ATTACHMENT 8: SEISMIC NETWORK 2013 ANNUAL SEISMICITY REPORT

SUSITNA-WATANA HYDRO

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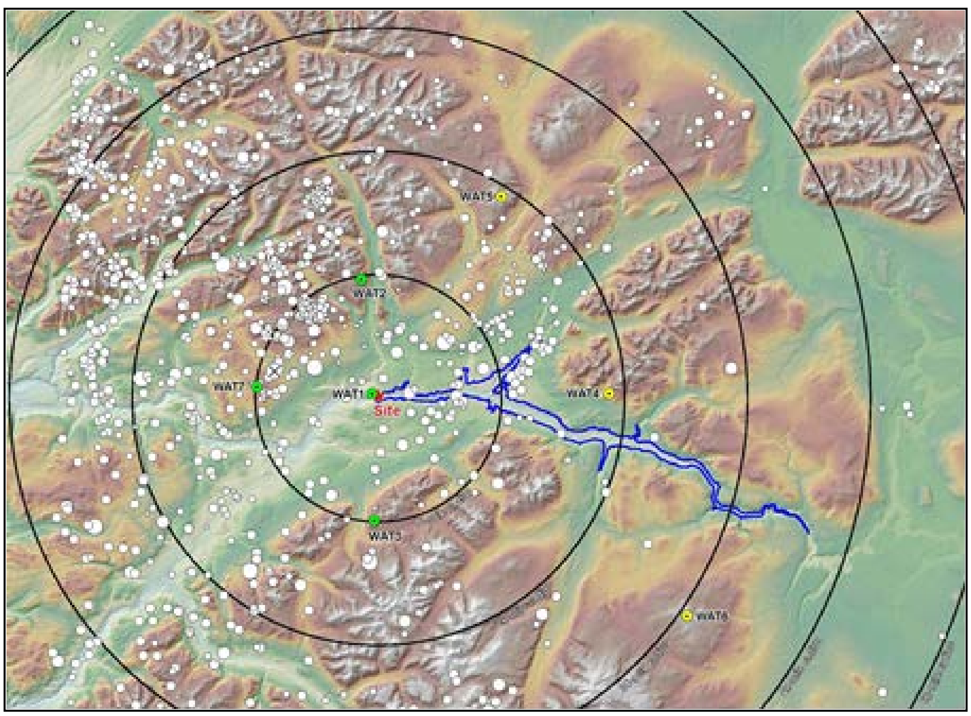
Technical Memorandum
14-06-REP

Susitna-Watana Hydroelectric Project
Seismic Network 2013 Annual Seismicity Report

AEA11-022



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Explanation of Abbreviations

AEA	Alaska Energy Authority
AEC	Alaska Earthquake Center (formerly known as the Alaska Earthquake Information Center; AEIC)
FCL	Fugro Consultants, Inc.
GPS	Global positioning system
km	Kilometer(s)
M	Magnitude
mi	Miles
MWH	MWH Americas, Inc.
RTS	Reservoir-triggered seismicity
SAB	Southern Alaska Block

EXECUTIVE SUMMARY

The proposed Susitna-Watana Dam is a hydroelectric power development project planned for the upper Susitna River under the auspices of the Alaska Energy Authority (AEA). Under subcontract to MWH Americas (MWH), Fugro Consultants, Inc. (FCL) is investigating and evaluating the seismic hazard in support of engineering feasibility and the licensing effort for the Susitna-Watana Hydroelectric Project. As part of the evaluation of seismic hazard in the Susitna-Watana project area, a project-specific long-term earthquake monitoring system (Susitna-Watana Seismic Network) was established in August-September 2012 to monitor seismic activity in the vicinity of the Susitna-Watana project area. This report summarizes the seismic activity that has been recorded by the Susitna-Watana Seismic Network since network initiation on November 16, 2012 through December 31, 2013.

Since initiation of the Susitna-Watana Seismic Network, 1,136 earthquakes have been recorded within the Susitna-Watana Seismic Network project area (defined as 62.3-63.25^{o}N and 146.6-149.35^{o}W for this report, and area of approximately 5,700 mi^2 (14,700 km^2)). Over the time span covered in this report, a daily average of 2.8 events was recorded (1.1 crustal events per day and 1.7 intraslab events per day). The largest event, M_L 4.0, occurred on October 23, 2013 at a depth of 42.0 mi (67.6 km), with an epicenter 8.7 mi (~14 km) west-northwest of the proposed Susitna-Watana dam site. The installation of the Susitna-Watana Seismic Network has increased the station density in the region, leading to greater magnitude and detection capabilities, a decrease in magnitude of completeness, and greater location accuracy. The increase in recorded events has led to a better picture of shallow crustal seismicity and intraslab seismicity associated with the subducting Pacific Plate below the proposed dam site. Focal mechanisms produced by the Alaska Earthquake Center (AEC) in the Susitna-Watana project area indicate that the shallow crust in the area around the proposed dam site is undergoing north-northwest south-southeast compression, consistent with the relative Pacific-North America plate motion, with the maximum horizontal stress rotating progressively in a counterclockwise direction from east to west in the project area. For the intraslab events, focal mechanisms indicate strike-parallel horizontal compression within the downgoing Pacific Plate (in an east-west direction), with maximum horizontal stress also rotating progressively in a counterclockwise direction to the west of the proposed dam site.

Based on recurrence calculations for the period of December 1, 2012 through December 31, 2013 (based on combined crustal and intraslab events), about two M 4 events per year can be expected within the Susitna-Watana project area, a M 5 can be expected about every three years, and a M 6 about every 20 years. This current rate of activity appears somewhat above the long-term rate of larger events based on the relative lack of M 6 events in the historical record for the project area, as well as the surrounding region. Caution is advised in extrapolating the rates of these larger events based on this relatively short period of record.

1. INTRODUCTION

A project-specific long-term earthquake monitoring system (Susitna-Watana Seismic Network) was established in August-September 2012 to monitor seismic activity in the vicinity of the Susitna-Watana project area. Data recorded by the Susitna-Watana Seismic Network is processed by the Alaska Earthquake Center (AEC)[1] who distributes a list of recorded seismic events and prepares quarterly reports on seismicity within the Project area for the Alaska Energy Authority (AEA). Fugro Consultants, Inc. (FCL) analyzes the data and produces a Susitna-Watana Seismic Network Monthly Status Report each month. These reports summarize the number, magnitudes, and depths of the events recorded within the Susitna-Watana Seismic Network project area each month, analyze the daily crustal and intraslab seismicity, and discuss any notable patterns that are apparent in the seismicity recorded that month.

This report summarizes the seismic activity that has been recorded by the Susitna-Watana Seismic Network since network inception on November 16, 2012 through December 31, 2013, within the project area[2] (defined as 62.3-63.25°N and 146.6-149.35°W for this report, an area of approximately 5,700 mi^2 (14,700 km^2)). Analysis and discussion of noted patterns in seismicity are made, along with a calculation of earthquake recurrence. A review of local tectonics in the Susitna-Watana project area is presented, as well as focal mechanisms produced by the AEC (AEIC, 2013b, 2013d; AEC, 2014), with an attempt to explain how the seismicity in the Susitna-Watana project area relates to regional tectonics of the Susitna-Watana project area.

1.1 Overview of the Susitna-Watana Seismic Network

A project-specific earthquake monitoring system (Susitna-Watana Seismic Network) was established in August-September 2012 to monitor seismic activity in the vicinity of the Susitna-Watana project area. The first group of stations consisted of four seismograph stations within 20 mi (~32 km) of the proposed Susitna-Watana dam site, with station spacing on the order of 10 mi (~16 km); one broadband station with a co-located strong motion sensor at the proposed dam site (WAT1), and three broadband stations (WAT2, WAT3, and WAT4). In August 2013, three additional seismograph stations were installed (WAT5, WAT6, and WAT7). The additional seismograph stations extended the network to cover the area within 32 mi (~51 km) of the proposed dam site. In the current network configuration, all seven seismograph stations have three-component broadband seismic sensors and four of the stations have co-located three-component strong motion sensors. In addition, a GPS station has been co-located with the

[1] Formerly referred to as the Alaska Earthquake Information Center of AEIC.

[2] The defined area used by AEC in their reports is 20% larger in areal extent (62.2° - 63.3°N by 147° - 150°W).

seismograph at the proposed dam site (WAT1) (AEC, 2014). Figure 1 shows the current Susitna-Watana Seismic Network configuration within the project area and the overall pattern of seismicity recorded in the Susitna-Watana Seismic Network project area.

Data recorded by the seismic network is processed by the AEC, who monitors seismic activity from ~400 seismograph stations located throughout Alaska and the neighboring regions (AEC, 2014). Data are currently recorded continuously in real time, at a sample rate of 50 Hz. AEC picks arrival times, and calculates locations and magnitudes for all events recorded on four or more stations. First-motion focal mechanisms are computed for events $M_L \geq 3.5$, and regional moment tensors are generated for events $M_L \geq 4$ (AEC, 2014).

Prior to the network installation, the magnitude of completeness in the area was between 1.2 and 1.4 (AEC, 2014). After the first four seismograph stations were installed, the magnitude of completeness decreased to between 1.0 and 1.2. As of December 2013, the magnitude of completeness is estimated at 1.0 (see Figure 2; AEC, 2014). Earthquakes with magnitudes as low as -0.3 have been located. Note: Magnitude of completeness was determined by AEC (2014) for a larger project area defined as 62.3-63.3^{o}N and 147-150^{o}W, and area of approximately 6,700 mi^2 (17,200 km^2).

The addition of the Susitna-Watana Seismic Network has increased the detection capabilities in the project area, decreased the magnitude of completeness, and improved hypocentral location precision. This has provided a clearer picture of seismicity within the Susitna-Watana project area. Figure 3 shows the distribution of seismicity at depth in the Susitna-Watana project area from 2010 through November 15, 2012; before installation of the Susitna-Watana Seismic Network. The location of the Figure 3 cross section is near the cross-section line shown on Figure 4, the basis for the cross sections in Figures 5 and 6 (which contain seismicity in the Susitna-Watana project area after network installation). When comparing Figure 3 to Figure 6, the limits of shallow crustal and intraslab seismicity, and the outline of the downgoing slab are better defined in Figure 6.

2. RECORDED SEISMICITY: NOVEMBER 16, 2012 - DECEMBER 31, 2013

Below is a summary of the events that have been located within the Susitna-Watana Seismic Network project area (defined as 62.3-63.25^{o}N and 146.6-149.35^{o}W for this report, an area of approximately 5,700 mi^2 (14,700 km^2)) from November 16, 2012 through December, 2013.

2.1 Summary of Recorded Events

A total of 1,136 earthquakes[3] were located within the Susitna-Watana Seismic Network project area of Figure 4 from November 16, 2012 through December 13, 2013. 459 events were located in the crust at depths of less than 18.6 mi (30 km), and 677 events were located deeper, within the subducting North American Plate (intraslab seismicity). The crustal events ranged in magnitude from -0.3 to 3.8; the intraslab events from 0.1 to 4.0.

Table 2-1 below summarizes the number of crustal and intraslab events recorded each month since the initiation of the network on November 16, 2012. The month with the greatest amount of recorded events was December 2013 (121 events total) and the month with the least amount of recorded events (58 total) was September 2013. (Note: November 2012 was not considered as the network stations did not go online until mid-November.) For most months, the number of recorded intraslab events was two to three times the number of recorded crustal events; the exception being the months of July and August 2013, when more crustal events were recorded than intraslab events.

[3] AEC reported a total of 1600 earthquakes over the same period, however the number of events are based on a defined area 20% greater than the "project area" defined herein.

Table 2-1. Summary of Susitna-Watana Seismic Network Events by Month

Month	Total # of Events	# of Crustal Events	# of Intraslab Events	Magnitude Range of Crustal Events	Magnitude Range of Intraslab Events
Nov 16 – 30, 2012	47	13	34	0.4 – 2.2	0.7 – 3.3
Dec 2012	98	36	62	0.5 – 1.8	0.6 – 2.9
Jan 2013	75	20	55	0.3 – 1.4	0.6 – 2.3
Feb 2013	62	24	38	0.4 – 2.4	0.7 – 2.0
Mar 2013	90	32	58	0.5 – 3.3	0.4 – 3.8
Apr 2013	81	36	45	0.0 – 1.9	0.4 – 3.4
May 2013	59	13	46	0.4 – 1.9	0.7 – 3.1
June 2013	62	29	33	0.4 – 1.7	0.6 – 2.9
July 2013	93	54	39	0.5 – 3.8	0.5 – 3.3
Aug 2013	85	47	38	0.1 – 2.6	0.6 – 3.1
Sep 2013	58	18	40	0.3 – 1.5	0.5 – 2.5
Oct 2013	101	41	60	0.0 – 1.5	0.1 – 4.0
Nov 2013	104	46	58	-0.1 – 2.8	0.5 – 2.4
Dec 2013	121	50	71	-0.3 – 1.4	0.4 – 2.9

Figure 4 shows a map of seismicity from November 16, 2012 through December 31, 2013. Red symbols signify crustal events (depth < 18.6 mi (30 km)) and blue symbols signify intraslab events (depths ≥ 18.6 mi (30 km)). The reservoir-triggered seismicity (RTS) zone is a defined 18.6 mi (30-km) minimum boundary around the proposed reservoir, in which most of it not all RTS is expected to occur (MWH, 2013). The Susitna-Watana project area defined for this report extends the RTS zone by 6.2 mi (10 km) in each direction, as an additional buffer, and defines the extent of seismicity analyzed for this report.

Figure 5 shows a cross section of the seismicity in Figure 4. Figure 6 shows a cross section of the seismicity in Figure 4, but with a 12.4 mi (20-km) buffer on either side of the cross-section line. The northwest-southeast section line is perpendicular to the strike of the downgoing slab.

2.2 Largest Crustal and Intraslab Events

Table 2-2 summarizes the largest crustal (depth < 18.6 mi (30 km)) and intraslab (depths ≥ 18.6 (30 km)) events that have been recorded in the Susitna-Watana Seismic Network project area since November 16, 2012.

Table 2-2. Largest Crustal and Intraslab Events

Largest Crustal Event											
Year	Month	Day	Hour	Min	Sec	Lat (N)	Lon (W)	Depth	Mag (M_L)	Epicentral Distance to Site	Hypocentral Distance to Site
2013	7	24	18	16	59.506	62.922	148.712	6.9 mi (11.1 km)	3.8	8.8 mi (14.2 km)	11.2 mi (18.0 km)
Largest Intraslab Event											
Year	Month	Day	Hour	Min	Sec	Lat (N)	Lon (W)	Depth	Mag (M_L)	Epicentral Distance to Site (km)	Hypocentral Distance to Site (km)
2013	10	23	7	38	21.625	62.852	148.804	42 mi (67.6 km)	4.0	8.7 mi (14.0 km)	43.0 mi (69.1 km)

2.3 Notable Seismicity Patterns and Events

A number of patterns have been seen in the seismicity recorded in the Susitna-Watana Seismic Network project area since network initiation on November 16, 2012. Below is a summary of some of the more notable and prominent patterns.

1. The spatial pattern of both crustal and intraslab seismicity is variable over the project area, but much more dense in the western half of the project area (see Figure 4). There is a lack of seismicity to the east and southeast of the dam site (see eastern and central part of Figure 4) in both crustal and intraslab seismicity.
2. Crustal seismicity seen in cross section in Figures 5 and 6 appears to have a sharp lower bound at a depth of about 12.4 mi (20 km), which is now better defined than prior to the installation of the Susitna-Watana Seismic Network stations (compare to Figure 3).
3. In crustal seismicity, a cluster of small-magnitude seismicity located at depths of ~ 6-9 mi (~10-15 km) (~16-19 mi (~25-30 km) north-northwest of the dam site) was active in the early part of 2013 (labeled 1A on Figure 7) before turning aseismic in the middle to later part of the year. ~6

mi (~10 km) to the southwest of this cluster, another small cluster of small-magnitude seismicity located at depths of ~6-11 mi (~10-18 km) (~14 mi (~22 km) northwest of the dam site) can be seen (labeled 1B on Figure 7). This cluster was mainly active in July and August 2013 and aseismic for the rest of the year.

4. There is a cluster of persistent small-magnitude seismicity located at shallow depths in the southwest corner of Figure 7 that may indicate a potential seismotectonic feature, but has not been examined in detail.

5. Intraslab seismicity dips about 25^{o} to the northwest, beginning at a depth of about 18.6 mi (30 km) and extending to ~56 mi (~90 km) in the network area. Comparison of Figures 3 and 6 shows the improved resolution of epicenters in the area due to the additional stations in the project area. The truncation of intraslab seismicity ~37 mi (~60 km) southeast of the site is artificial, due to the plot boundaries; it most probably extends further updip and merges with seismicity at the Pacific-North American plate interface as seen in Figure 8. Similar to the crustal seismicity pattern, intraslab seismicity is absent east and southeast of the site. The cluster of activity seen at ~25-31 mi (~40-50 km) depths in Figure 6 can be attributed almost exclusively to seismicity south of latitude 62.5^{o}N.

6. There appears to be a gap in the intraslab seismicity at about 31.1 mi (50 km) depth (more prominent in Figure 6 than Figure 5). Intraslab seismicity in the ~19-31 mi (~30-50 km) depth range occurs about 24.9 mi (40 km) south of the dam site, and is absent east of the site (see Figure 7), particularly within the 12.4 mi (20 km) buffer zone.

7. The 07/24/2013 M_L 3.8 crustal earthquake occurred 8.8 mi (14.2 km) northwest of the dam site at a depth of 6.9 mi (11.1 km) (USGS ShakeMap for event; see Figure 9). This was the largest recorded crustal event within the project area since network initiation. A cluster of small-magnitude seismicity located at depths of ~5-9 mi (~8-15 km), ~9 mi (~ 15 km) northwest of the dam site was recorded in the month of July and for the next few months, appearing to consist of aftershocks from the 07/24/2013 event (labeled 2A on Figure 7). In November 2013, just to the west of the 07/24/2013 event, an additional small cluster of small-magnitude events located at depths of ~6-11 mi (~10-18 km) (~9 mi (~15 km) northwest of the dam site) was observed (labeled 2B on Figure 7). This cluster may be an additional area of aftershocks from the 07/24/2013 M_L 3.8 event.

8. The 10/23/2013 M_L 4.0 intraslab earthquake occurred just northeast of the WAT7 seismograph station (18.7 mi (14.0 km) west-northwest of the dam site) at a depth of 42.0 mi (67.6 km). This was the largest recorded intraslab event within the project area since network initiation. A few small-magnitude, deeper events, occurred in the same area in November 2013, appearing to consist of aftershocks (labeled 3 on Figure 7).

2.4 Daily Rates of Crustal and Intraslab Events

Figure 10 below shows average daily rates for crustal, intraslab, and total seismicity since the Susitna-Watana Seismic Network initiation on November 16, 2012 (i.e., the seismicity shown in Figure 4). The algorithm uses a moving time window scheme, where each daily rate point is the average of a 5-day window centered on the midpoint of the window.

From November 2012 to May 2013, peaks of both crustal and intraslab seismicity appear correlated, with peaks about a month apart, suggesting possible response to lunar tide stresses. After May 2013, however, this pattern breaks down, with intraslab seismicity being relatively constant and crustal seismicity showing greater fluctuations. In September 2013, the peaks of both crustal and intraslab seismicity appear correlated once again. In October 2013, the pattern shows crustal and intraslab rates to be correlated, with roughly equal rates for each. In November 2013, the peaks of both crustal and intraslab seismicity appear correlated for only the first week or so, and then appear anti-correlated. Note that aftershocks of the larger events (~M_L 3 and larger) have not been removed.

3. SEISMOTECTONIC INTERPRETATION

3.1 Seismotectonic Setting

The Susitna-Watana project area is located in south-central Alaska (Figure 11), which experiences tectonic deformation from the movement of the Pacific Plate northwest as it converges with the North American Plate. Southeast of the Susitna-Watana project area, convergent movement occurs as the Pacific Plate is subducted under the North American Plate almost perpendicular to the strike of the Alaska-Aleutian megathrust, while right-lateral transform faulting occurs along the Queen Charlotte and Fairweather fault zones to the southeast (outside figure boundary of Figure 11). Closer to the Susitna-Watana project area, transpressional deformation is occurring on the right-lateral Denali fault to the north and the Castle Mountain fault to the south (FCL, 2012).

The Susitna-Watana proposed dam site is located within the Talkeetna block, which encompasses the north-central portion of the Southern Alaska Block (SAB) of Haeussler (2008) (Figure 11). The Talkeetna block is bounded by the Denali fault system to the north, the Wrangell Mountains to the east, the Castle Mountain fault to the south, and the Tordrillo Mountains volcanic ranges to the west (Figure 11). Strain release occurs on the northern and southern block boundaries of this crustal block (i.e., Quaternary Denali and Castle Mountain faults), but strain mechanisms are less well defined to the east and west (FCL, 2012). There is a lack of mapped faults within the Talkeetna block that have Quaternary displacement (FCL, 2012; Koehler, 2013). There is also a relative absence of large historic earthquakes within the Talkeetna block, although large events have occurred along the northern boundary on the Denali fault (M 7.9) and to the south on the Alaska-Aleutian plate interface megathrust (M 9.2) (FCL, 2012).

Earthquakes within the region generally occur within the subducting slab (intraslab events; depths $\geq$ 18.6 mi (30 km)),the crust (depths $<$ 18.6 mi (30 km)), and along the interface of the Pacific and North American plates at depths of ~19-25 mi (~30-40 km), ~31 mi (~50 km) southeast of the proposed dam site (see Figure 8(B)). Within the Susitna-Watana project area, there has been a fairly high rate of low magnitude seismicity (crustal and intraslab events), as evidenced by Figure 4.

3.2 Relation to Regional Seismicity

Figure 8 shows AEC seismicity from July 1988 to July 1998 in the region and in the Susitna-Watana project area (Ratchkovski and Hansen, 2002). The subducting slab is outlined by the seismicity that increases with depth from east to west. Note in Figure 8(A) that the seismicity appears to outline the edge of the slab and that the slab appears to change strike from the southwest to the northeast of the figure. Ratchkovski and Hansen (2002) note that the slab strike undergoes a 20^{o} counterclockwise turn (from north to south) at about 59° N latitude and a 35° clockwise change around 63° N latitude. These changes in strike of the subducting slab have led to the proposal that the subducting slab is segmented with different 'blocks' having unique strikes and dips. Ratchkovski and Hansen (2002) identify these in Figure 8(A) as the McKinley, Kenai, and Kodiak, from north to south. These changes in strike and dip direction may indicate areas where there may be a tear or warp in the slab (Ratchkovski and Hansen, 2002; Fuis et al., 2008). Figure 8(B) shows a cross section near the Susitna-Watana proposed dam site, showing the subducting slab below the site, with intraslab events occurring at ~19 mi (~30 km) to ~93 mi (~150 km) in depth. This is consistent with the intraslab seismicity seen in Figures 5 and 6.

3.3 AEC Focal Mechanisms and Regional Stresses

The AEC quarterly reports summarize the seismicity within the Susitna-Watana project area (AEIC, 2013a, 2013b, 2013c, 2013d; AEC, 2014). Figure 12 shows focal mechanisms produced by the AEC for events within the Susitna-Watana project area for the time span covered in this report. Table 3-1 summarizes each event and Table 3-2 summarizes the focal mechanism parameters for each event. (Note: some of these events are outside the RTS zone and therefore were not included within the boundaries of Figure 4.)

For the crustal events (depths < 18.6 mi (30 km); red compressional quadrants in Figure 12), there is one oblique normal event (8/13/13), one strike-slip event (3/25/13), and four reverse events (7/24/13, 9/29/13, 11/6/13, and 11/8/13) shown in Figure 12. Three of the reverse events (7/24/13; M_L 3.8, 11/6/13, and 11/8/13) are located ~9-11 mi (~14-18 km) northwest of the proposed dam site and the strike-slip event (3/25/13) is located ~21 km south of the proposed dam site. All four events have p-axes oriented from ~310-330° (see Table 3-2) consistent with what was found by Ruppert (see Figure 3A in Ruppert, 2008). The remaining reverse event (9/29/13) is located ~34 mi (~54 km) southwest of the proposed dam site and has a p-axis azimuth of 284°, consistent with what was found by Ruppert (2008) (see Figure 3A in Ruppert, 2008); showing a slight counterclockwise rotation of the maximum horizontal stress in the area from northwest to west. The oblique normal event (8/13/13) is located ~32 mi (~52 km) northwest of the proposed dam site and has a t-axis azimuth of 39°. The direction of minimum horizontal stress is consistent with what was found by Ruppert (2008) (see Figure 3B in Ruppert, 2008), but the normal faulting is an anomaly within the overall compressive stress regime in the area. However, the P-axis is consistent with the other crustal events.

For the deeper, intraslab events (depths ≥ 18.6 mi (30 km); yellow compressional quadrants in Figure 12), there are two strike-slip events (1/21/13 and 10/23/13) and one oblique reverse event (3/2/13) shown in Figure 12. One strike-slip event (10/23/13; M_L 4.0) and the oblique reverse event (3/2/13) are located ~9 mi (~14 km) west and ~17 mi (~28 km) south-southwest, respectively, of the proposed dam site. Both have p-axes oriented ~east-west (see Table 3-2), indicating that the maximum horizontal stress is in the east-west direction. This is consistent with what was found by Ruppert (2008) (see Figure

1A in Ruppert, 2008). The other strike-slip event (1/21/13) is located ~33 mi (~53 km) southwest of the proposed dam site and has a p-axis azimuth of 243^{o}. This is also consistent with Ruppert (2008) (see Figure 1A in Ruppert, 2008); showing a counterclockwise rotation of the maximum horizontal stress in the area, from east to west. Overall, the intraslab events are indicating horizontal, strike-parallel compression within the slab.

Table 3-1. Focal Mechanisms Produced by the AEC for the Susitna-Watana Project Area

Event Date	Lat (N)	Lon (W)	Magnitude (M_L)	Depth	Epicentral Distance to Site	Mechanism
Crustal Events						
3/25/13	62.6323	-148.5455	3.3	4.4 mi (7.1 km)	13.2 mi (21.2 km)	strike-slip
7/24/13	62.9221	-148.7133	3.8	6.9 mi (11.1 km)	8.8 mi (14.2 km)	reverse
8/13/13	63.1410	-149.2942	2.6	10.5 mi (16.9 km)	32.4 mi (52.1 km)	oblique normal
9/29/13	62.6319	-149.5092	2.7	9.9 mi (15.9 km)	33.6 mi (53.9 km)	oblique reverse
11/6/13	62.9016	-148.8529	2.8	8.4 mi (13.6 km)	11.4 mi (18.3 km)	reverse
11/8/13	62.9080	-148.7863	2.5	8.8 mi (14.2 km)	9.8 mi (15.8 km)	oblique reverse
Intraslab Events						
1/21/13	62.6856	-149.5287	4.0	41.3 mi (66.4 km)	32.8 mi (52.8 km)	strike-slip
3/2/13	62.6181	-148.8506	3.8	36.7 mi (59.1 km)	17.3 mi (27.9 km)	oblique reverse
10/23/13	62.8522	-148.8045	4.0	42.0 mi (67.6 km)	8.7 mi (14.0 km)	strike-slip

Reference: AEIC, 2013b, 2013d; AEC, 2014

Table 3-2. Focal Mechanism Parameters

Event Date	Strike 1 (deg)	Dip1 (deg)	Rake1 (deg)	Strike 2 (deg)	Dip2 (deg)	Rake2 (deg)	T-axis (azimuth) (deg)	T-axis (plunge) (deg)	P-axis (azimuth) (deg)	P-axis (plunge) (deg)
Crustal Events										
3/25/13	275	71	171	8	81	19	233	20	140	7
7/24/13	75	41	143	195	67	55	61	54	309	15
8/13/13	348	70	-27	88	65	-158	39	3	307	33
9/29/13	64	40	166	165	81	51	39	41	284	26
11/6/13	69	40	104	231	51	79	92	79	329	6
11/8/13	235	41	99	43	50	82	265	83	139	4
Intraslab Events										
1/21/13	110	81	14	18	76	171	334	16	243	3
3/2/13	118	59	40	5	57	142	332	49	241	1
10/23/13	222	67	-173	129	84	-23	178	11	83	21

Reference: Natalia Ruppert, personal communication, February 18, 2014
Strike = azimuth of the horizontal line in a dipping plane or the intersection between a given plane and the horizontal surface
Dip = the slope of a surface; the angle of a plane with the horizontal measured in an imaginary vertical plane that is perpendicular to the strike
Rake = angle between a linear element that lies in a given plane and the strike of that plane
T-axis = tension axis; minimum compressive stress direction
P-axis = pressure axis; maximum compressive stress direction
Plunge = angle of linear element with earth's surface in an imaginary vertical plane

4. EARTHQUAKE RECURRENCE

4.1 Recurrence Calculations

Recurrence calculations were performed for the period of Susitna-Watana Seismic Network operation from December 1, 2012, through December 31, 2013. Calculations were done for the total seismicity shown in Figure 4 (for events within the Susitna-Watana Seismic Network project area; defined as 62.3-63.25°N and 146.6-149.35°W for this report, an area of approximately 5,700 mi^2 (14,700 km^2)), and separately for crustal (depth < 18.6 mi (30 km)) and intraslab (depth ≥ 18.6 mi (30 km)) seismicity within the project area.

The data set was not declustered. Declustering of magnitudes less than 3 (which comprise most of the data set) is problematical, as the standard declustering techniques rely on assumptions and observations relevant to larger magnitudes only. In any case, aftershocks and swarm events appear to comprise a very small percentage of the total number of events, and the magnitude cutoff of 1.5 is likely to eliminate most of such events from the data set. The recurrence calculations presented here thus show recurrence rates of all earthquakes.

Three data sets were considered: total seismicity, and crustal and intraslab seismicity independently. The seismicity was grouped into 0.5 magnitude unit bins, and the maximum likelihood technique of Weichert (1980) was employed. Table 4-1 shows the number of events in each bin, for the three data sets. Preliminary calculations using minimum magnitudes (Mmin) of 1.0 and 1.5 showed that Mmin of 1.5 gave more stable results, and better consistency with rates of magnitude 3.0 and above.

Table 4-1. Event Counts by Source and Magnitude Range

Magnitude Range	Crustal	Intraslab	Project Area Total
1.50 - 2.00	54	47	101
2.00 - 2.50	15	26	41
2.50 - 3.00	6	14	20
3.00 - 3.50	5	3	8
3.50 - 4.00	2	0	2
4.00 - 4.50	0	1	1

Figure 13 shows the maximum likelihood incremental fit to the observations for the three sources. Though the fits to the observations are not perfect, the observations all lie within the 95% confidence model bounds.

The computed recurrence parameters are shown in Table 4-2. The parameters Acum and b are equivalent to *a* and *b* in the Gutenberg-Richter relation:

$$Log(N) = a - b(M) \quad (1)$$

Where *N* is the cumulative number of events greater than or equal to *M*. Na is the annual rate of events greater than or equal to Mmin, 1.5 in this case. Acum(norm) is the Acum value normalized to square km/year, based on a Susitna-Watana Seismic Network project area (Figure 4) of approximately 5,700 mi^2 (14,700 km^2).

Table 4-2. Recurrence Parameters

Parameter	Crustal	Intraslab	Project Area Total
b	0.801	0.709	0.758
Na	75.6	83.9	158.5
Acum	3.085	2.990	3.339
Acum(norm)	-1.08	-1.176	-0.827

Using the parameters in Table 4-2, cumulative rates for various magnitude ranges can be computed, using the Cornell and van Marke (1969) relation:

$$N(m) = Na\beta \exp(-\beta(m - m^0))/(1 - \exp(-\beta(m^u - m^0)) \quad (2)$$

Where $N(m)$ is the annual number of events greater than or equal to m, m^0 is minimum magnitude, m^u is maximum magnitude, Na is the number of events greater than or equal to m^0, and β is b x ln(10).

Table 4-3 shows the expected rates and return periods of 3 through 6 based on these calculations. The table indicates that about two M 4 events per year can be expected within the Susitna-Watana project area (shown in Figure 4; defined as approximately 5,700 mi^2 (14,700 km^2)), a M 5 can be expected about every three years, and a M 6 about every 20 years, assuming magnitude 5 and greater events obey equation (1). Note that these rates are based on only 13 months of data, and are subject to future updates based on a longer data record.

Note that given the expected rate of M $\geq$ 6 events, within the past 100 years five such events would be expected to exist in the historic record in the Susitna-Watana project area of Figure 4, and none have occurred. In a larger region encompassing the Susitna-Watana project area (FCL, 2012; Figure 23), four M 6 events have been seen in an area about twice as large as the project area of Figure 4. Therefore, scaling by area, about 10 M 6 events would be expected in the larger region of Figure 23 in FCL (2012), whereas only four have occurred. The recurrence statistics computed here thus appear to overestimate the rate of M $\geq$ 6 events in the larger region surrounding the project area by about a factor of 2. Therefore it is inadvisable to extrapolate recurrence rates beyond magnitudes observed in the relatively short 13 month time period of this analysis.

Table 4-3. Annual Rates and Return Periods for the Susitna-Watana Seismic Network Project Area

Magnitude	**Crustal**		**Intraslab**		**Project Area (Total)**	
	Annual Rate	Return Period	Annual Rate	Return Period	Annual Rate	Return Period
>= 3	4.7520	0.2	7.2428	0.1	11.5610	0.1
>= 4	0.7500	1.3	1.4103	0.7	2.0131	0.5
>= 5	0.1172	8.5	0.2704	3.7	0.3462	2.9
>= 6	0.0171	58.5	0.0476	21.0	0.0552	18.1

Note: Rates based on data from December 1, 2012 through December 31, 2013 with the Susitna-Watana Seismic Network project area of approximately 5,700 mi^2 (14,700 km^2)

Seismicity plots at many scales, e.g. Figure 1, Figure 4, and plots in FCL (2012), show a marked decrease in the apparent activity rates southeast of the proposed Susitna-Watana dam site. The reason for this is unclear, but may be due to a tear, detachment, or other discontinuity in the Pacific Plate, as described in Section 3.2 above. In detail, patterns between intraslab and crustal seismicity differ somewhat. For seismic source models, these differences correspond to the eastern margin of the intraslab source and to alternative source zones with different rates of crustal earthquake recurrence (e.g., SAB Central and SAB East in FCL, 2012).

5. CONCLUSIONS

With the installation of the Susitna-Watana Seismic Network, the seismic station density in the region has increased. This has led to greater magnitude detection capabilities, a decrease in magnitude of completeness, and greater location accuracy. The Susitna-Watana Seismic Network has recorded a high number of low magnitude events since its initiation on November 16, 2012: an average of 2.8 events have been recorded per day (1.1 crustal events per day and 1.7 intraslab events per day). The increase in number and location quality of local earthquakes has led to a better picture of shallow crustal seismicity and of seismicity associated with the subducting Pacific Plate below the proposed dam site (Figures 5 and 6).

Focal mechanisms produced by the AEC in the Susitna-Watana project area indicate that the crust around the proposed dam site is undergoing north-northwest south-southeast compression, consistent with the relative Pacific – North America plate motion, with the maximum horizontal stress rotating in a counterclockwise direction from east to west in the network area. This appears to be consistent with what is known about the seismotectonic regime in the project area (Haeussler et al., 2008) and with other studies in the area (Ratchkovski and Hansen, 2002; Fuis et al., 2008; and Ruppert, 2008). Stresses within the downgoing Pacific Plate appear to be characterized by strike-parallel horizontal compression. Future seismic data from the Susitna-Watana Seismic Network should help to provide an even clearer picture of the seismotectonic environment in Susitna-Watana project area.

Based on recurrence calculations for the period of December 1, 2012 through December 31, 2013, about two M 4 events per year can be expected within the Susitna-Watana project area (shown in Figure 4; defined as approximately 5,700 mi^2 (14,700 km^2)), a M 5 can be expected about every three years, and a M 6 about every 20 years. The extrapolated rates for the larger events are somewhat higher than those indicated by longer-term historical and prior network data (e.g., FCL, 2012). However, the current recurrence calculations are based on a limited amount of data and maximum event of ~M 4, since the Susitna-Watana Seismic Network has only been active for a short period of time. It also is important to note that because of the short amount of time in which data has been recorded, these rates should not be extrapolated for larger events.

6. REFERENCES

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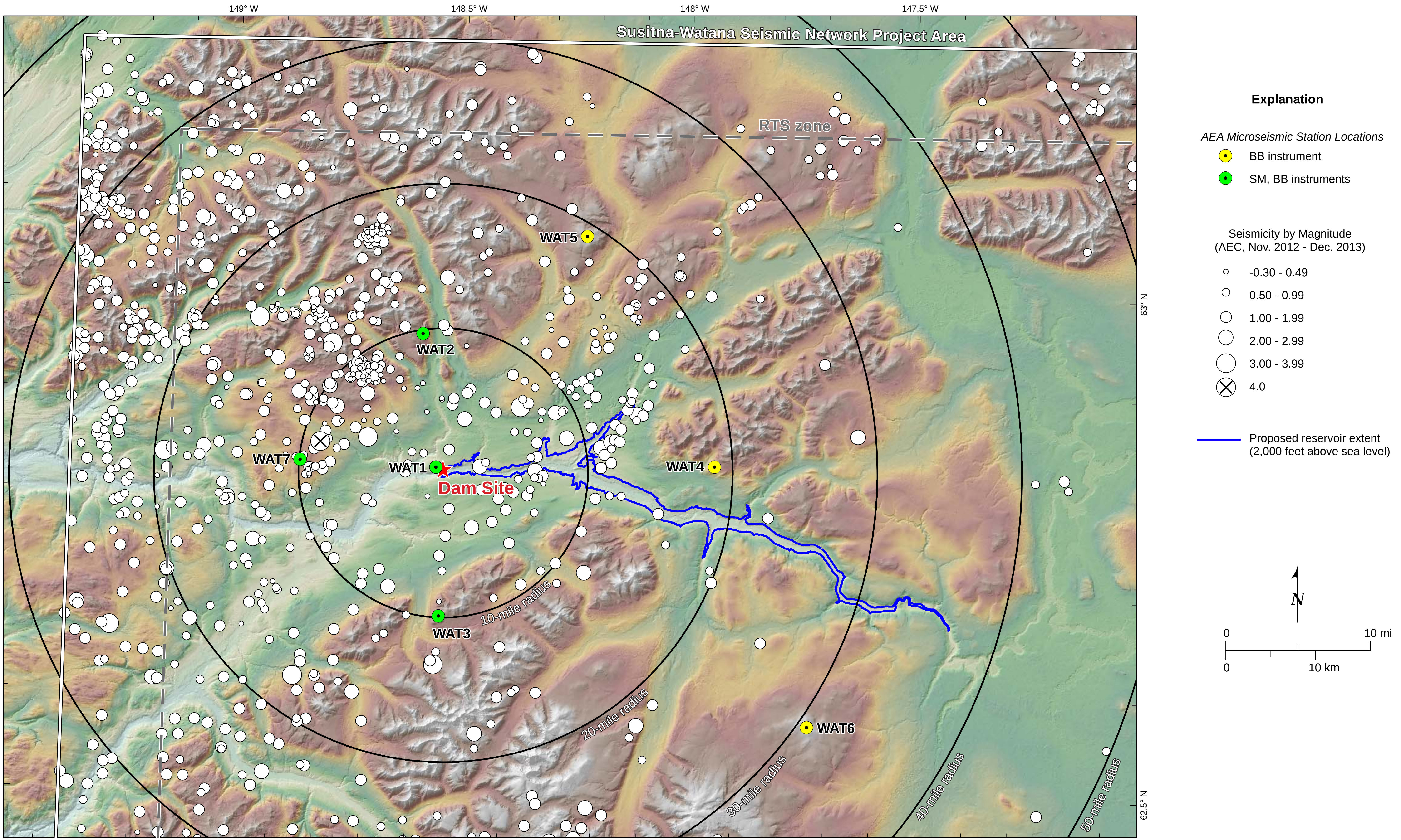
Figures



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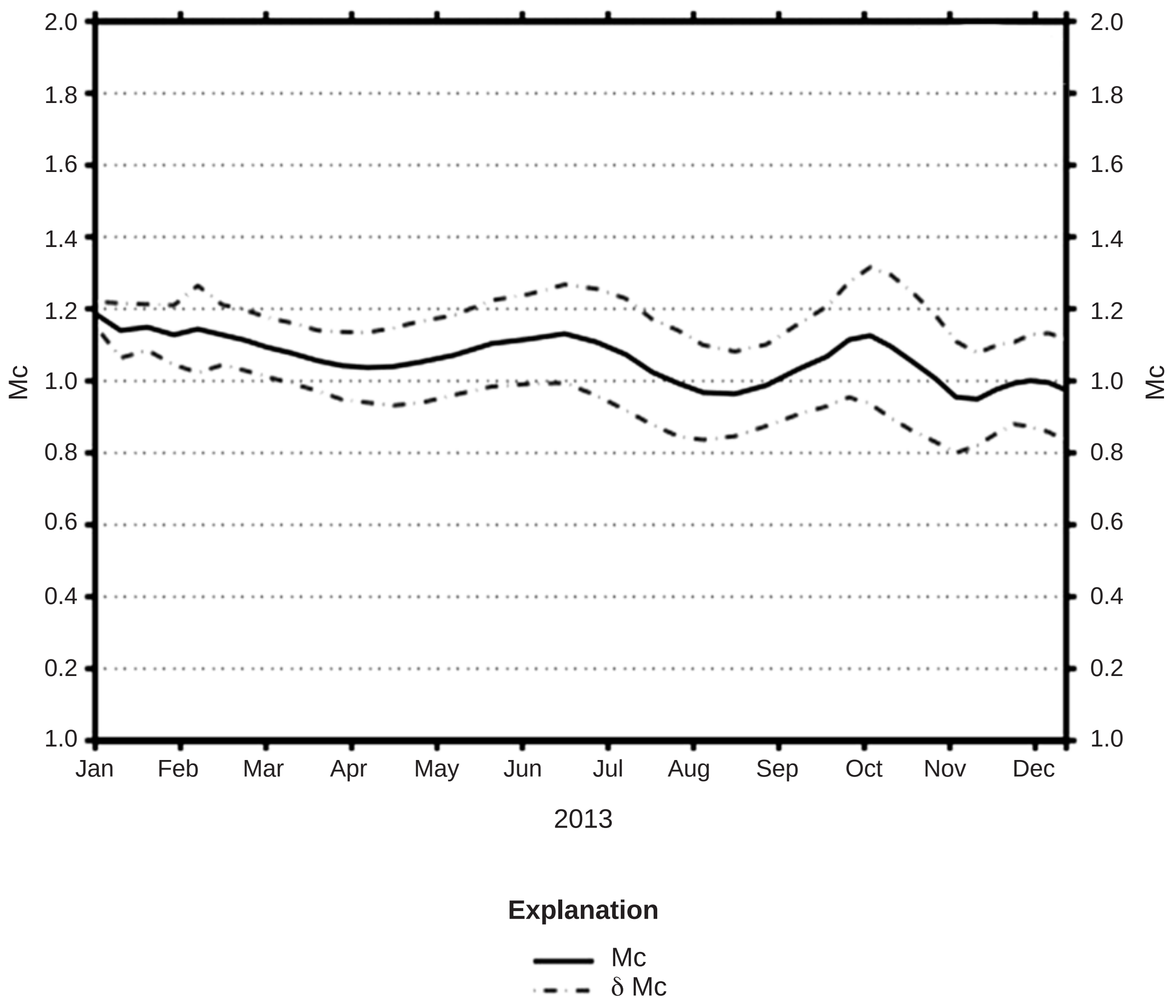
STATE OF ALASKA
ALASKA ENERGY AUTHORITY

SUSITNA-WATANA HYDROELECTRIC PROJECT
SUSITNA-WATANA SEISMIC NETWORK
LOCATION PLAN AND NOVEMBER 16, 2012
THROUGH DECEMBER 31, 2013 SEISMIC EVENTS

FIGURE
1



Reference: Figure 4 from AEC, 2014

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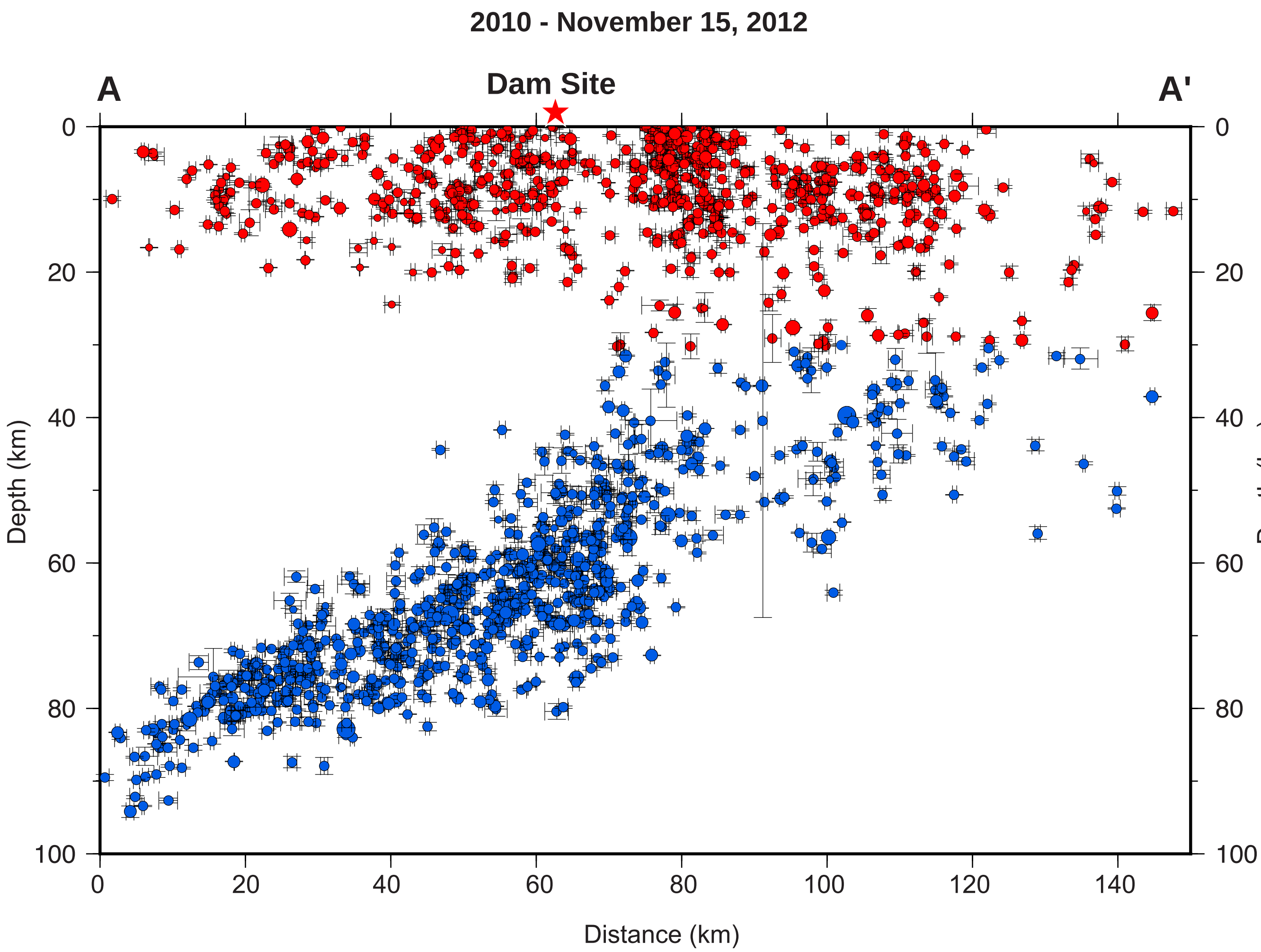
SUSITNA-WATANA HYDROELECTRIC PROJECT

TIME-MAGNITUDE OF COMPLETENESS PLOT OF EARTHQUAKES LOCATED BETWEEN JANUARY 1, 2013 AND DECEMBER 31, 2013 IN THE SUSITNA-WATANA PROJECT AREA

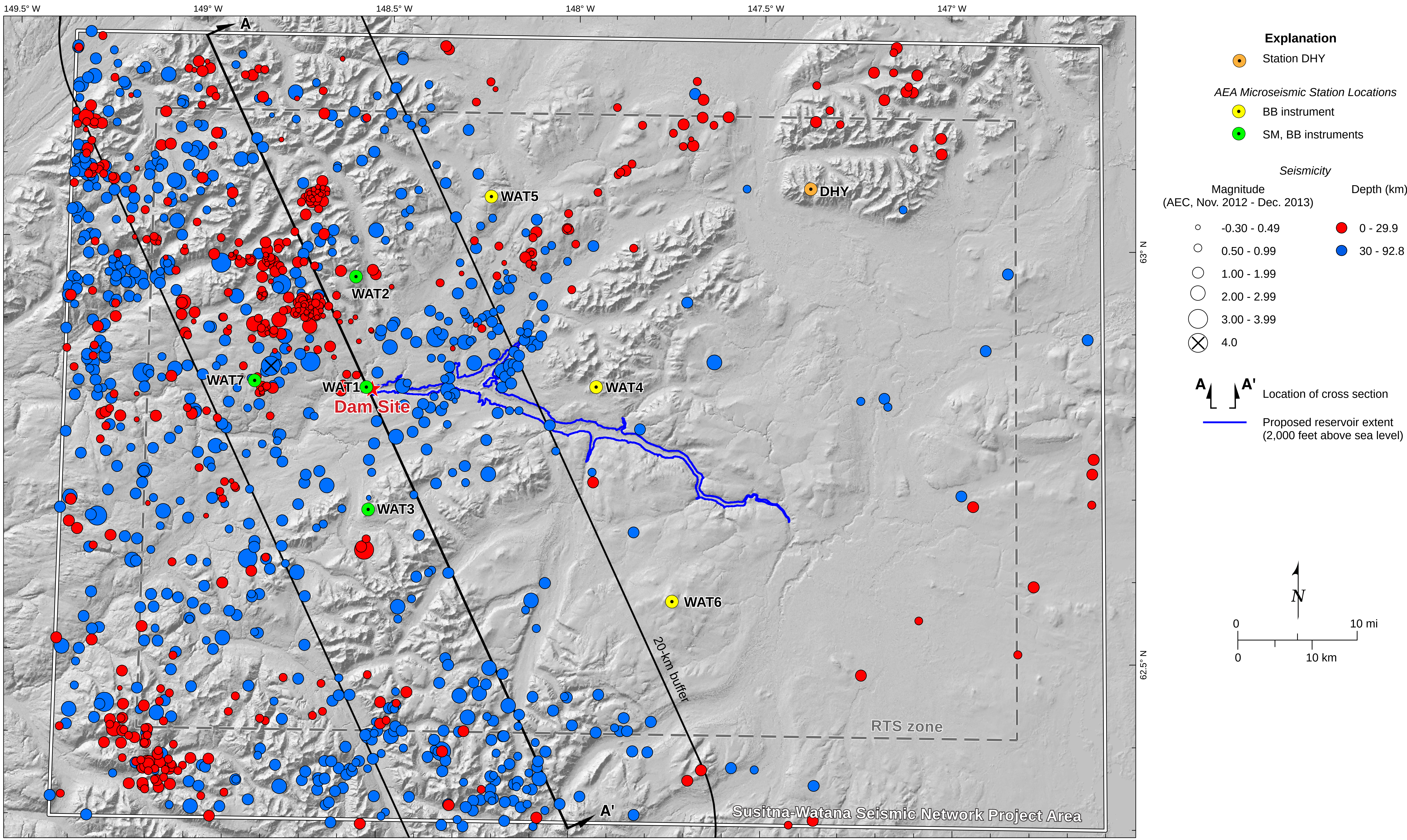
FIGURE 2



Explanation

- Crustal events (depths <30 km)
- Intraslab events (depths ≥30 km)

Notes: 1. Vertical and horizontal standard location errors are shown.
2. Location of section is shown on Figure 4.



FUGRO Date 03/06/14	STATE OF ALASKA ALASKA ENERGY AUTHORITY ALASKA ENERGY AUTHORITY	SUSITNA-WATANA HYDROELECTRIC PROJECT SEISMICITY FROM NOVEMBER 16, 2012 THROUGH DECEMBER 31, 2013	FIGURE 4

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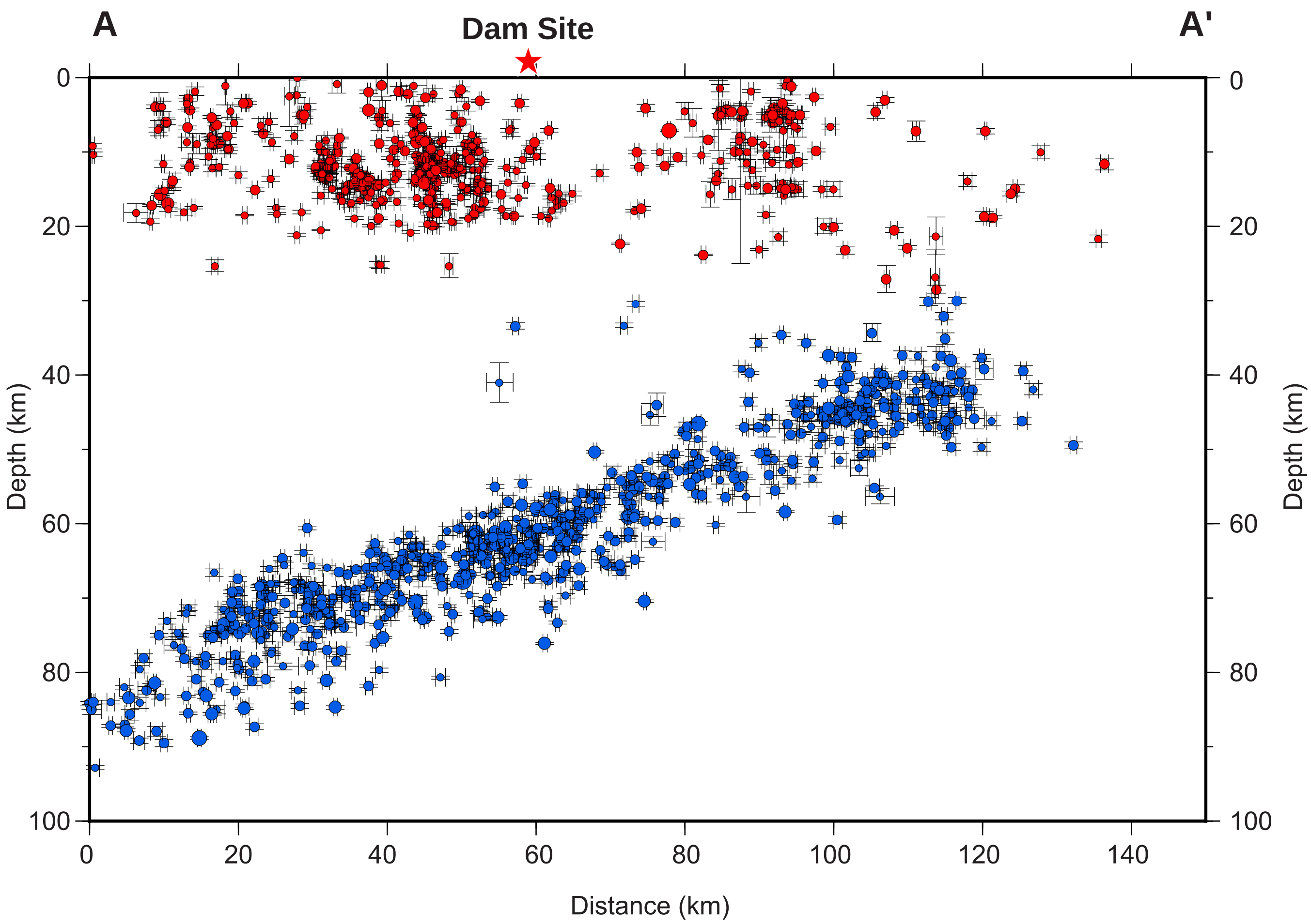
November 16, 2012 - December 31, 2013



Explanation

- Crustal events (depths <30 km)
- Intraslab events (depths ≥30 km)

Notes: 1. Vertical and horizontal standard location errors are shown.
2. Location of section is shown on Figure 4.

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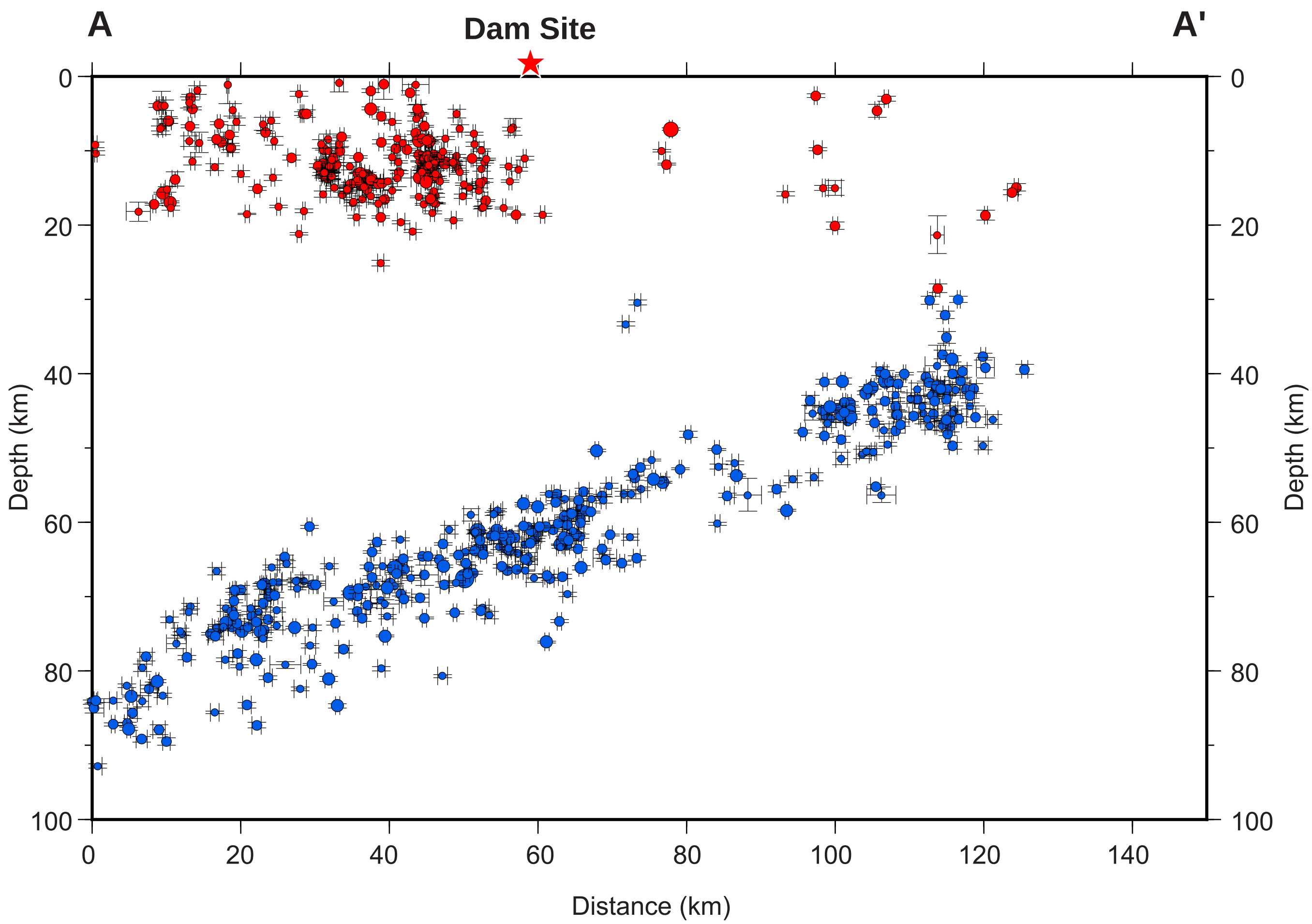
FUGRO Date 03/06/14	STATE OF ALASKA ALASKA ENERGY AUTHORITY ALASKA ENERGY AUTHORITY	SUSITNA-WATANA HYDROELECTRIC PROJECT CROSS SECTION OF NOVEMBER 16, 2012 THROUGH DECEMBER 31, 2013 SEISMICITY IN FIGURE 4	FIGURE 5

November 16, 2012 - December 31, 2013, 20-km Buffer



Explanation

- Crustal events (depths <30 km)
- Intraslab events (depths ≥30 km)

Notes: 1. Vertical and horizontal standard location errors are shown.
2. Location of section is shown on Figure 4.

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Date 03/06/14

STATE OF ALASKA
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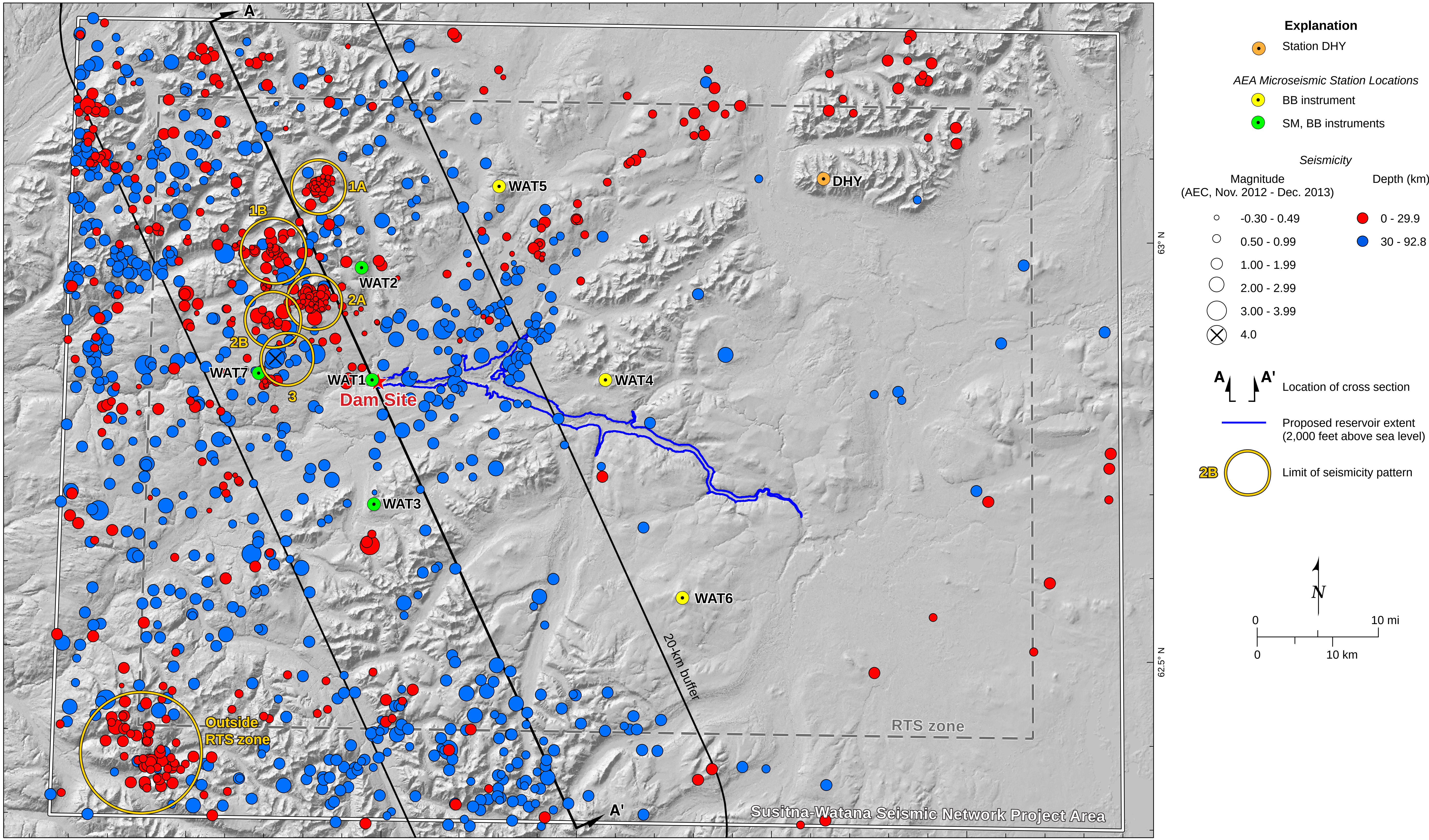
SUSITNA-WATANA HYDROELECTRIC PROJECT
CROSS SECTION OF NOVEMBER 16, 2012 THROUGH DECEMBER 31, 2013 SEISMICITY IN FIGURE 4 WITHIN 20-KM BUFFER

FIGURE 6



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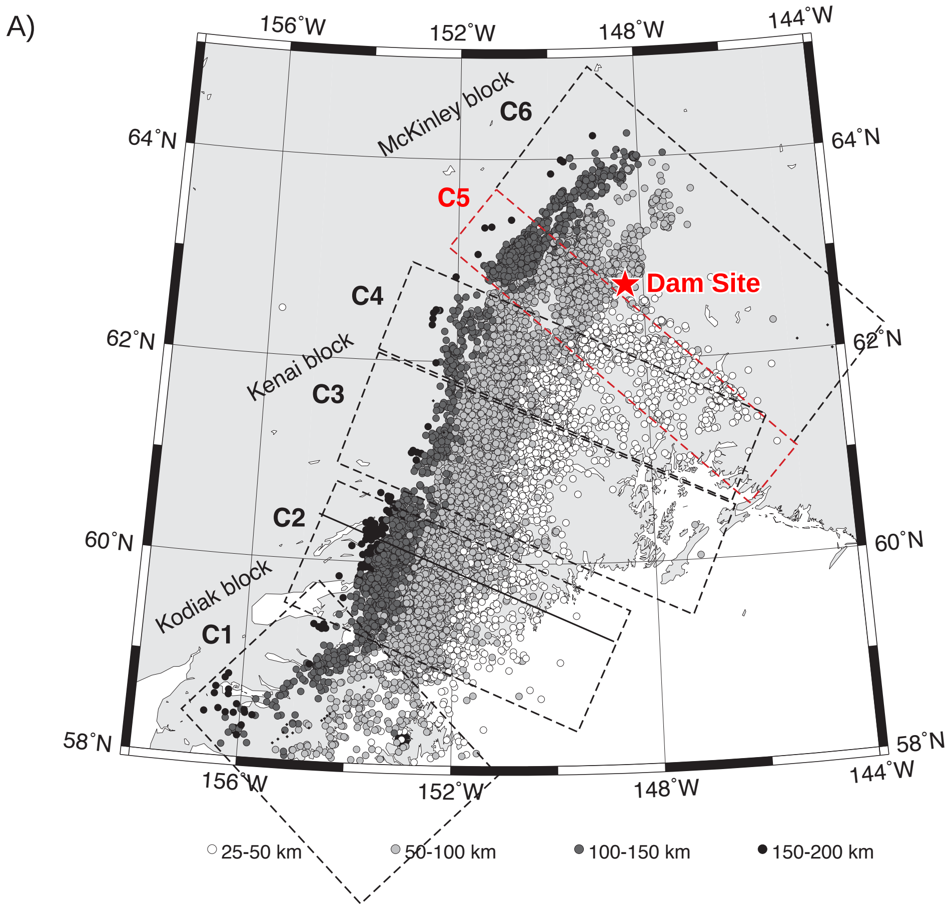
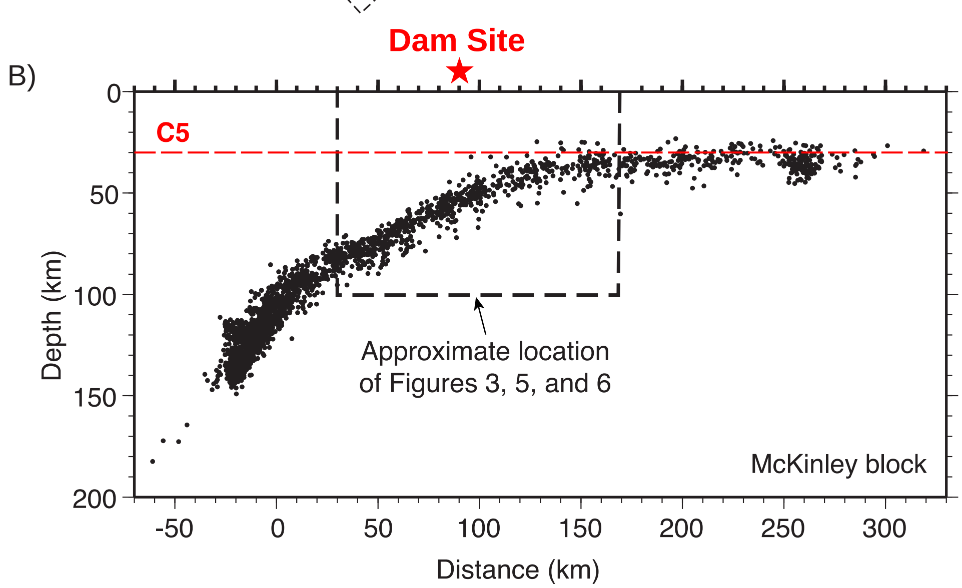
SUSITNA-WATANA HYDROELECTRIC PROJECT

SEISMICITY FROM NOVEMBER 16, 2012 THROUGH DECEMBER 31, 2013 WITH NOTABLE SEISMICITY PATTERNS

FIGURE

7





A) Map of earthquakes showing location of cross section (dashed rectangle labeled C5) shown in B), modified from Figure 5 of Ratchkovski and Hansen (2002). (B) Cross section (C5) of earthquakes, modified from Figure 6 of Ratchkovski and Hansen (2002). Star indicates approximate site location.

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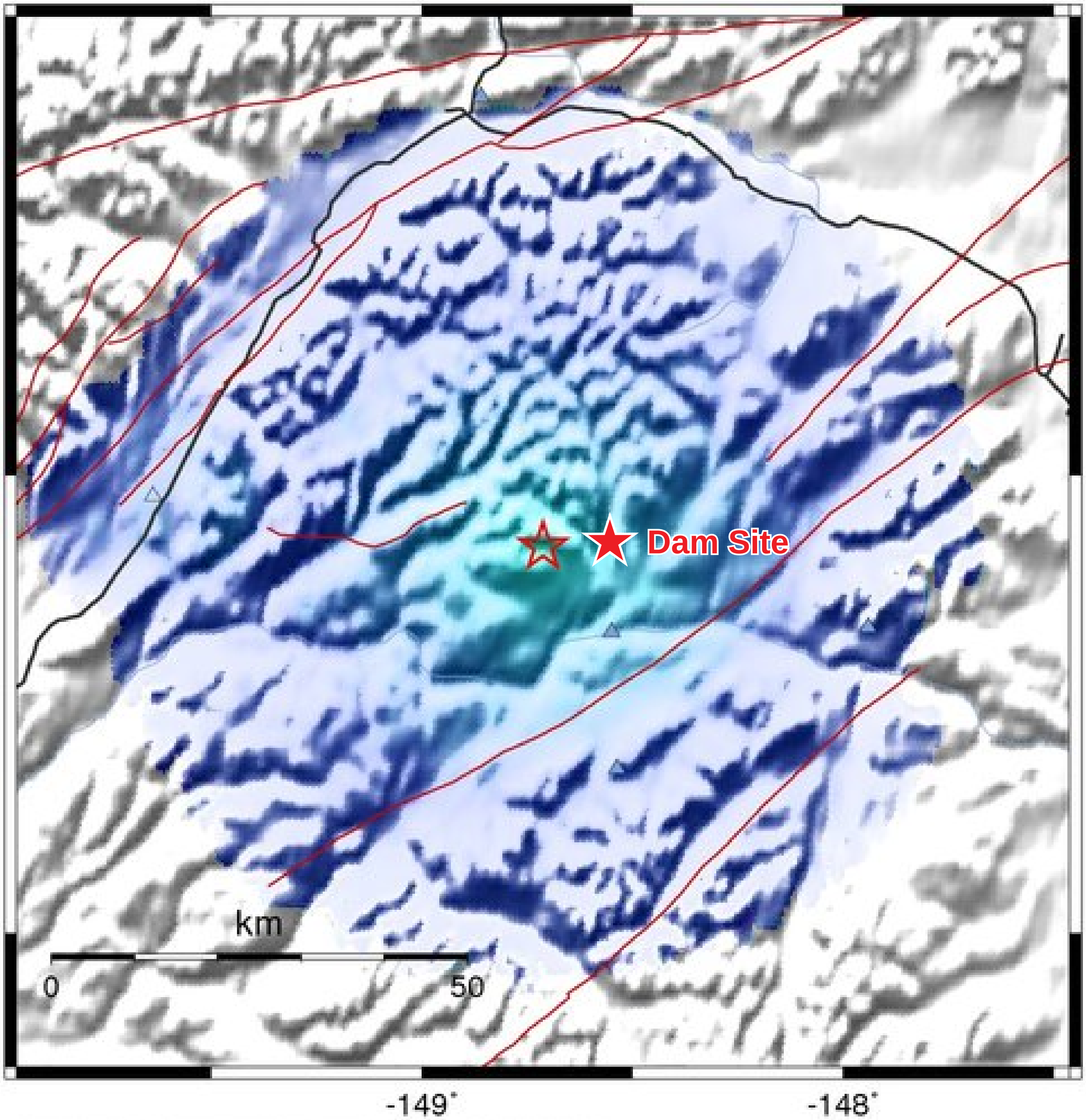
FUGRO Date 03/06/14	STATE OF ALASKA ALASKA ENERGY AUTHORITY ALASKA ENERGY AUTHORITY	SUSITNA-WATANA HYDROELECTRIC PROJECT SUBDUCTION-ZONE EARTHQUAKES PLAN AND SECTION	FIGURE 8

AEIC ShakeMap : 33.1 miles SSE of Cantwell

Wed Jul 24, 2013 10:16:59 AM YDT M 3.8 N62.92 W148.71 Depth: 11.1km ID:10766225

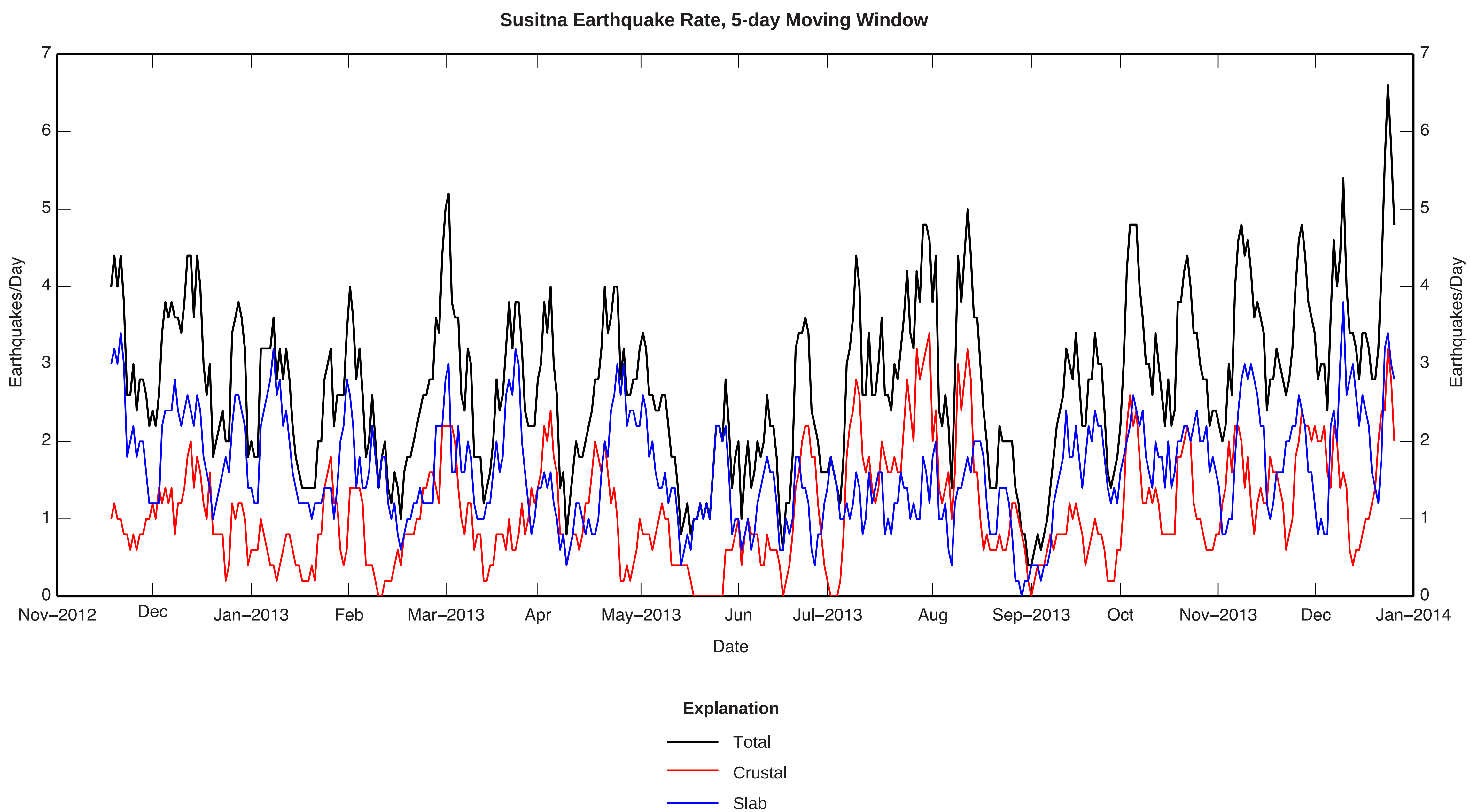


Map Version 2 Processed Mon Jul 29, 2013 02:53:08 PM YDT

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.03	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.01	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

FUGRO Date 03/06/14	STATE OF ALASKA ALASKA ENERGY AUTHORITY ALASKA ENERGY AUTHORITY	SUSITNA-WATANA HYDROELECTRIC PROJECT USGS SHAKEMAP OF 7/24/13 M_L 3.8 EVENT	FIGURE 9



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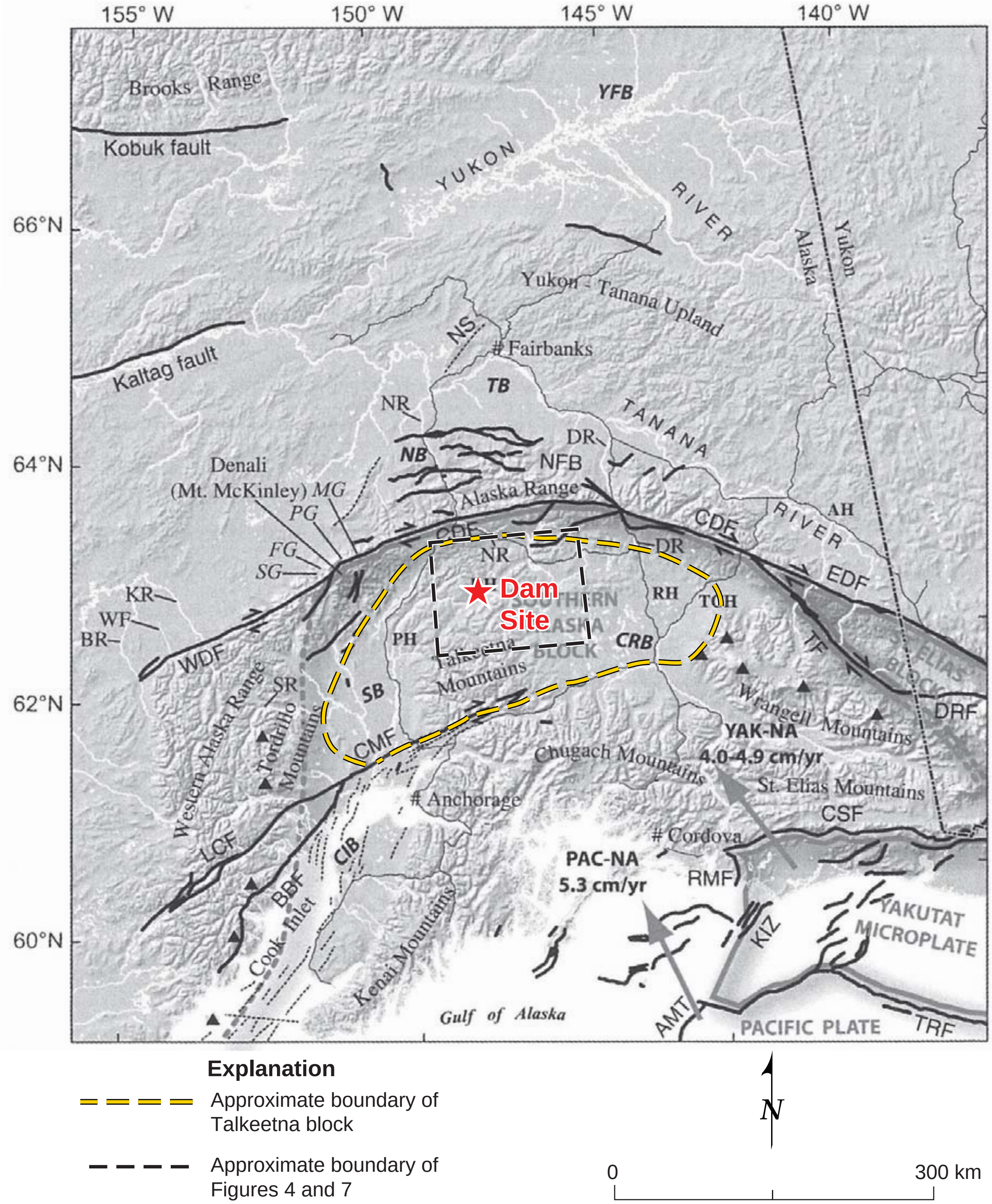
STATE OF ALASKA
ALASKA ENERGY AUTHORITY

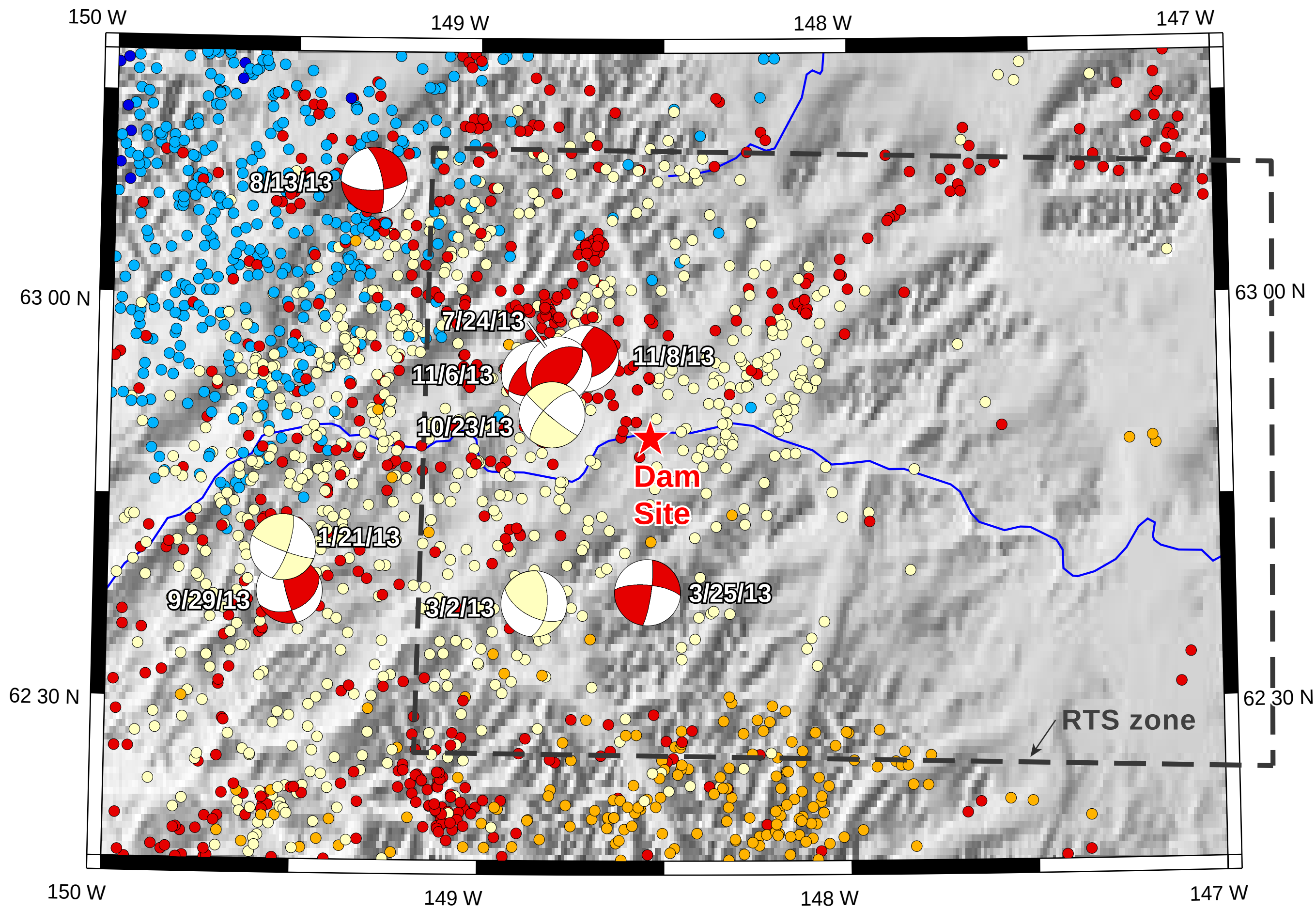
SUSITNA-WATANA HYDROELECTRIC PROJECT
DAILY AVERAGE EARTHQUAKE RATES
OF SEISMICITY
SHOWN IN FIGURE 4

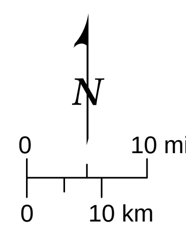
FIGURE
10



Black lines are Neogene and active faults, dashed lines are anticlines. Triangles show active volcanoes. Crustal blocks are outlined in gray and are dashed where boundaries are uncertain. Faults: WDF, western Denali fault; CDF, central Denali fault; EDF, eastern Denali fault; NFB, northern foothills fold-and-thrust belt; NS, Nenana structure; TF, Totschunda fault; DRF, Duke River fault; LCF, Lake Clark fault; CMF, Castle Mountain fault; BBF, Bruin Bay fault; CSF, Chugach-St. Elias thrust fault; KIZ, Kayak Island fault zone; RMF, Ragged Mountain fault; AMT, Aleutian megathrust; TRF, Transition fault. Major roads are shown with thin black lines. AH, Alaska highway; PH, Parks highway; DH, Denali highway; RH, Richardson highway; DH, Denali highway; TCH, Tok cutoff highway. Abbreviated river names mentioned in text: NR, Nenana River, Delta River (both rivers flow north); BR, Big River; WF, Windy Fork; KR, Kuskokwim River; SR, Skwentna River. Glaciers: SG, Straightaway Glacier; FG, Foraker Glacier; PG, Peters Glacier; MG, Muldow Glacier. Sedimentary basins: cm, Cook Inlet basin; SB, Susitna basin; CRB, Copper River basin; NB, Nenana basin; TB, Tanana basin; YFB, Yukon Flats basin. Modified from Haeussler, 2008.

FUGRO Date 03/06/14	STATE OF ALASKA ALASKA ENERGY AUTHORITY ALASKA ENERGY AUTHORITY	SUSITNA-WATANA HYDROELECTRIC PROJECT TECTONIC OVERVIEW OF CENTRAL INTERIOR ALASKA	FIGURE 11





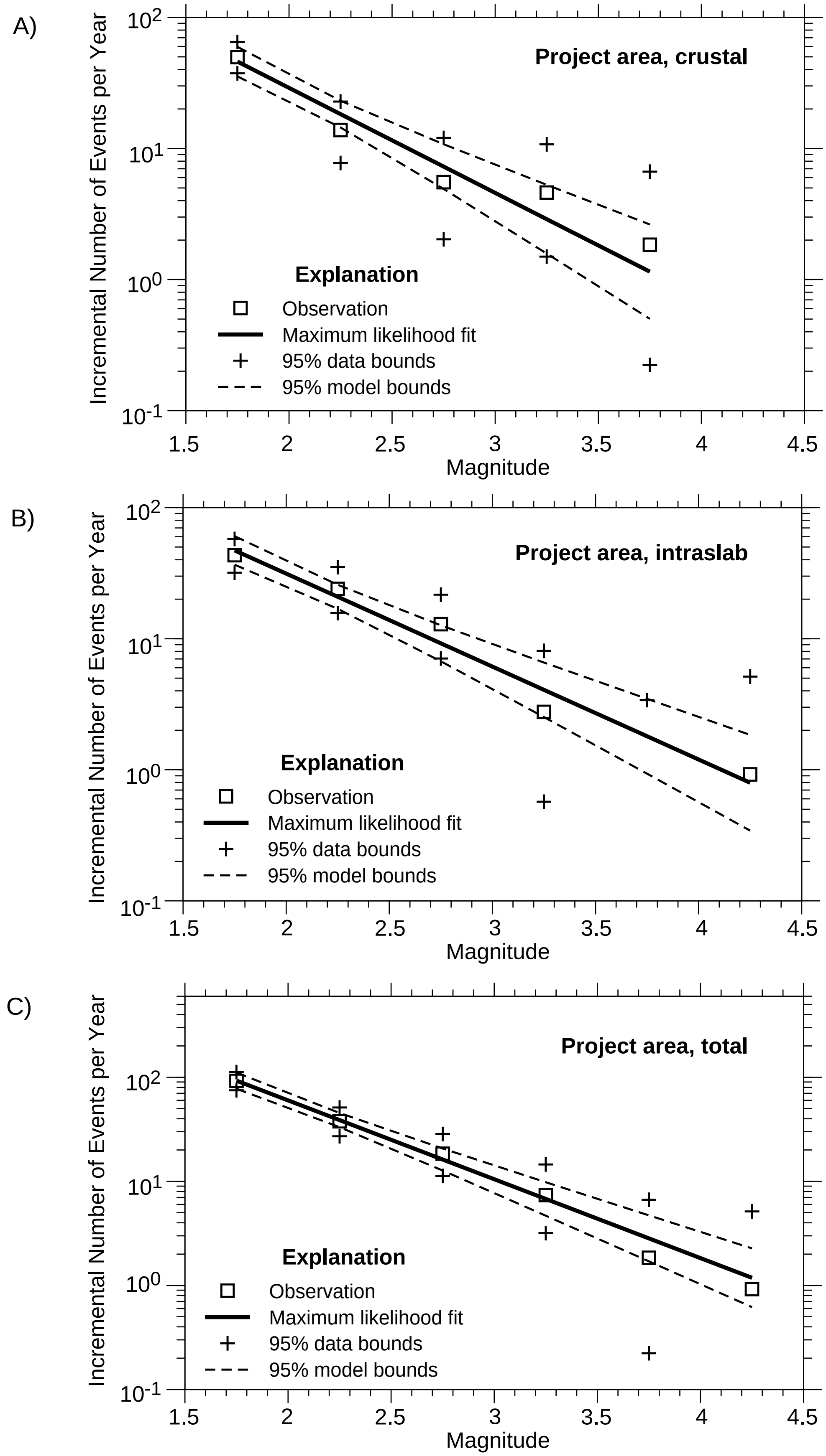
Explanation

Seismicity (depth in km)

- 0 to 25.0
- 25.1 to 50.0
- 50.1 to 75.0
- 75.1 to 100.0
- >100.1

Note: P-wave first motion focal mechanisms from AEC are shown as lower hemisphere projection of the focal sphere. Compressional quadrants are shaded with color corresponding to depth.

FUGRO Date 03/06/14	STATE OF ALASKA ALASKA ENERGY AUTHORITY ALASKA ENERGY AUTHORITY	SUSITNA-WATANA HYDROELECTRIC PROJECT FOCAL MECHANISMS IN THE SUSITNA-WATANA PROJECT AREA	FIGURE 12



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STATE OF ALASKA
ALASKA ENERGY AUTHORITY
ALASKA ENERGY AUTHORITY

SUSITNA-WATANA HYDROELECTRIC PROJECT

INCREMENTAL MAXIMUM LIKELIHOOD FIT, OBSERVATIONS, AND 95% CONFIDENCE DATA AND MODEL BOUNDS, DECEMBER 1, 2012 THROUGH DECEMBER 31, 2013

FIGURE 13

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