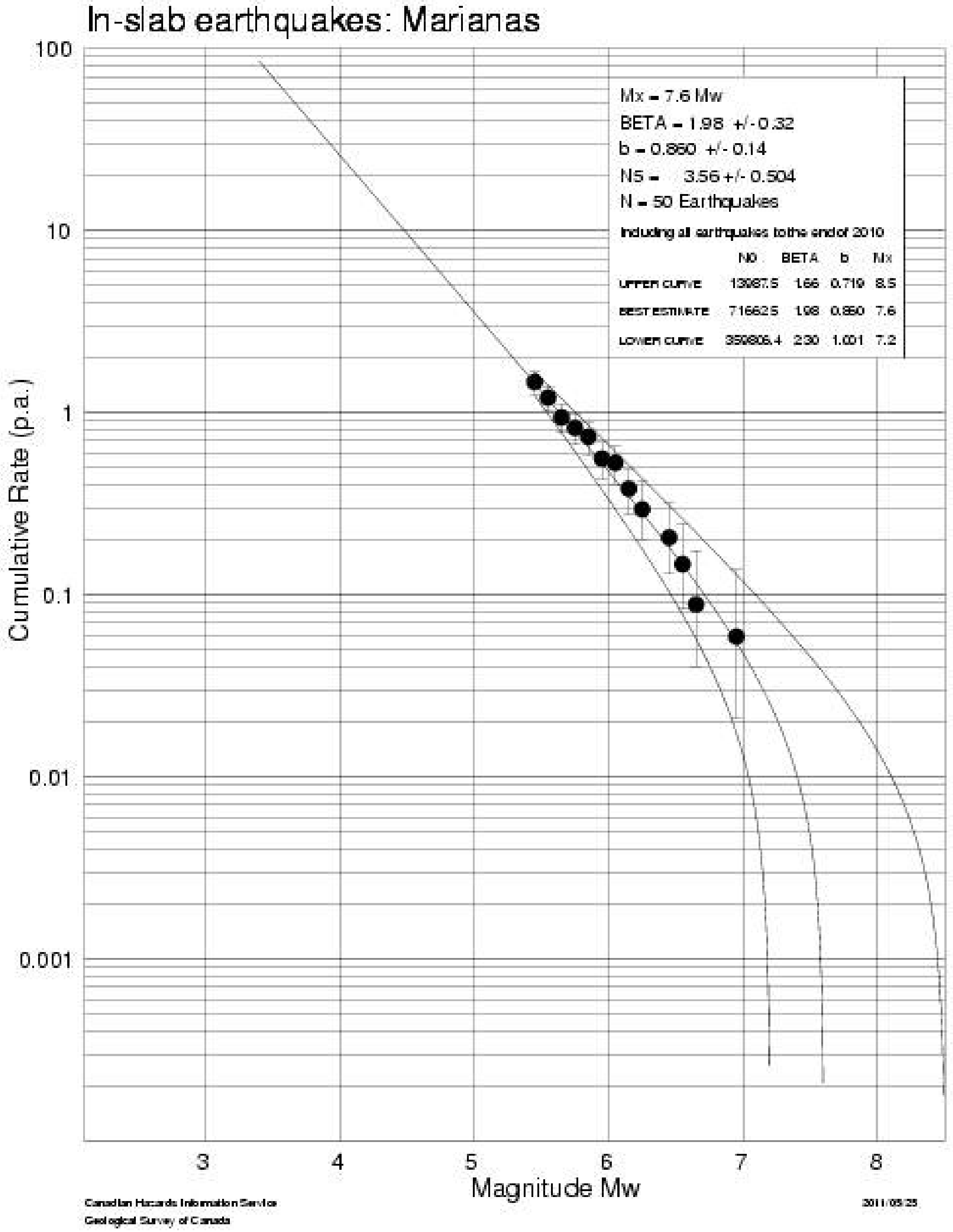
In-slab earthquakes: Marianas
Mx = 7.6 Mw
BETA = 1.98 +/- 0.32
b = 0.860 +/- 0.14
N5 = 3.56 +/- 0.504
N = 50 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 13987.5 1.66 0.719 8.5
BEST ESTIMATE 716625 1.98 0.860 7.6
LOWER CURVE 359806.4 2.30 1.001 7.2
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 20

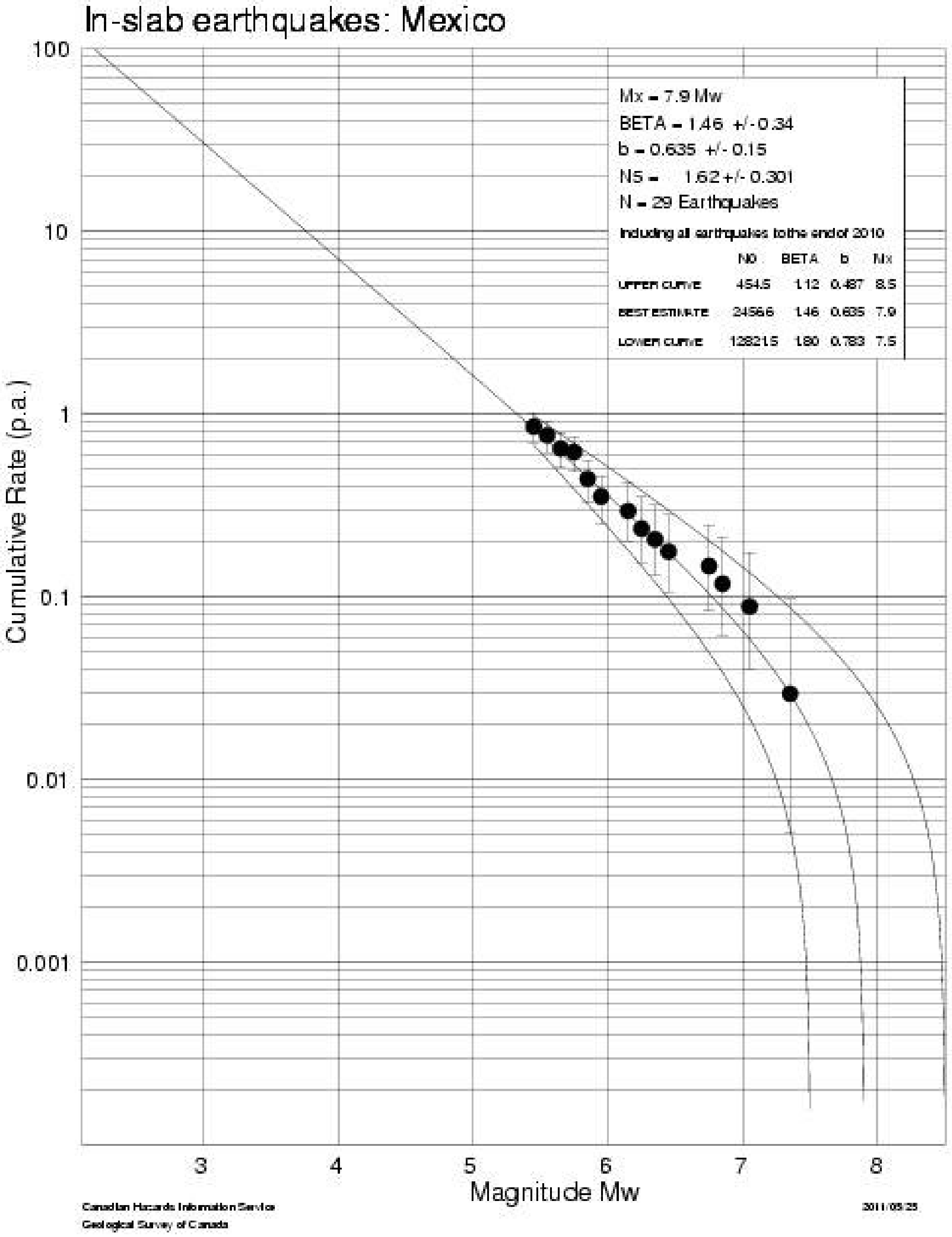
In-slab earthquakes: Mexico
Mx = 7.9 Mw
BETA = 1.46 +/- 0.34
b = 0.635 +/- 0.15
N5 = 1.62 +/- 0.301
N = 29 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 454.5 1.12 0.487 8.5
BEST ESTIMATE 2456.6 1.46 0.635 7.9
LOWER CURVE 12821.5 1.80 0.783 7.5
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 21

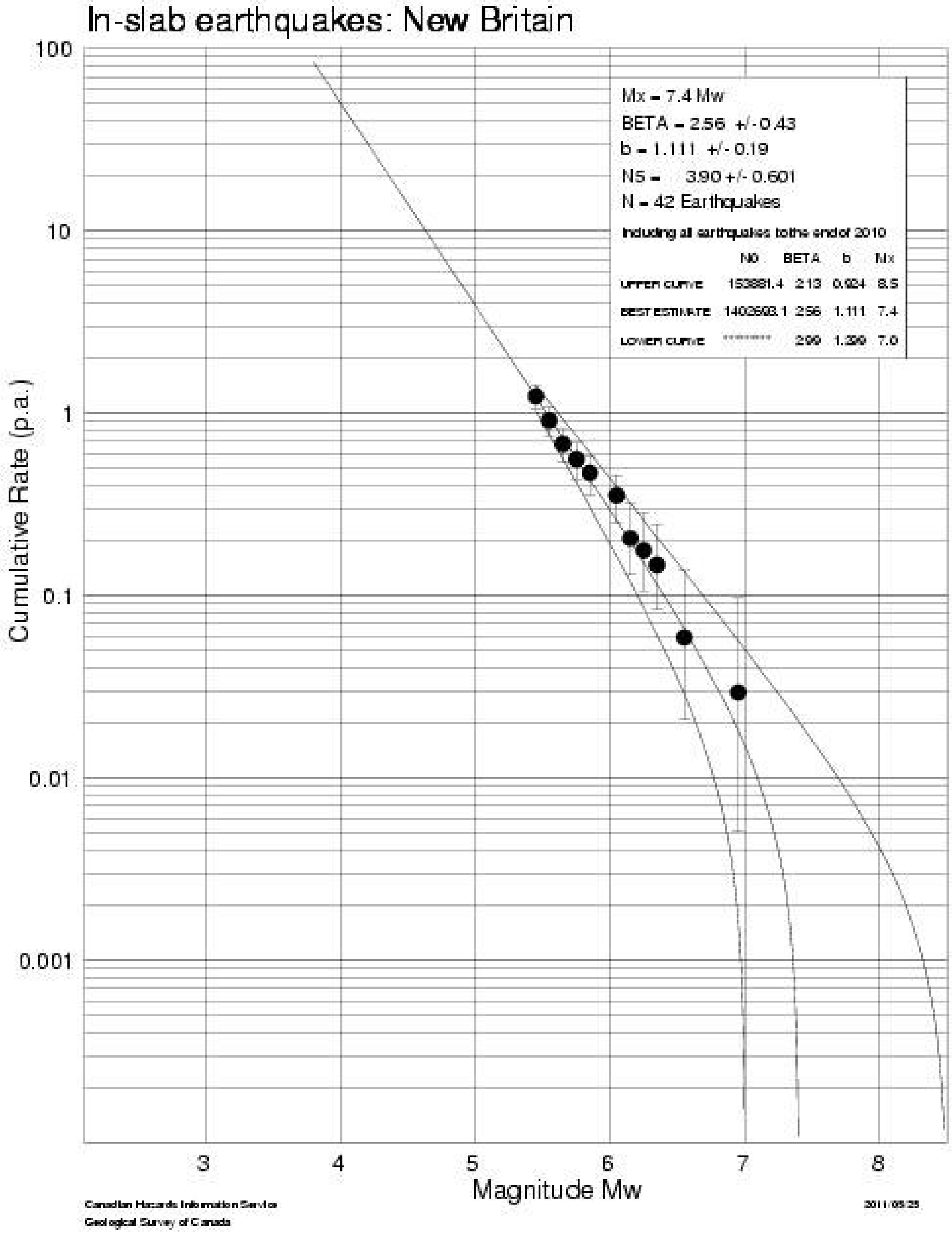
In-slab earthquakes: New Britain
Mx = 7.4 Mw
BETA = 2.56 +/- 0.43
b = 1.111 +/- 0.19
N5 = 3.90 +/- 0.601
N = 42 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 153881.4 2.13 0.924 8.5
BEST ESTIMATE 1402603.1 2.56 1.111 7.4
LOWER CURVE ******** 2.99 1.299 7.0
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 22

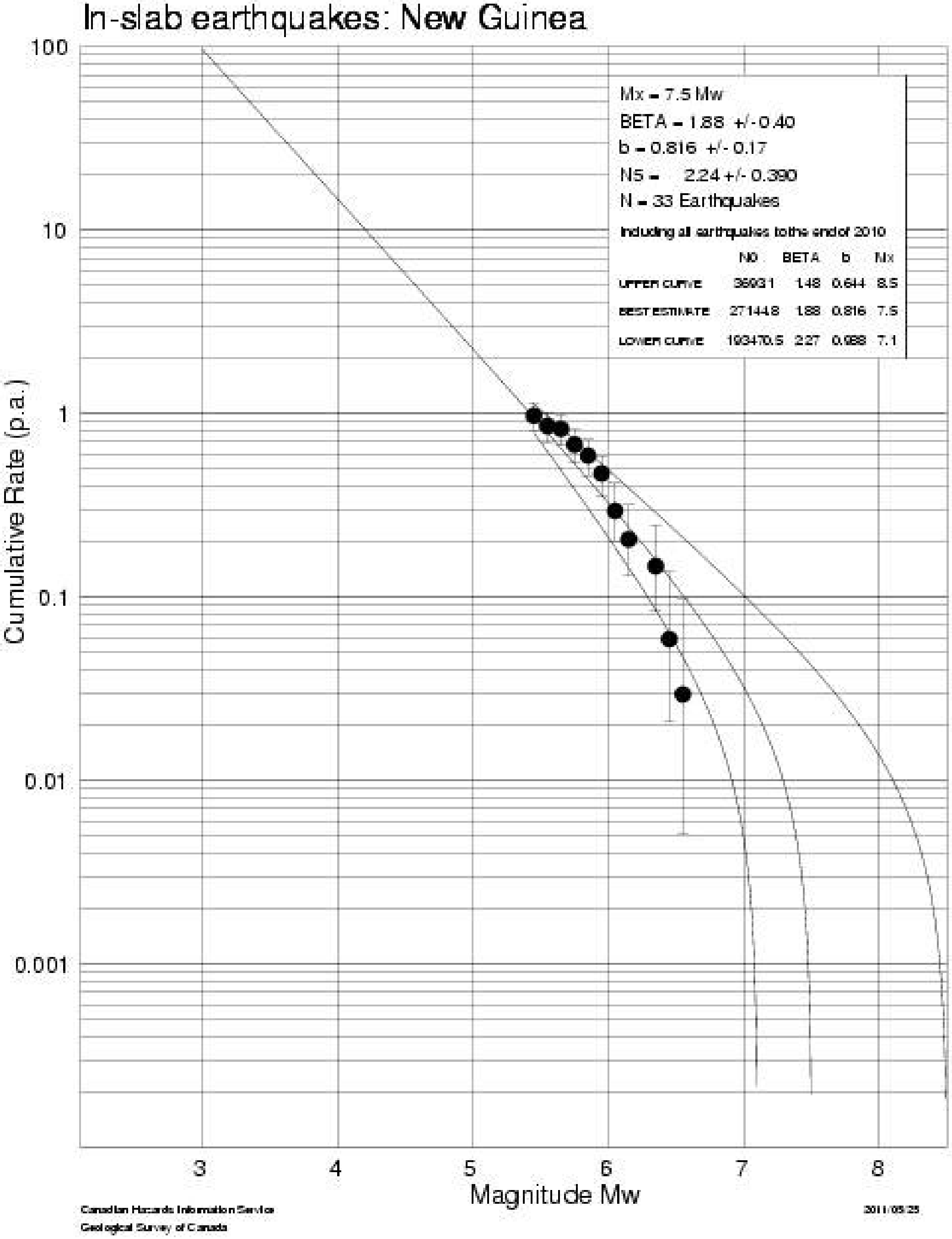
In-slab earthquakes: New Guinea
Mx = 7.5 Mw
BETA = 1.88 +/- 0.40
b = 0.816 +/- 0.17
N5 = 2.24 +/- 0.390
N = 33 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 36931.1 1.48 0.644 8.5
BEST ESTIMATE 27144.8 1.88 0.816 7.5
LOWER CURVE 193470.5 2.27 0.988 7.1
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 23

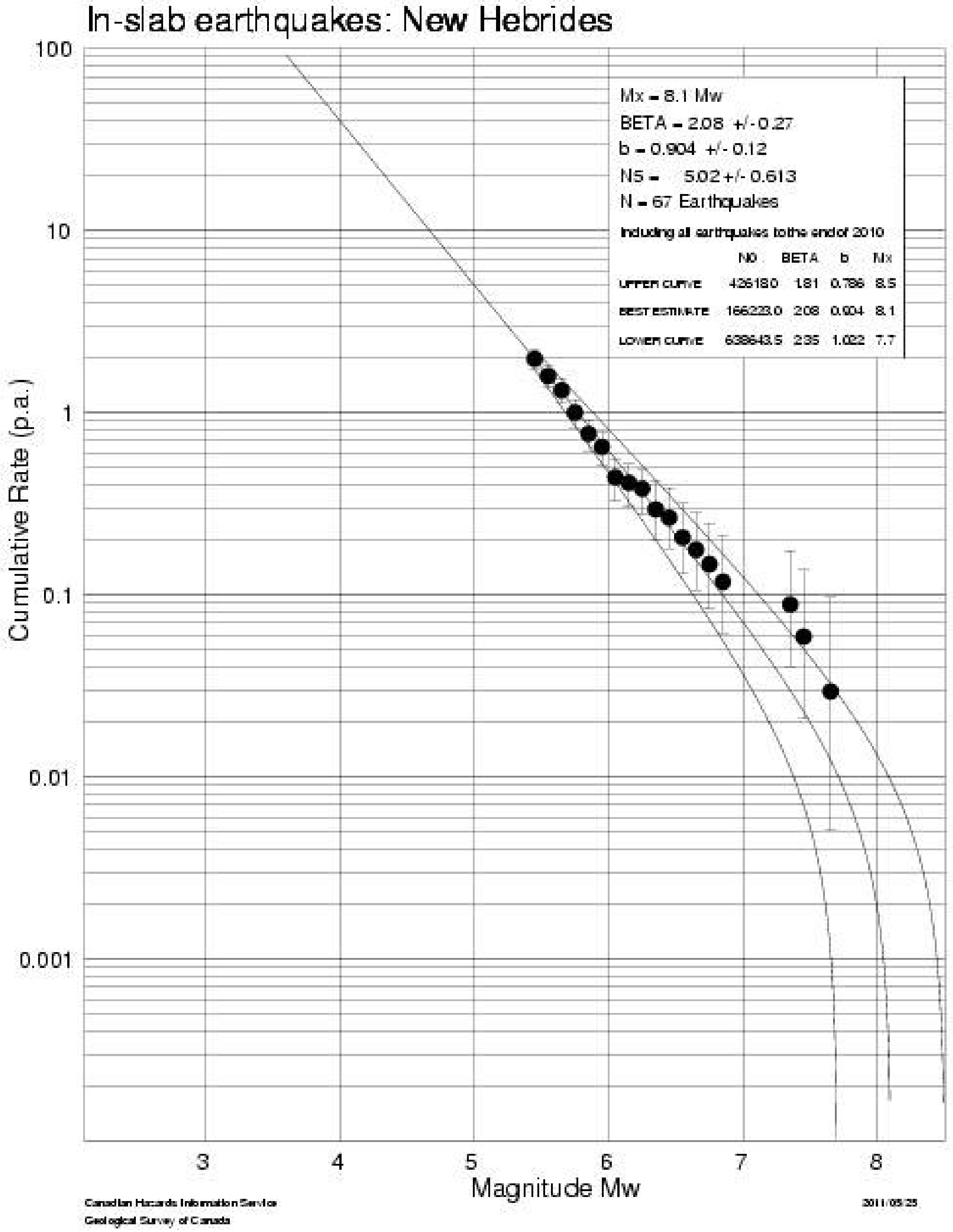
In-slab earthquakes: New Hebrides
Mx = 8.1 Mw
BETA = 2.08 +/- 0.27
b = 0.904 +/- 0.12
N5 = 5.02 +/- 0.613
N = 67 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 426180 1.81 0.786 8.5
BEST ESTIMATE 166223.0 2.08 0.904 8.1
LOWER CURVE 638643.5 2.35 1.022 7.7
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 24

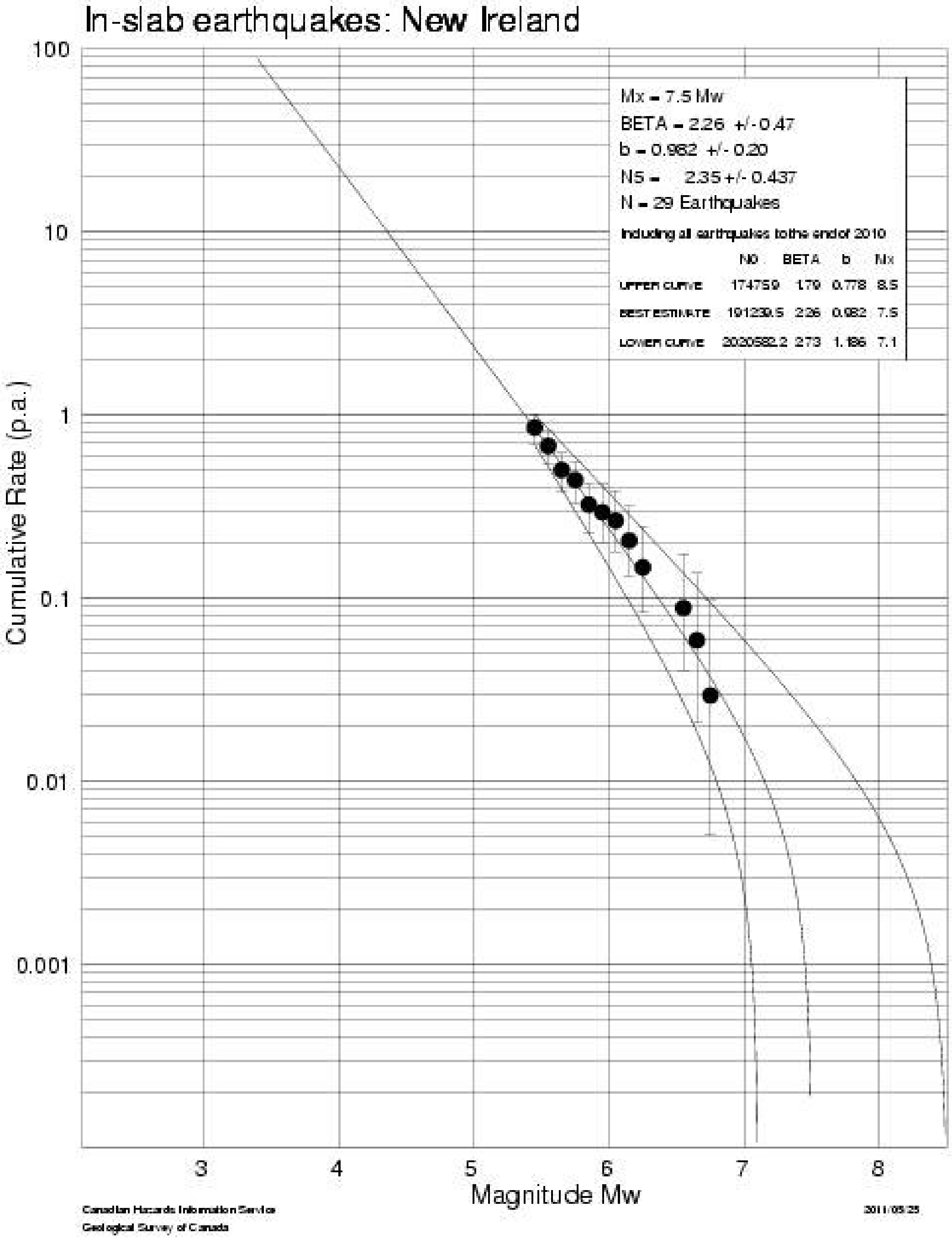
In-slab earthquakes: New Ireland
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
Mx = 7.5 Mw
BETA = 2.26 +/- 0.47
b = 0.982 +/- 0.20
N5 = 2.35 +/- 0.437
N = 29 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 174759 1.79 0.778 8.5
BEST ESTIMATE 191239.5 2.26 0.982 7.5
LOWER CURVE 2020582.2 2.73 1.186 7.1
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 25

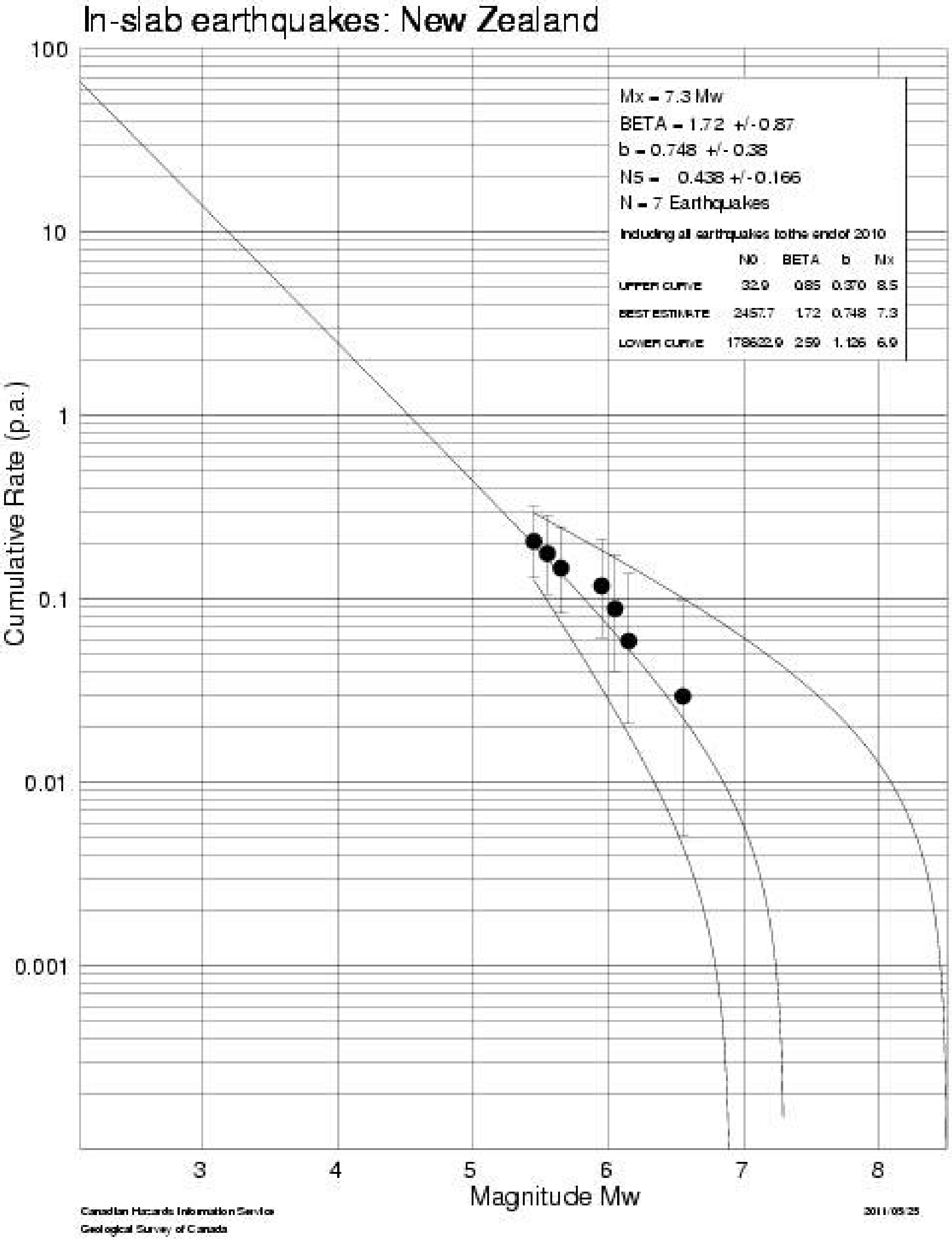
In-slab earthquakes: New Zealand
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Mx = 7.3 Mw
BETA = 1.72 +/- 0.87
b = 0.748 +/- 0.38
N5 = 0.438 +/- 0.166
N = 7 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 32.9 0.85 0.370 8.5
BEST ESTIMATE 2457.7 1.72 0.748 7.3
LOWER CURVE 178622.9 2.59 1.126 6.9
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 26

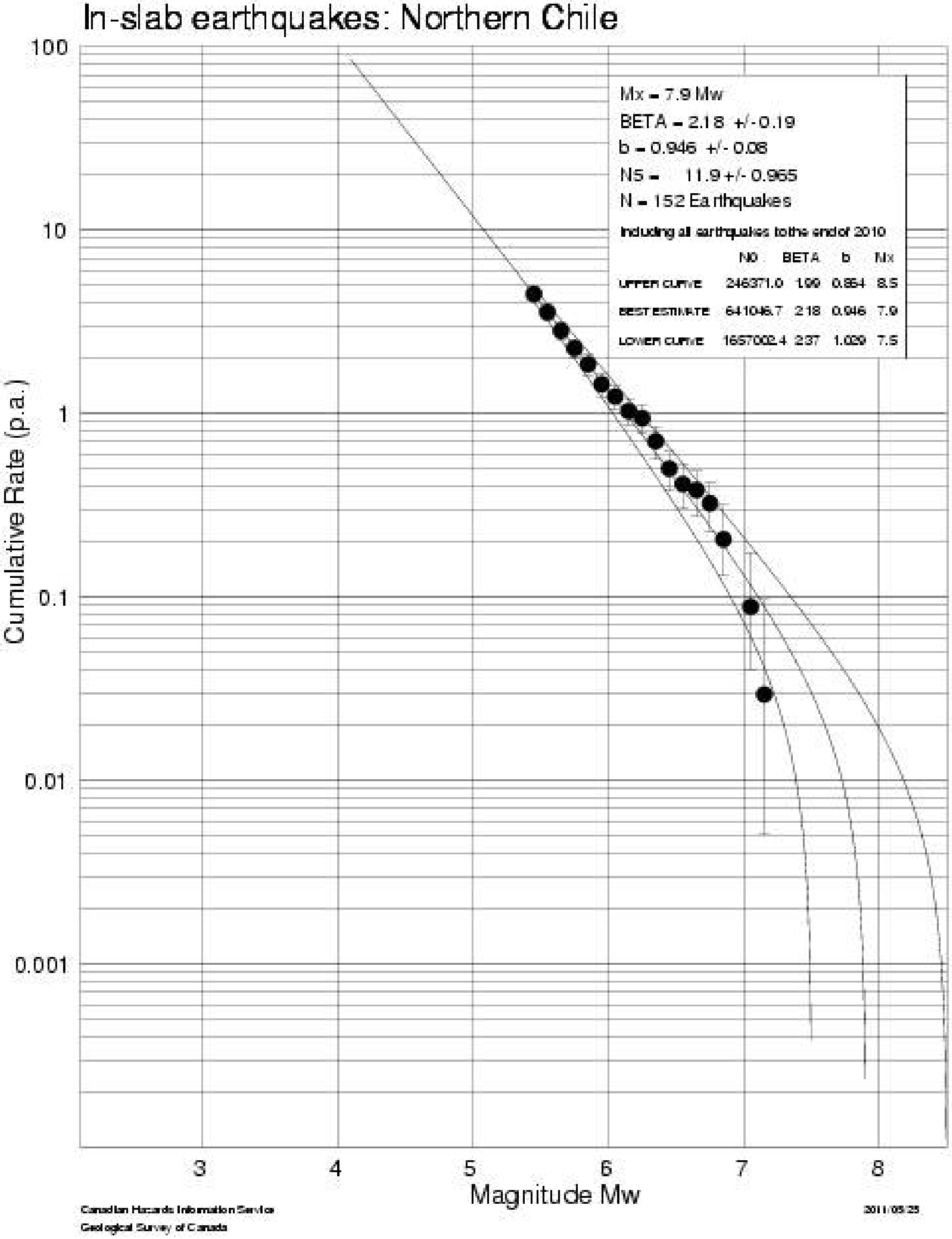
In-slab earthquakes: Northern Chile
Mx = 7.9 Mw
BETA = 2.18 +/- 0.19
b = 0.946 +/- 0.08
N5 = 11.9 +/- 0.965
N = 152 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 246371.0 1.99 0.854 8.5
BEST ESTIMATE 641046.7 2.18 0.946 7.9
LOWER CURVE 1657002.4 2.37 1.029 7.5
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 27

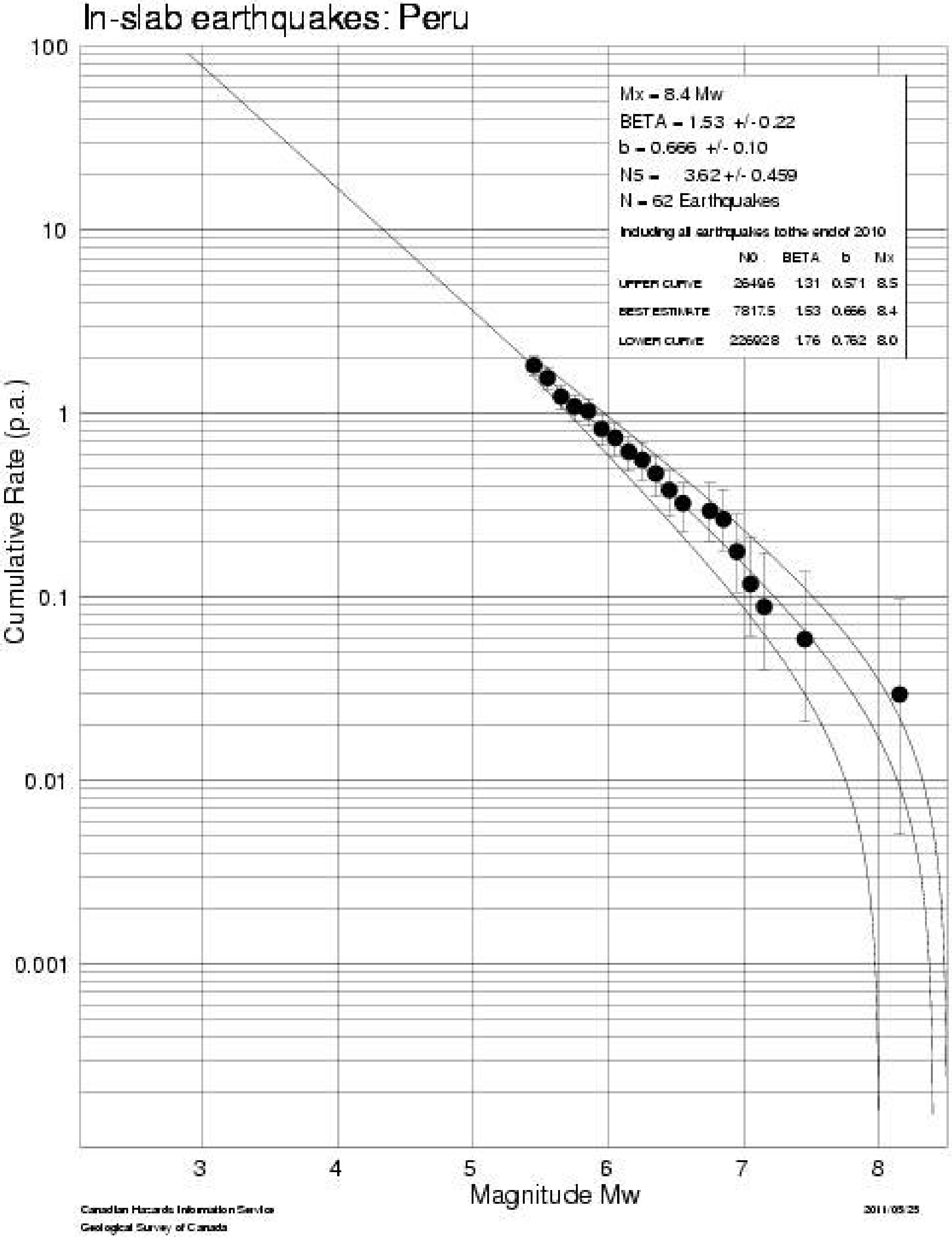
In-slab earthquakes: Peru
Mx = 8.4 Mw
BETA = 1.53 +/- 0.22
b = 0.666 +/- 0.10
N5 = 3.62 +/- 0.459
N = 62 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 26496 1.31 0.571 8.5
BEST ESTIMATE 7817.5 1.53 0.666 8.4
LOWER CURVE 226928 1.76 0.762 8.0
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 28

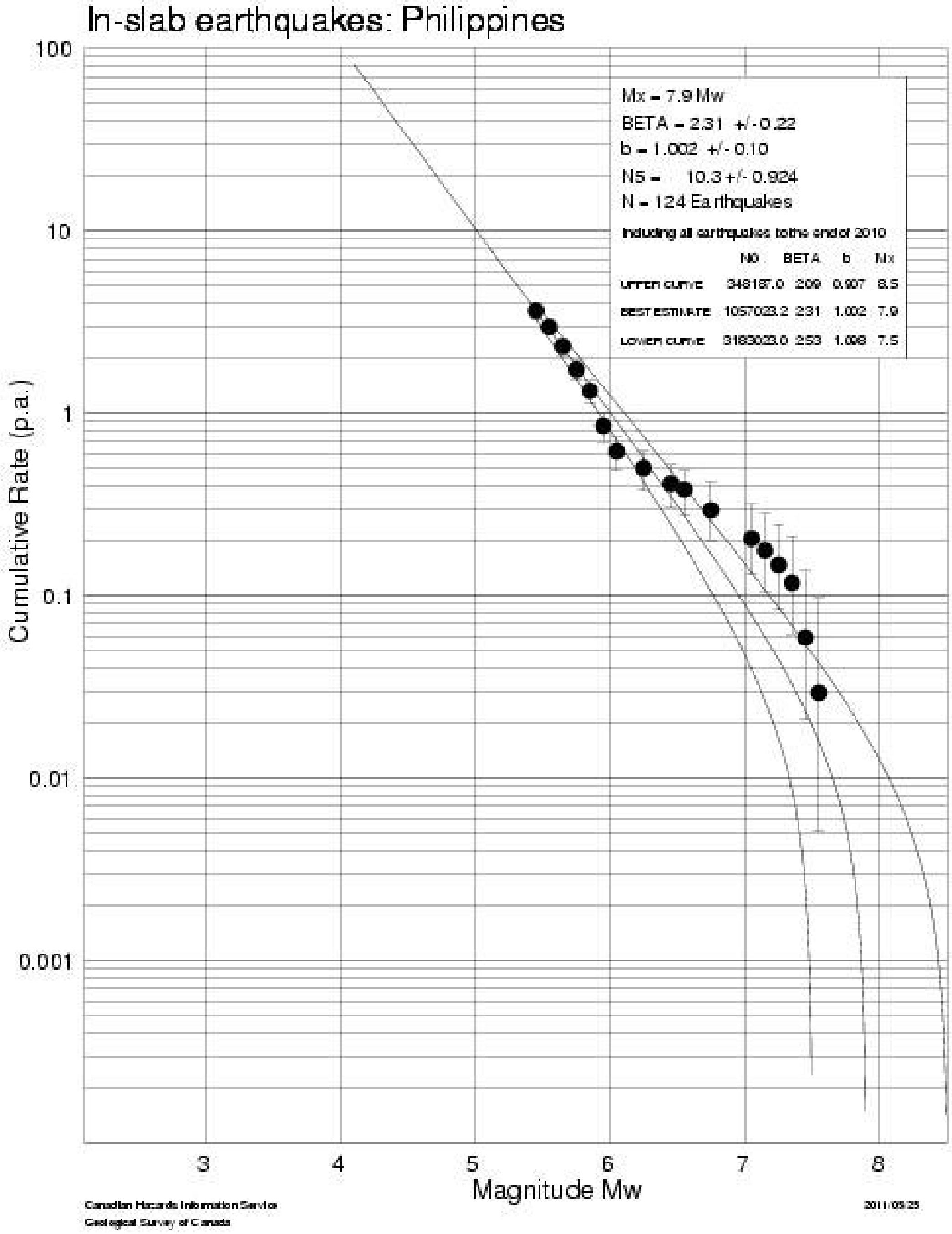
In-slab earthquakes: Philippines
Mx = 7.9 Mw
BETA = 2.31 +/- 0.22
b = 1.002 +/- 0.10
N5 = 10.3 +/- 0.924
N = 124 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 348187.0 2.09 0.907 8.5
BEST ESTIMATE 1057023.2 2.31 1.002 7.9
LOWER CURVE 3183023.0 2.53 1.098 7.5
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 29

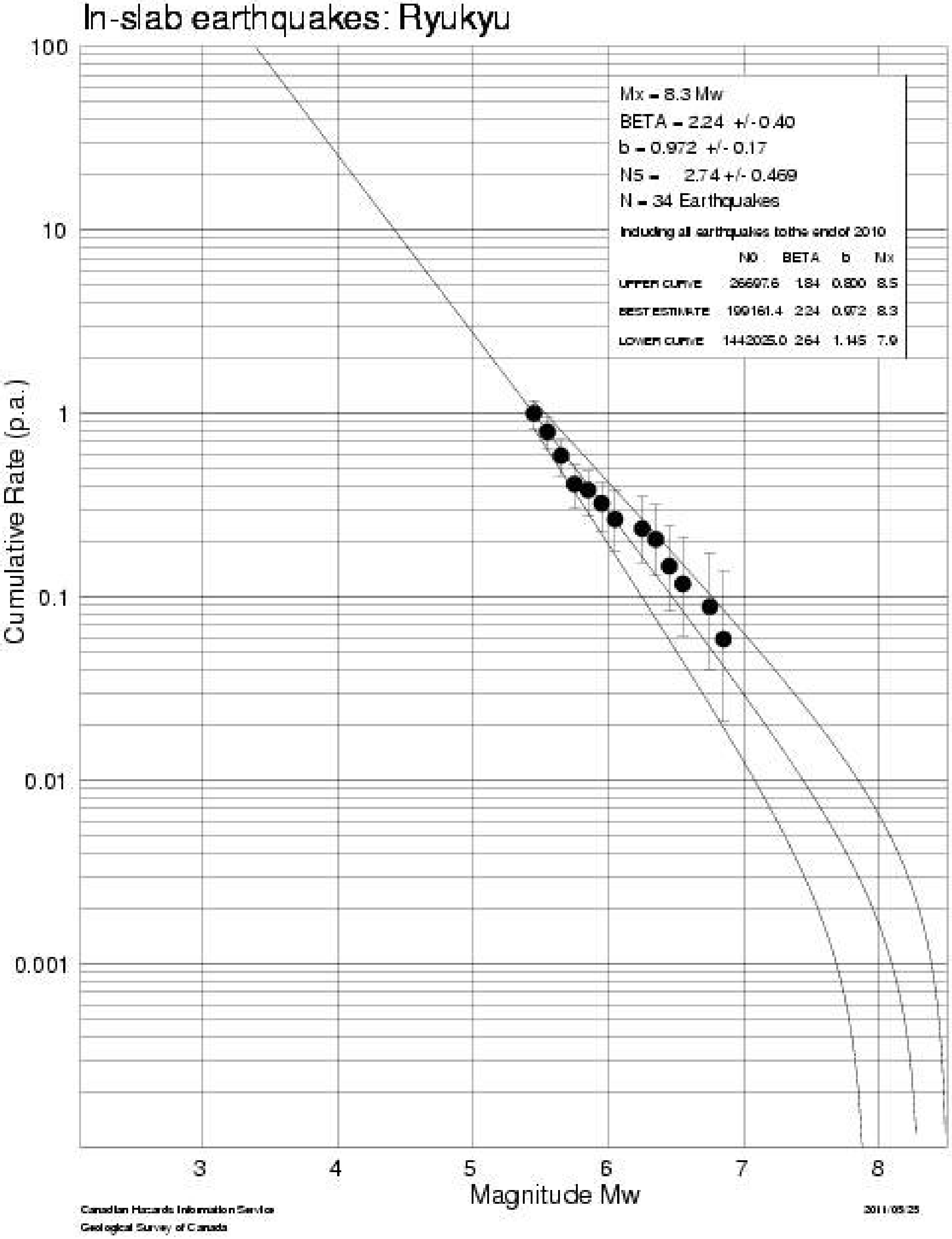
In-slab earthquakes: Ryukyu
Mx = 8.3 Mw
BETA = 2.24 +/- 0.40
b = 0.972 +/- 0.17
N5 = 2.74 +/- 0.469
N = 34 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 26697.6 1.84 0.800 8.5
BEST ESTIMATE 199161.4 2.24 0.972 8.3
LOWER CURVE 1442025.0 2.64 1.145 7.9
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 30

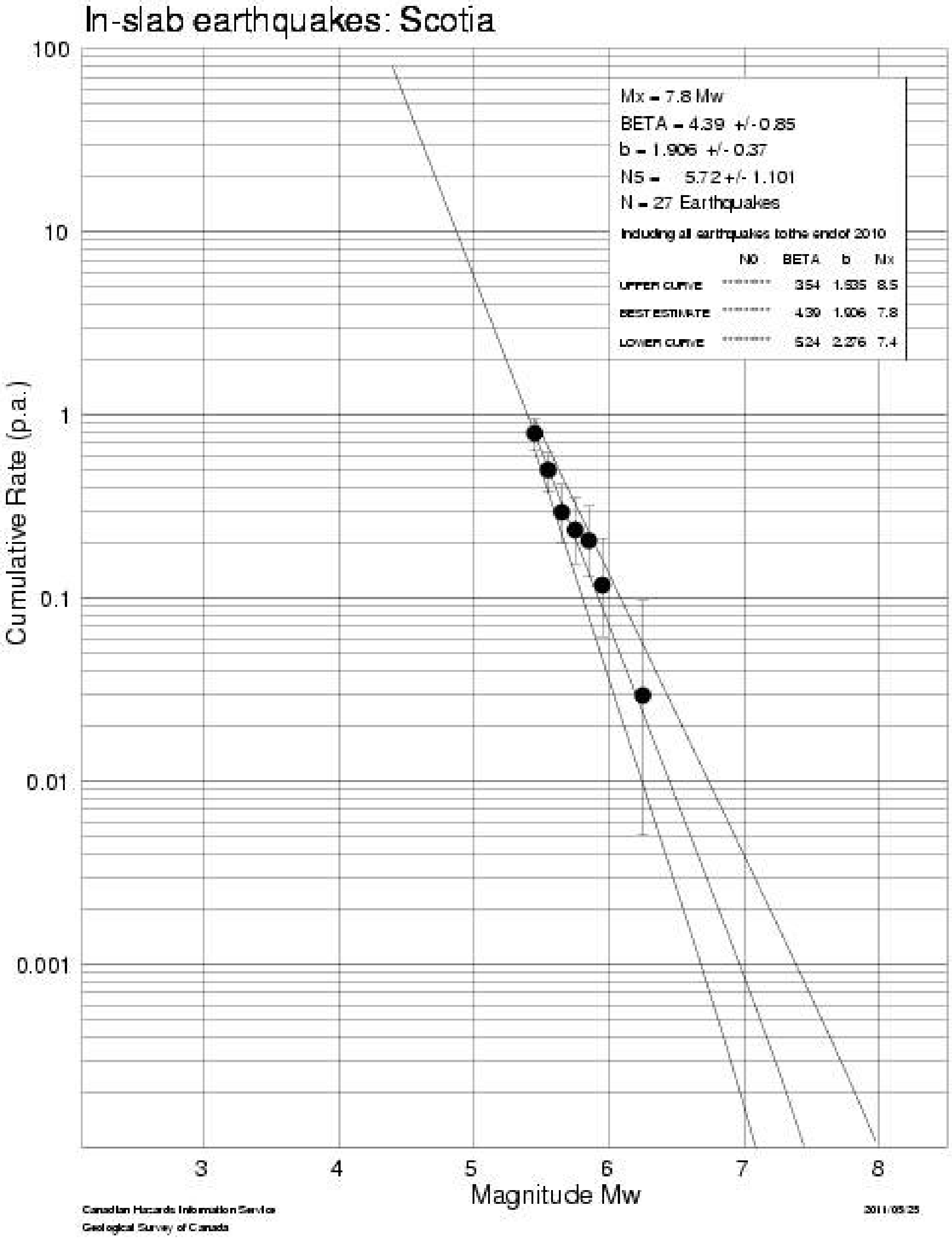
In-slab earthquakes: Scotia
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
Magnitude Mw
3
4
5
6
7
8
Mx = 7.8 Mw
BETA = 4.39 +/- 0.85
b = 1.906 +/- 0.37
N5 = 5.72 +/- 1.101
N = 27 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE ******** 3.54 1.535 8.5
BEST ESTIMATE ******** 4.39 1.906 7.8
LOWER CURVE ******** 5.24 2.276 7.4
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Figure 31

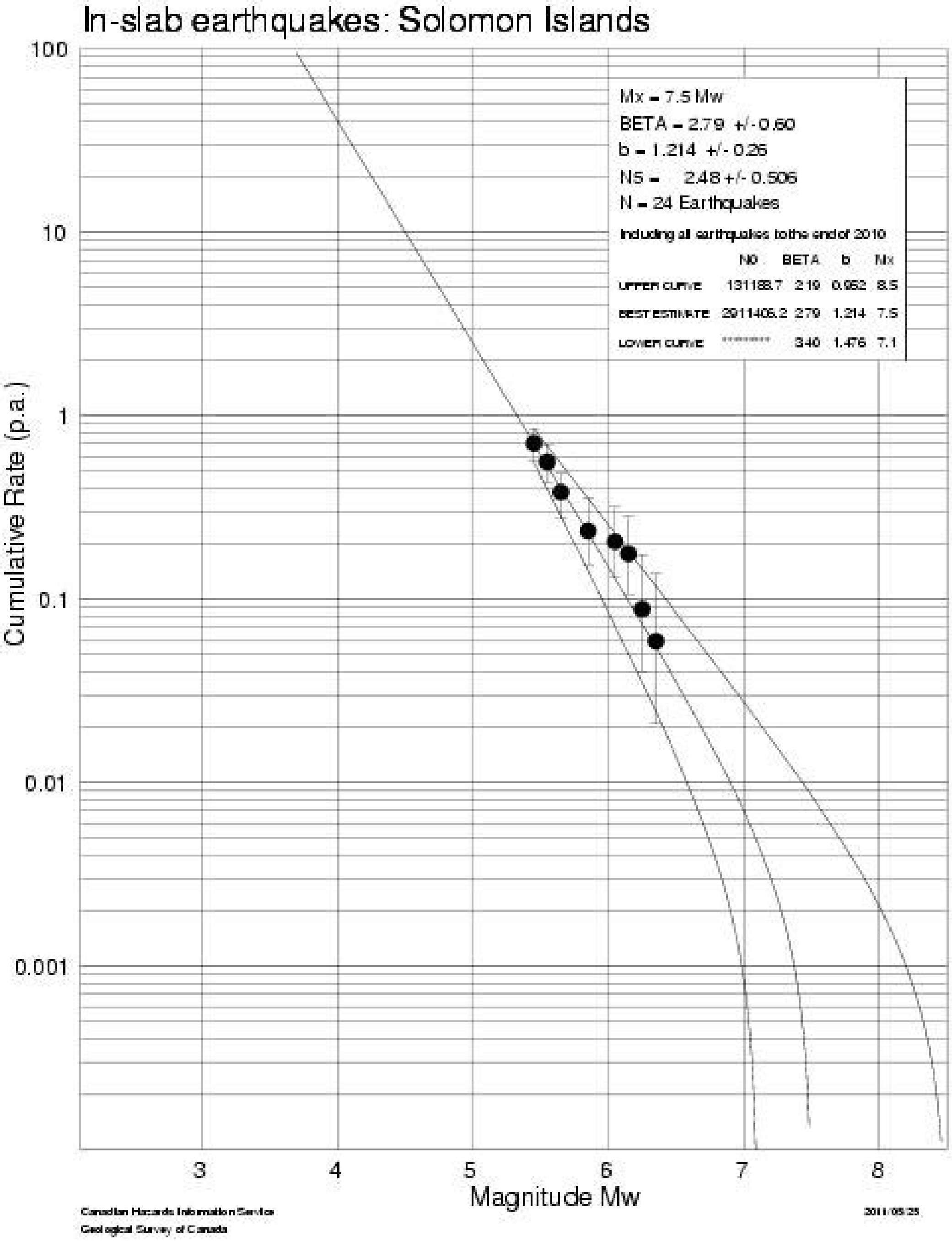
In-slab earthquakes: Solomon Islands
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Mx = 7.5 Mw
BETA = 2.79 +/- 0.60
b = 1.214 +/- 0.26
N5 = 2.48 +/- 0.506
N = 24 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 131188.7 2.19 0.952 8.5
BEST ESTIMATE 2911405.2 2.79 1.214 7.5
LOWER CURVE ********* 3.40 1.476 7.1
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Figure 32

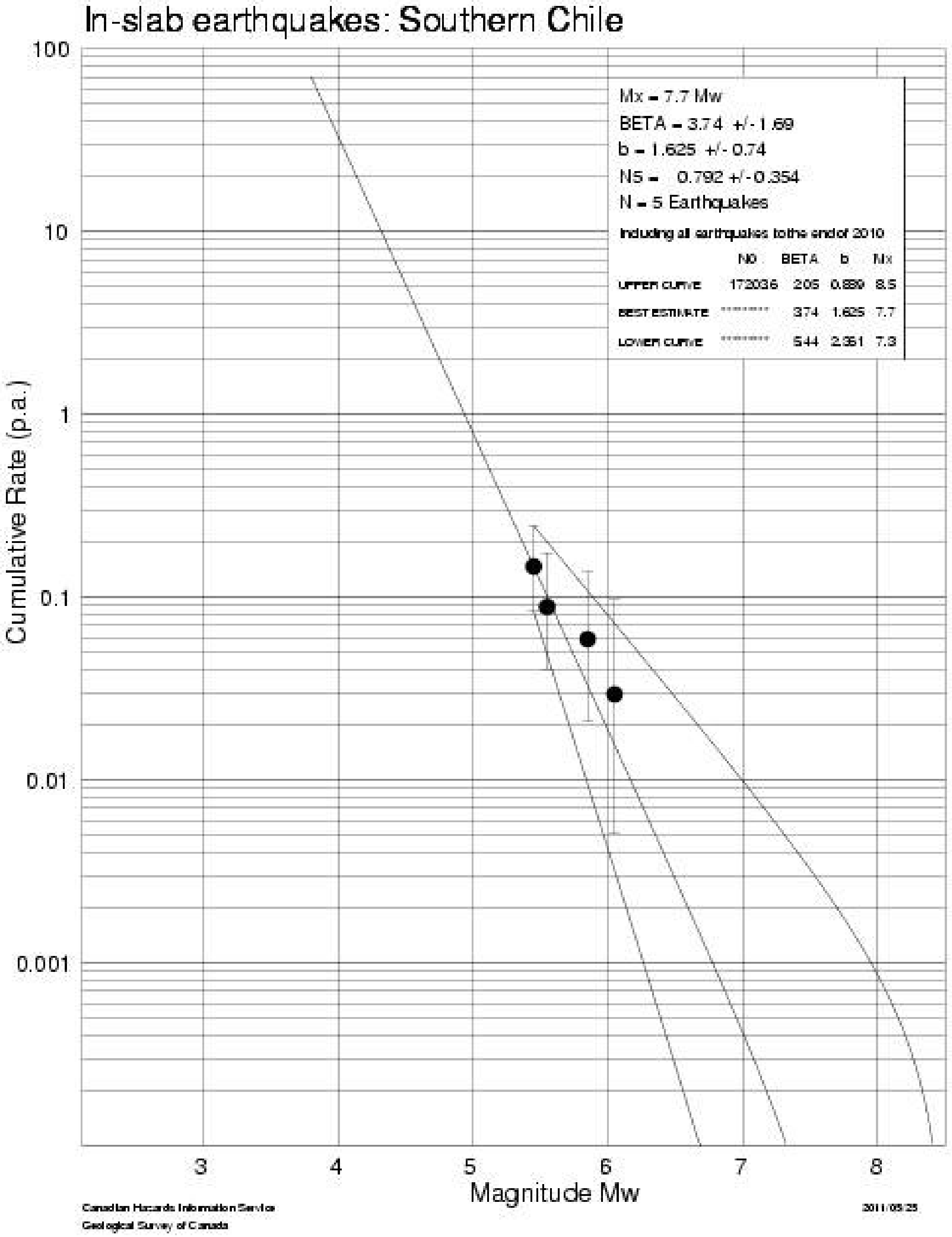

In-slab earthquakes: Southern Chile
Mx = 7.7 Mw
BETA = 3.74 +/- 1.69
b = 1.625 +/- 0.74
N5 = 0.792 +/- 0.354
N = 5 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 172036 2.05 0.889 8.5
BEST ESTIMATE ******** 3.74 1.625 7.7
LOWER CURVE ******** 5.44 2.361 7.3
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 33

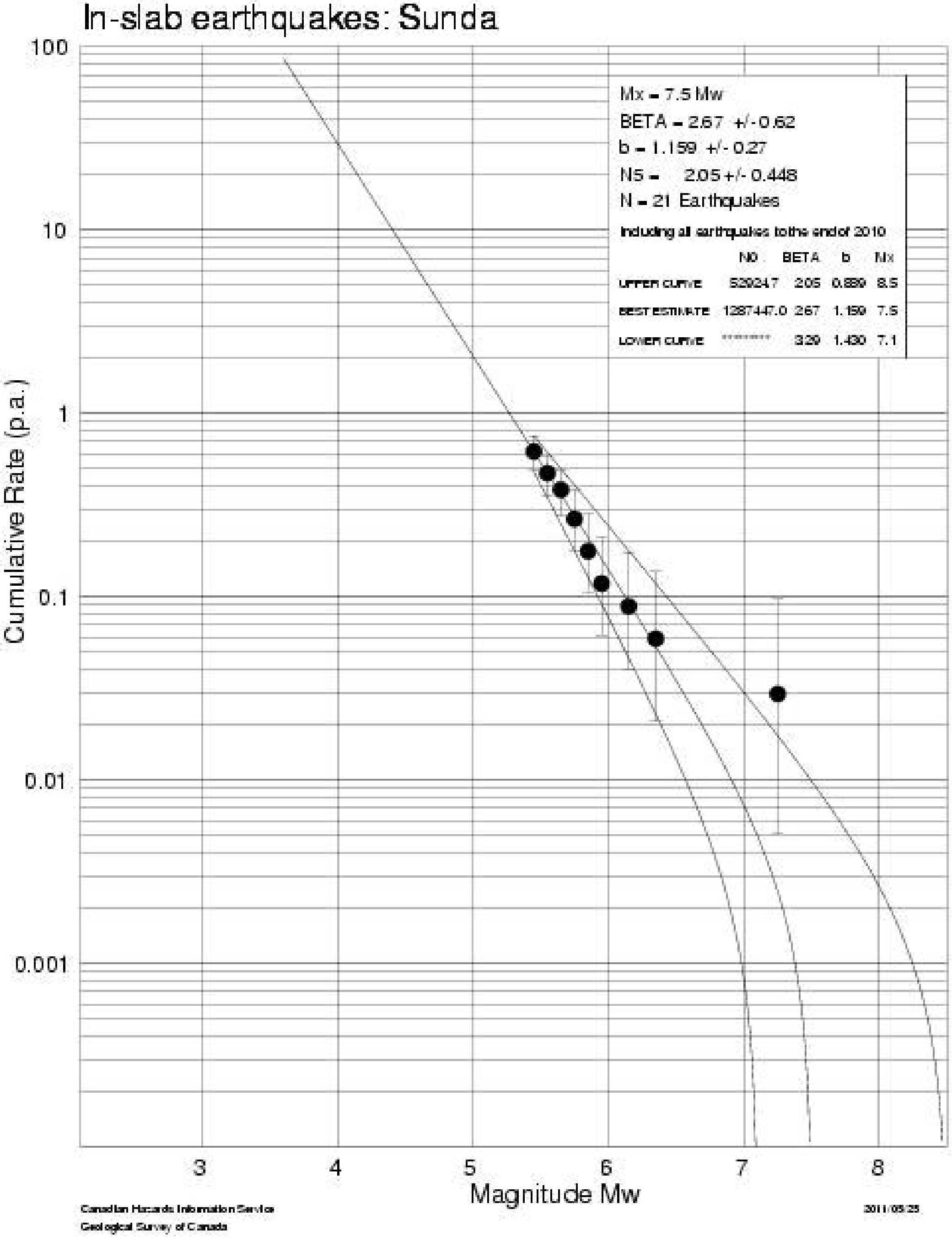
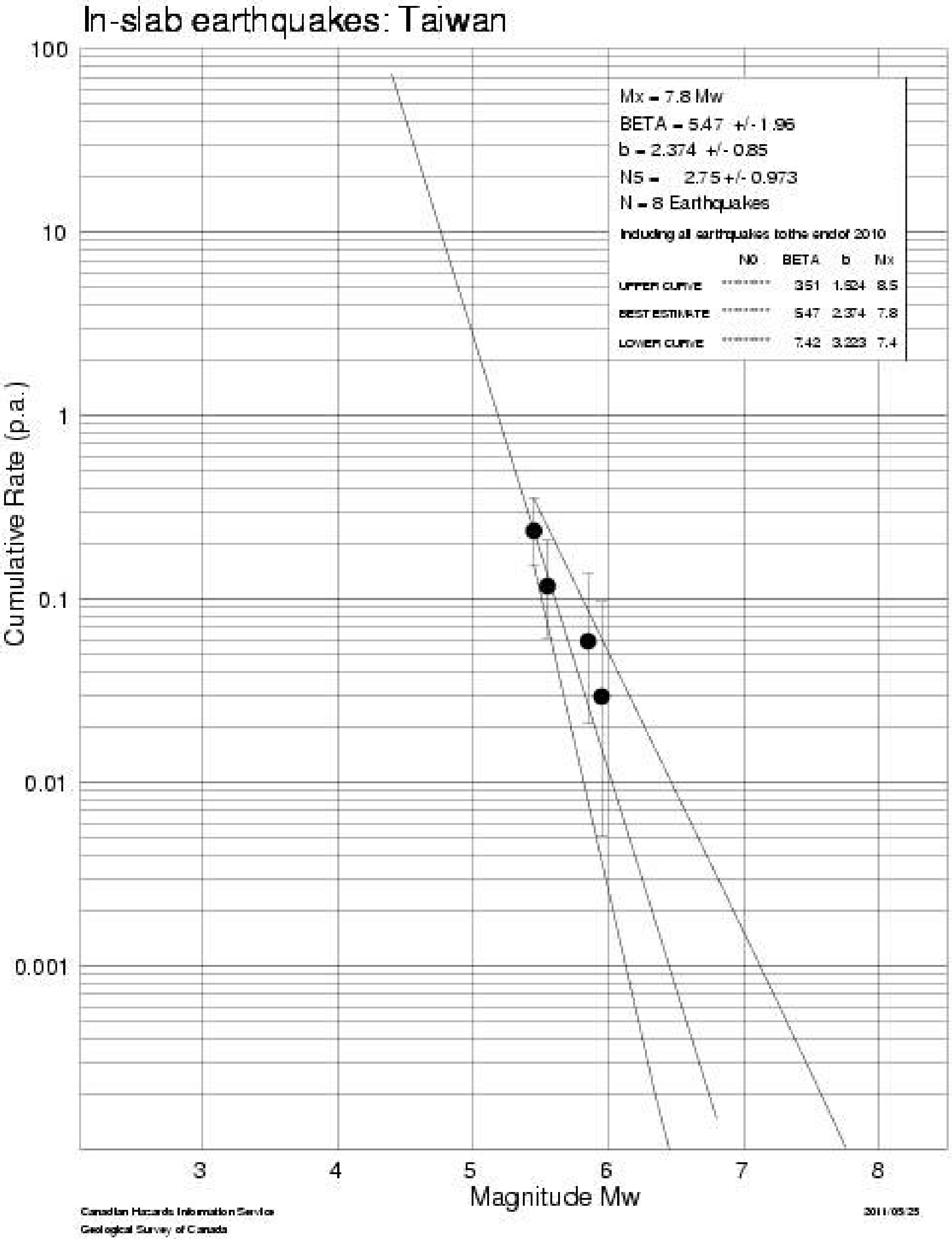

In-slab earthquakes: Sunda
Mx = 7.5 Mw
BETA = 2.67 +/- 0.62
b = 1.159 +/- 0.27
N5 = 2.05 +/- 0.448
N = 21 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 52924.7 2.05 0.889 8.5
BEST ESTIMATE 1287447.0 2.67 1.159 7.5
LOWER CURVE ******** 3.29 1.430 7.1
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 34


In-slab earthquakes: Taiwan
100
10
1
0.1
0.01
0.001
Cumulative Rate (p.a.)
3
4
5
6
7
8
Magnitude Mw
Mx = 7.8 Mw
BETA = 5.47 +/- 1.96
b = 2.374 +/- 0.85
N5 = 2.75 +/- 0.973
N = 8 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE ********* 3.51 1.524 8.5
BEST ESTIMATE ********* 5.47 2.374 7.8
LOWER CURVE ********* 7.42 3.223 7.4
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2011/05/25

Figure 35

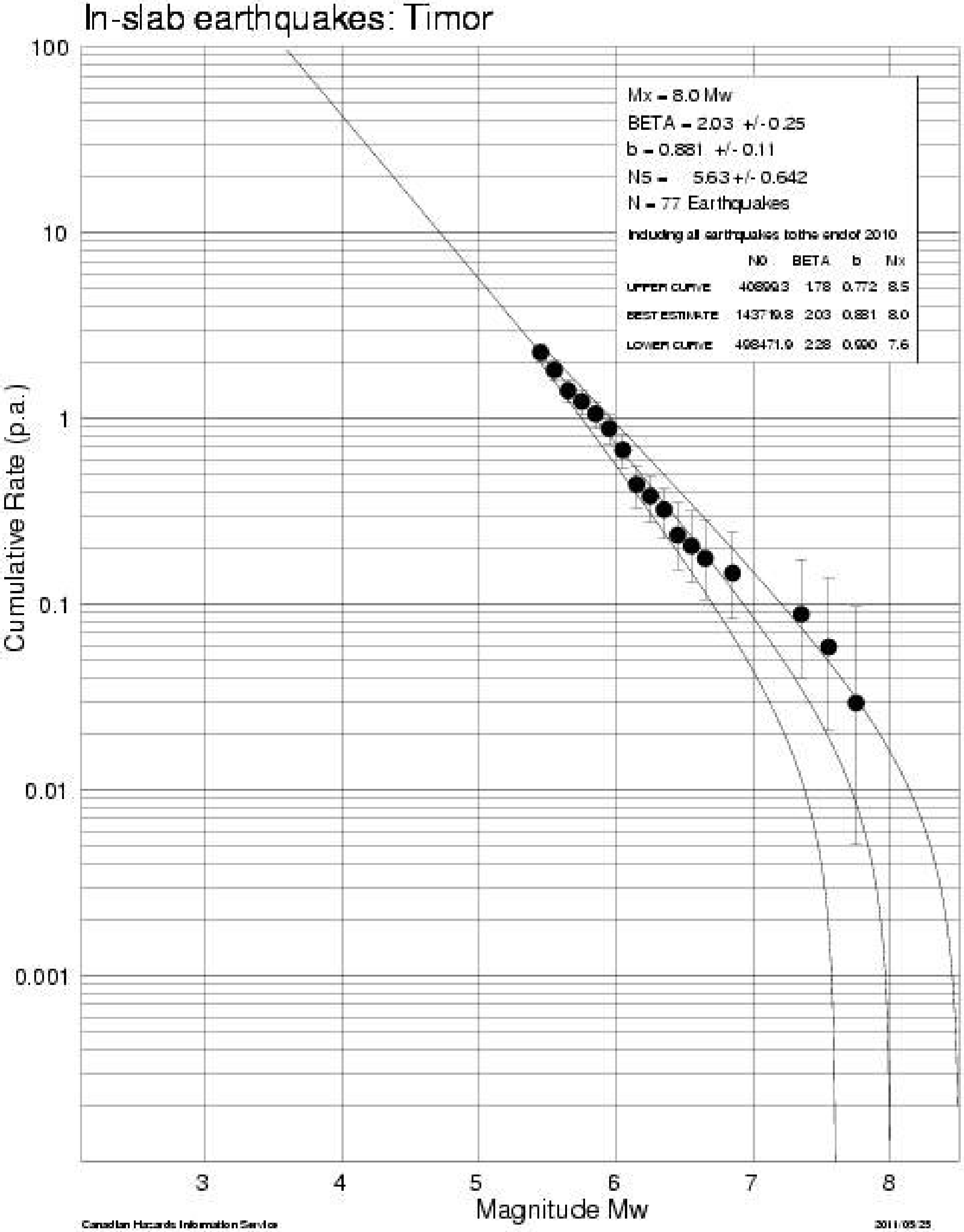

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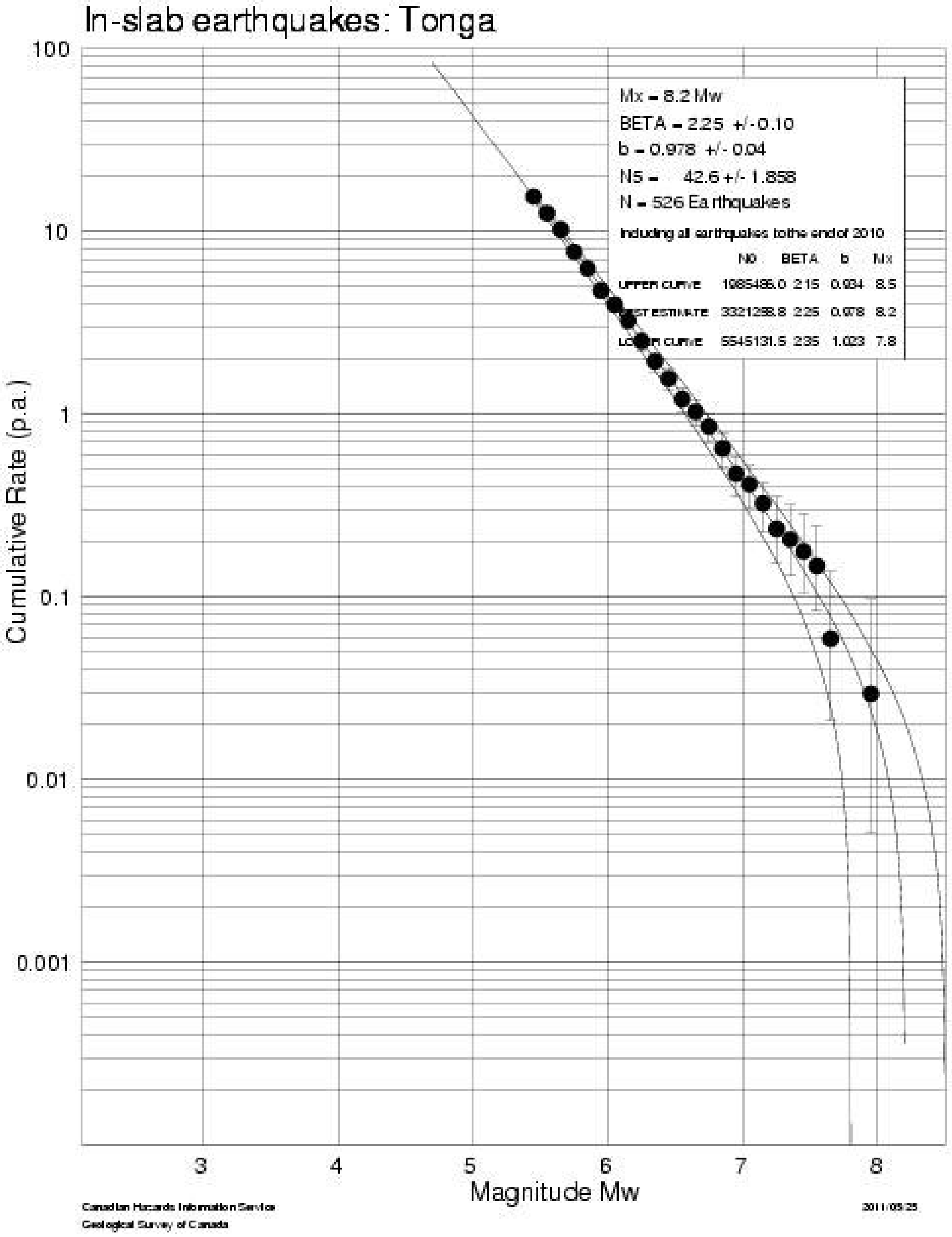
Figure 36



In-slab earthquakes: Tonga
Mx = 8.2 Mw
BETA = 2.25 +/- 0.10
b = 0.978 +/- 0.04
N5 = 42.6 +/- 1.858
N = 526 Earthquakes
Including all earthquakes to the end of 2010
N0 BETA b Mx
UPPER CURVE 1985485.0 2.15 0.934 8.5
BEST ESTIMATE 3321258.8 2.25 0.978 8.2
LOWER CURVE 5545131.5 2.35 1.023 7.8
Cumulative Rate (p.a.)
100
10
1
0.1
0.01
0.001
3
4
5
6
7
8
Magnitude Mw
Canadian Hazards Information Service
Geological Survey of Canada
2011/05/25

Figure 37

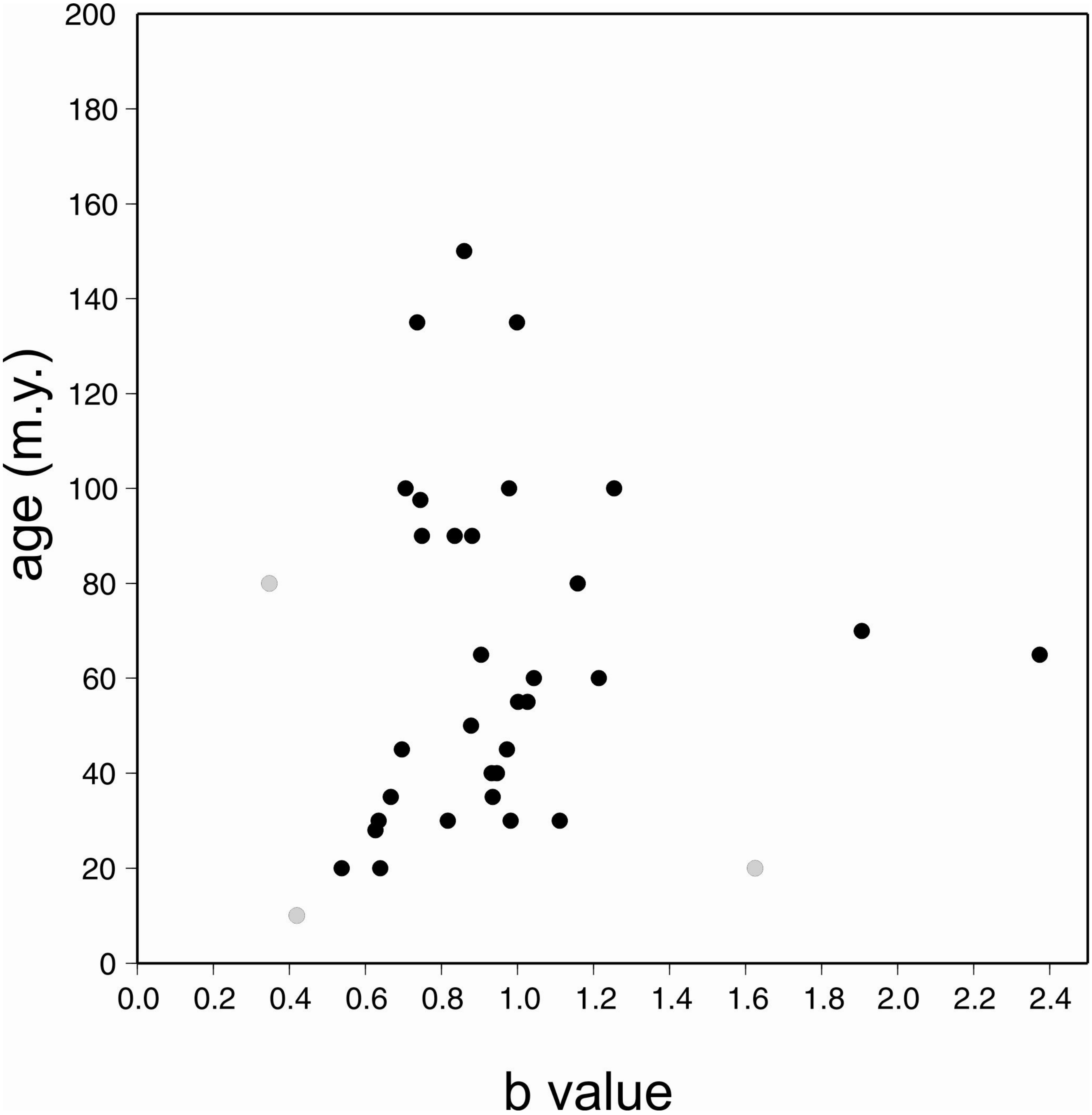


Figure 38: b value vs age of the subducting plate. In this and subsequent figures the gray symbol indicates that the results are based on five or fewer data points.

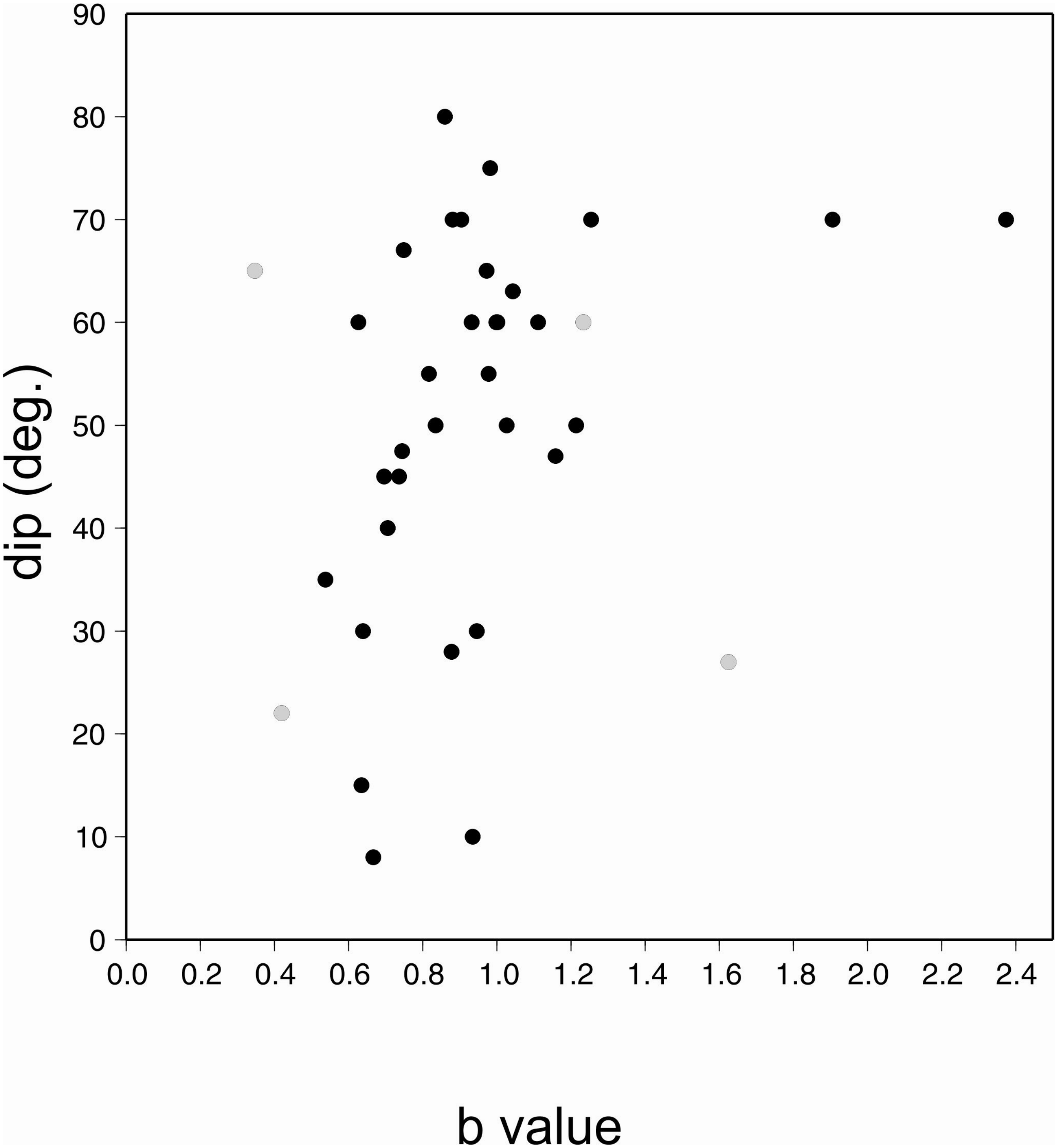


Figure 39. b value vs dip of the subducting slab

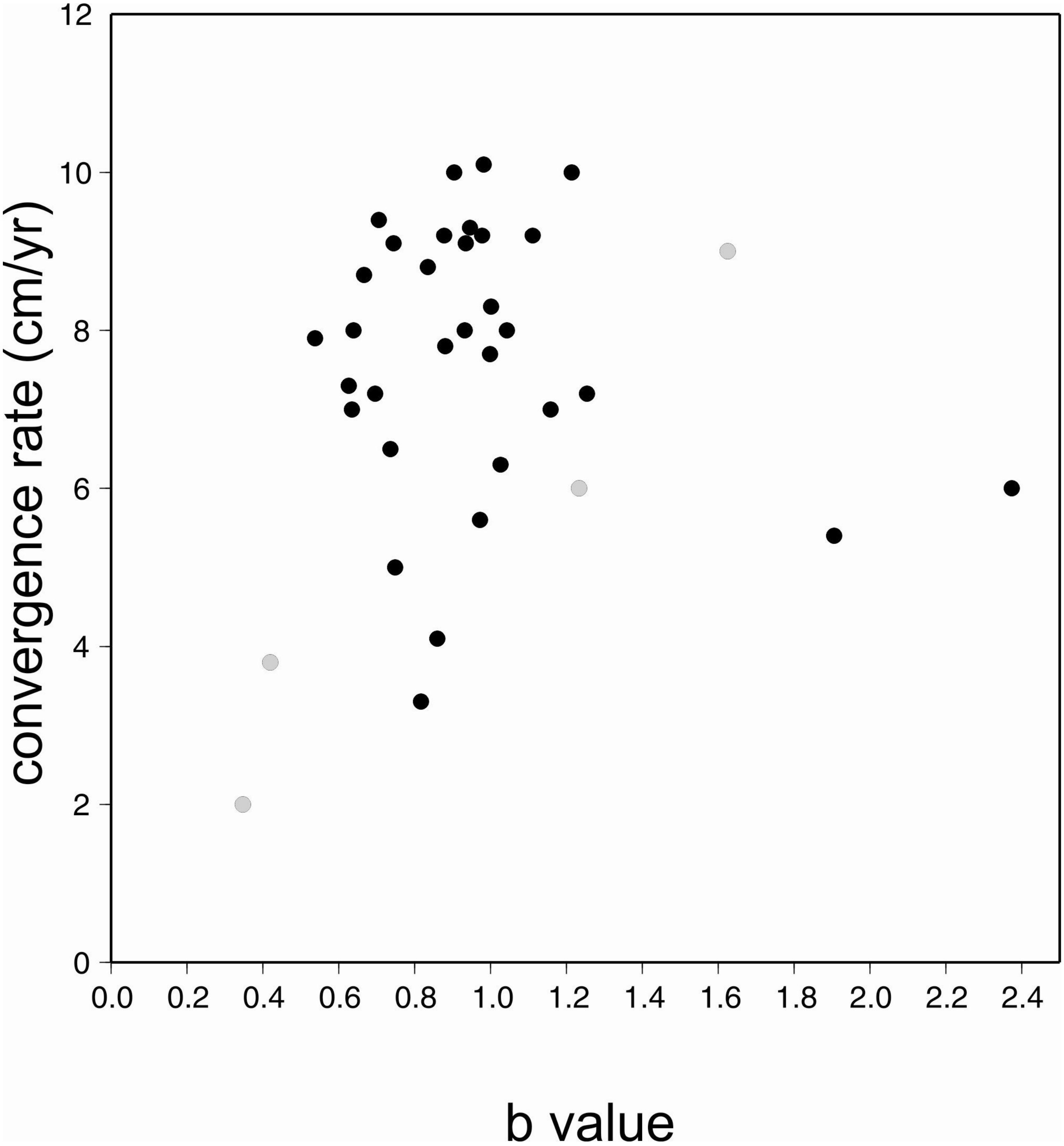


Figure 40. b value vs rate of convergence

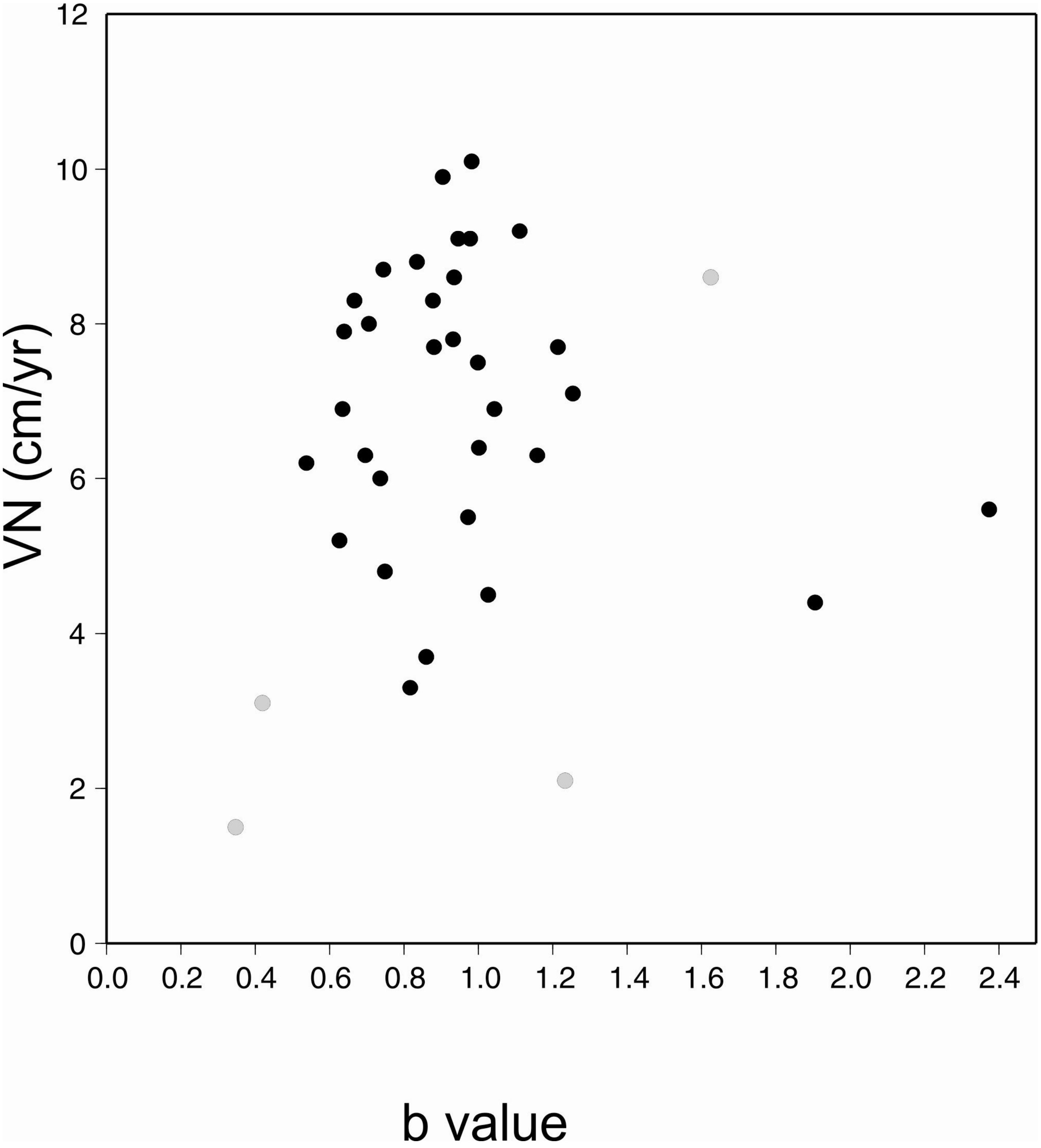


Figure 41. b value vs rate of convergence perpendicular to the trench axis

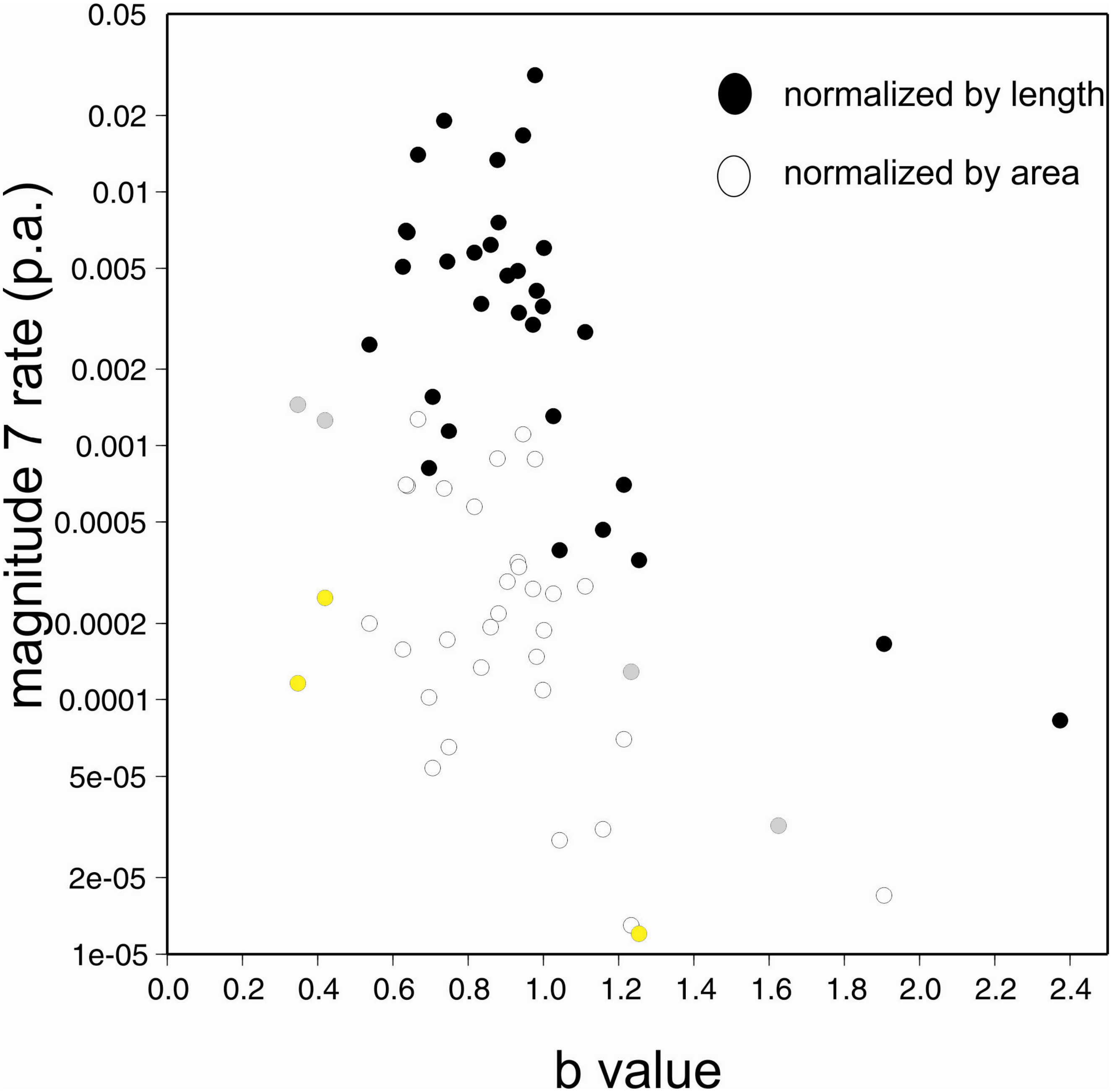


Figure 42. b value vs magnitude 7 recurrence. In this and subsequent figures the black symbols (gray if five or fewer data points) indicate the recurrence rate normalized to a length of 100 km and the white symbols (yellow if five or few data points) indicate the recurrence rate normalized to a 100 km by 20 km fault area. Note that the area normalized rate for southern Chile plots below the minimum y-axis value on these plots.

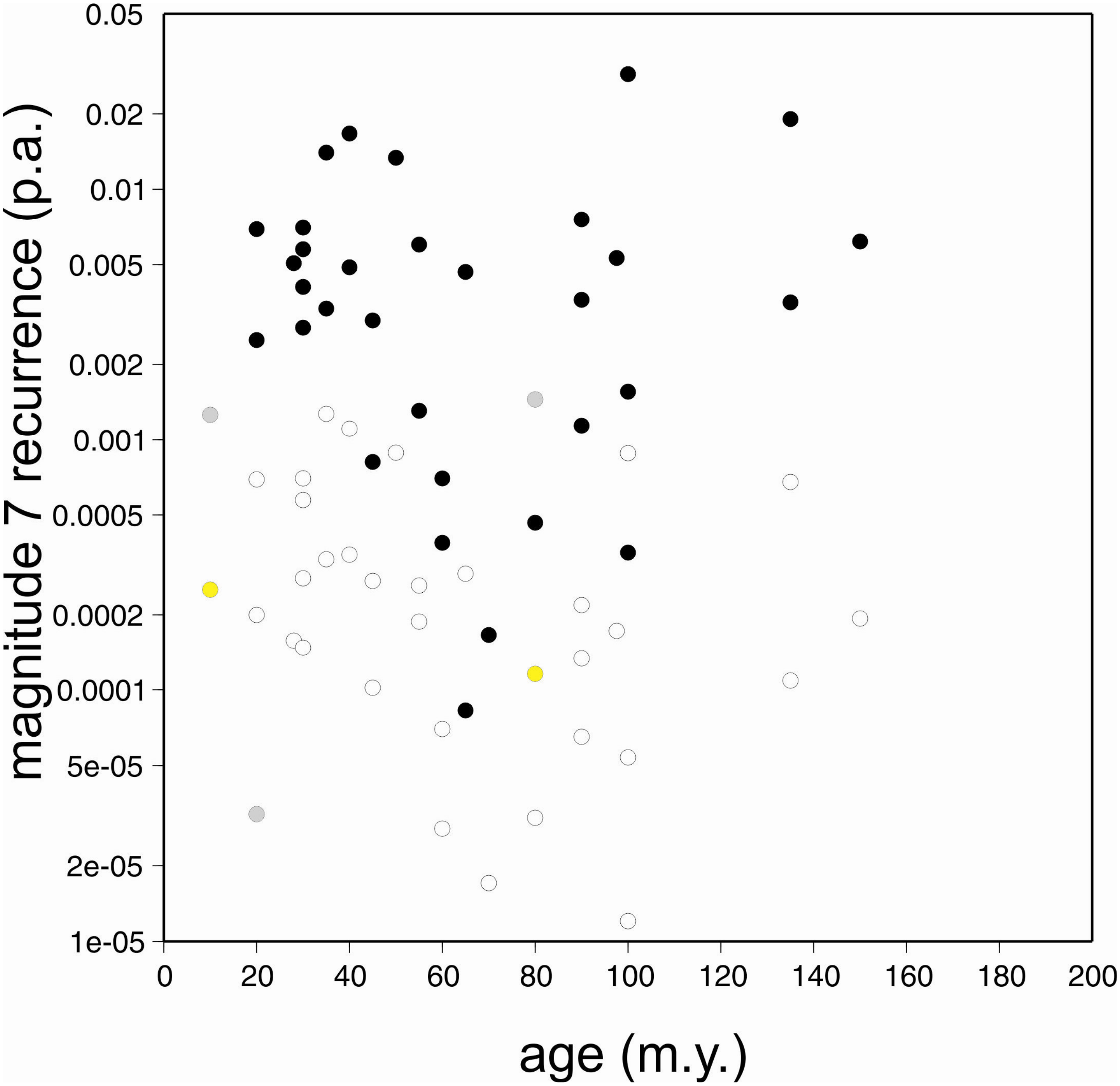


Figure 43. Age of the subducting slab vs the magnitude 7 recurrence rate. Symbols as in Figure 42.

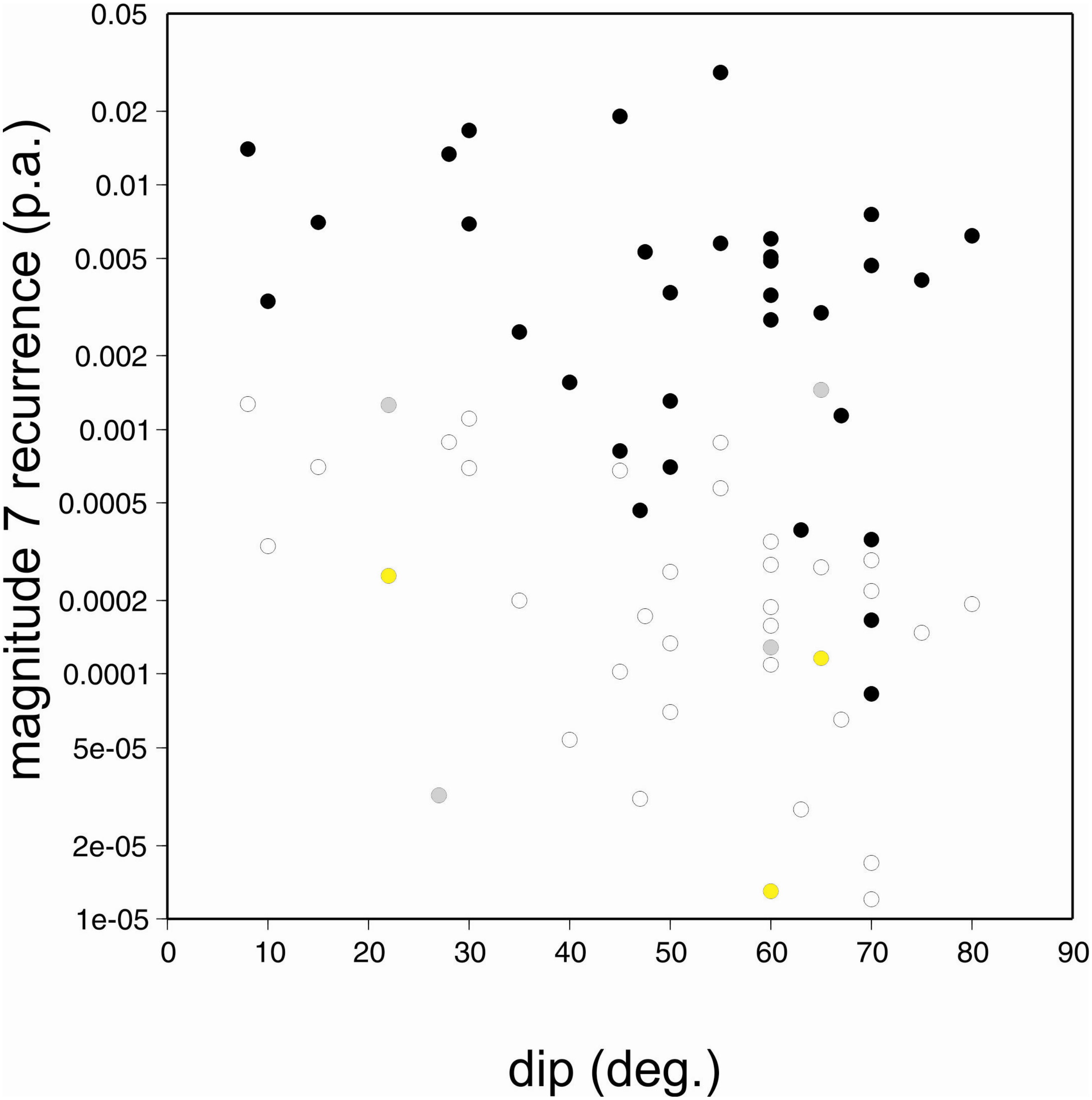


Figure 44. Dip of subducting slab vs magnitude 7 recurrence rate. Symbols as in Figure 42.

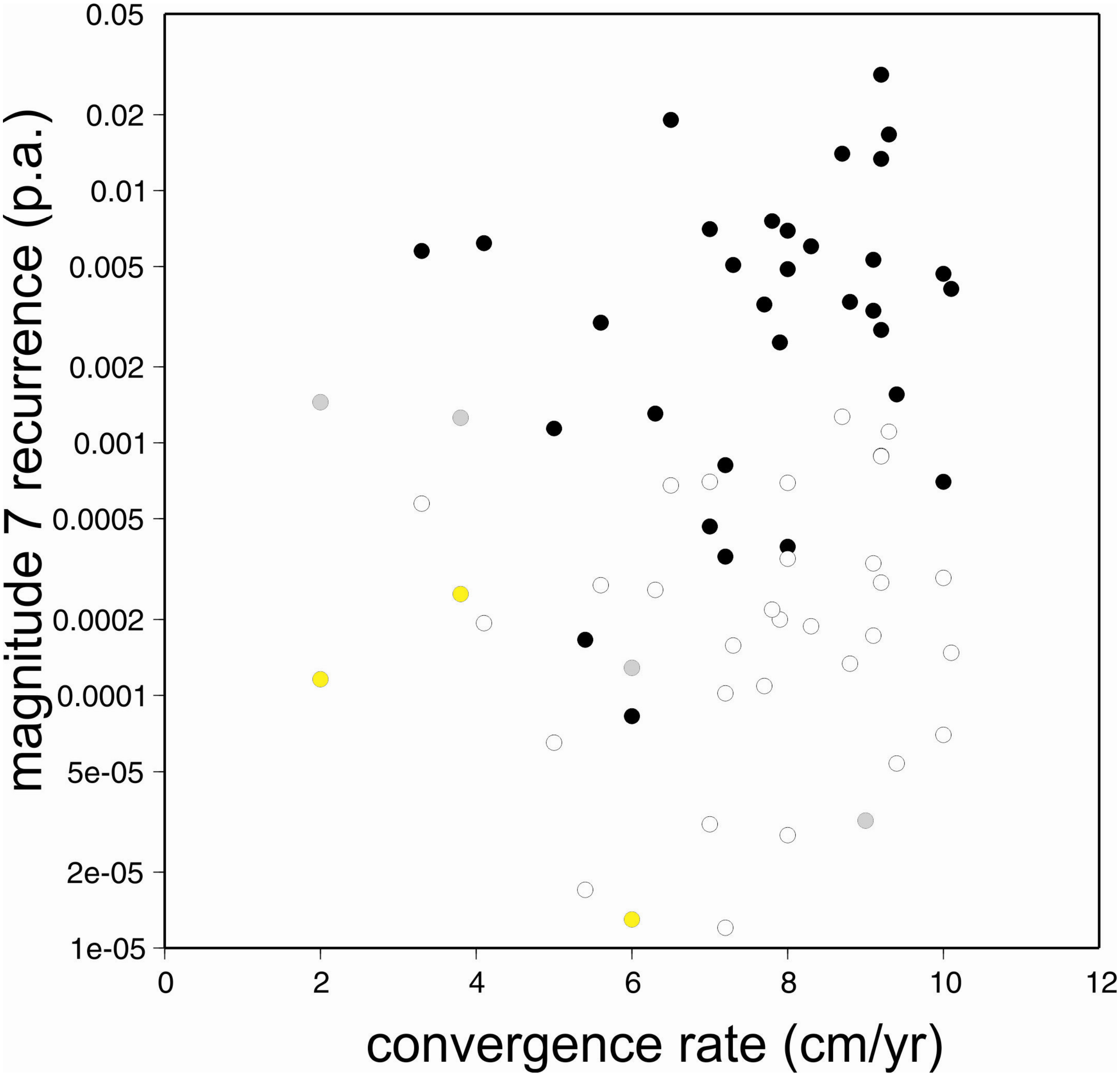


Figure 45. Convergence rate vs magnitude 7 recurrence rate. Symbols as in Figure 42.

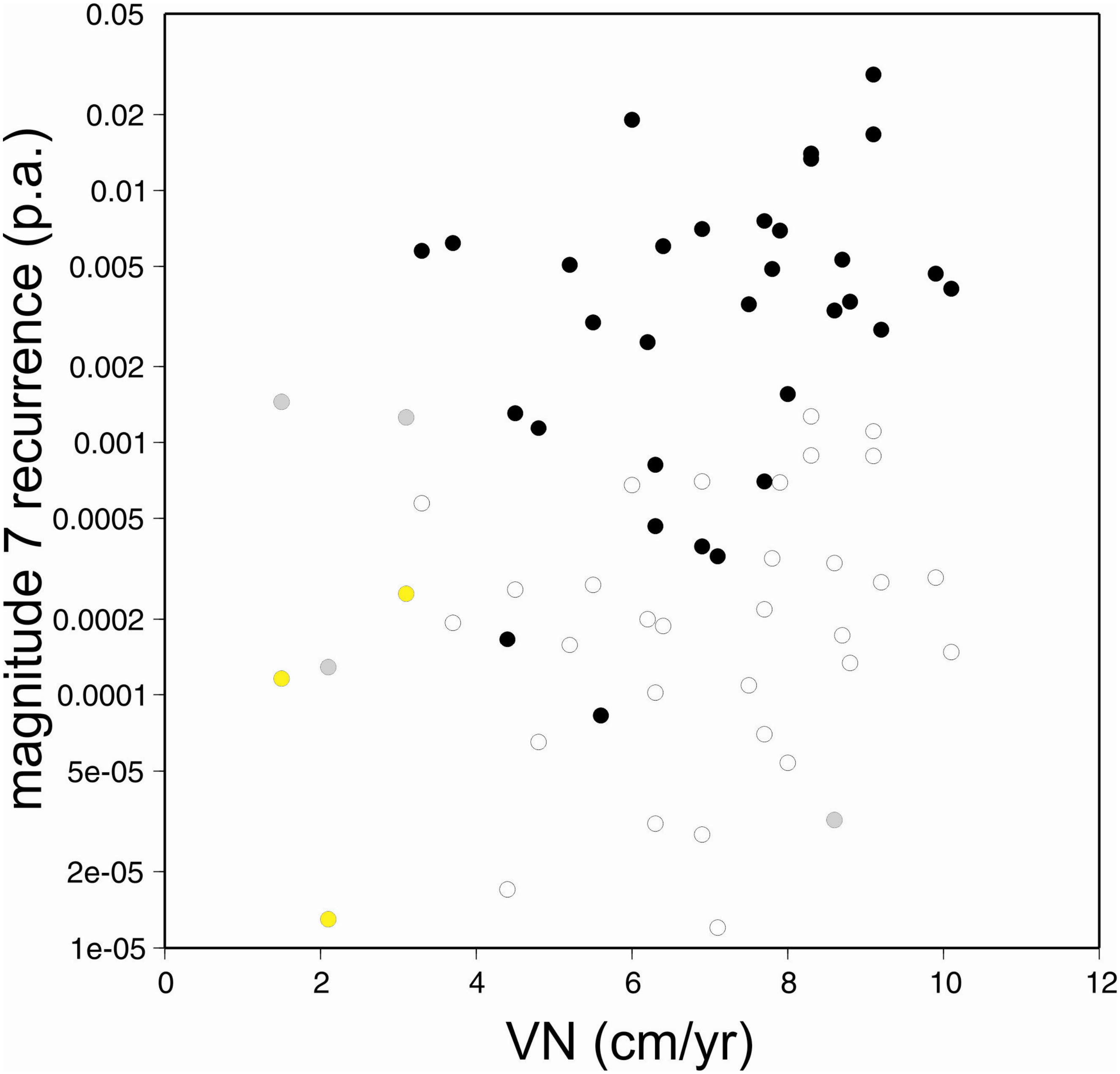


Figure 46. Convergence rate perpendicular to the trench axis vs magnitude 7 recurrence rate. Symbols as in figure 42.