6. SUSITNA BASIN AND DAM SITE CHARACTERISTICS

6.1. Climatology

The proposed Susitna-Watana Project is located in the south-central region of Alaska, approximately 125 miles north-northeast of Anchorage and 140 miles south-southwest of Fairbanks. The Susitna River basin, which has a drainage area of almost 20,000 square miles at its mouth and 5,180 square miles at the proposed Watana Dam site, has a wide range in climate due to elevation differences and proximity to the Gulf of Alaska. The climate of the upper Susitna basin is characterized by cold dry winters and warm but moderately moist summers. The yearly precipitation distribution shows that about two-thirds of the annual precipitation occurs from June through October. The climate is classified into three categories: (1) a coastal zone dominated almost entirely by maritime influences; (2) a zone of transition from maritime to continental influences; and (3) a zone dominated by continental climatic conditions. The upper Susitna basin, where the Susitna-Watana Project is located, falls within the transitional zone.

The contrast between coastal maritime-influenced areas and continental conditions at Fairbanks are marked. Within the confines of the upper Susitna basin, the lack of moderating influence of maritime air results in greater temperature extremes than on the coast of the Gulf of Alaska. Relatively severe winter temperatures contrasted by warm summers will occur within the basin. Mean annual precipitation at lower elevations of the basin would be expected to range between 18 and 22 inches, while precipitation in higher elevations, because of orographic effects, would be expected to reach 80 inches per year. Mean annual snowfall would range from 60 inches in the lowlands to as much as 400 inches in the high mountains. Monthly average precipitation values for long-term stations (60 years of data at Fairbanks; 56 years at Talkeetna; 55 years at Anchorage) are presented in Table 6.1-1 and plotted on Figure 6.1-1. Talkeetna is representative of the lower Susitna River basin.

Table 6.1-1. Monthly Precipitation (inches)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fairbanks	0.59	0.43	0.34	0.29	0.60	1.37	2.03	1.83	1.07	0.78	0.66	0.69
Talkeetna	1.49	1.51	1.28	1.27	1.44	2.18	3.34	4.63	4.23	2.84	1.64	1.73
Anchorage	0.75	0.82	0.64	0.56	0.66	1.04	1.89	2.63	2.78	1.89	1.11	1.12
Project Site	No data											

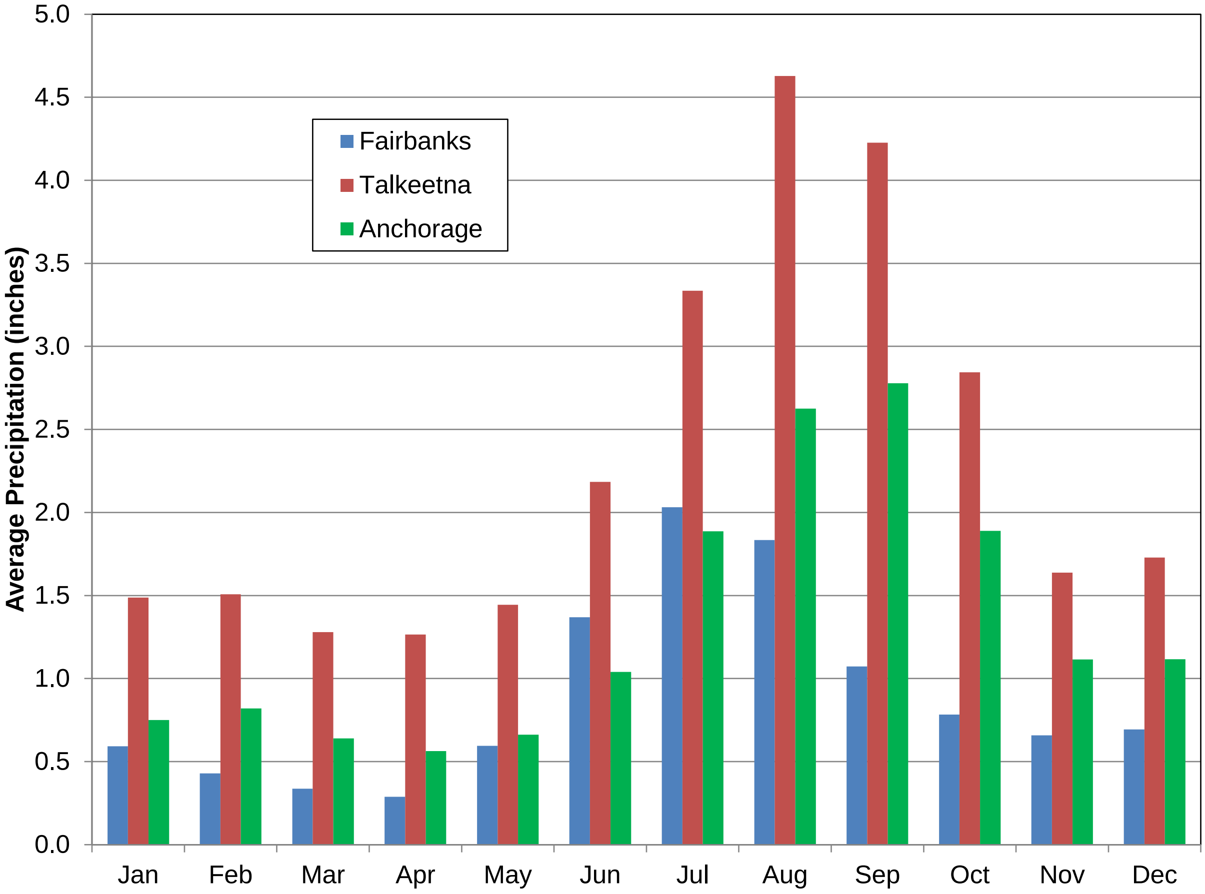


Figure 6.1-1. Monthly Average Precipitation

Table 6.1-2 and Figure 6.1-2 shows the significant annual variation in maximum, minimum, and average monthly temperatures among Fairbanks, Talkeetna, and Anchorage, from National Weather Service data. Data for the project site was derived from 1980s records. The continental climatic zone winter temperatures exhibited at Fairbanks are far lower, while summer temperatures are slightly higher at Fairbanks than at Talkeetna and Anchorage.

Table 6.1-2. Maximum, Minimum, and Average Monthly Temperatures

Maximum Temperature (°F)												
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fairbanks	-1.1	8.2	23.9	42.4	59.9	70.7	72.7	66.3	54.5	32.1	11.5	1.6
Talkeetna	19.7	26.1	33.6	44.6	56.9	65.7	67.9	64.8	55.4	39.9	26.3	20.5
Anchorage	21.7	26.0	32.9	43.6	55.1	62.3	65.3	63.4	55.1	40.5	27.8	22.8
Project Site	32.2	31.2	34.4	36.3	71.9	85.5	81.1	76.5	60.5	44.3	27.4	35.1

Minimum Temperature (°F)												
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fairbanks	-18.7	-14.2	-3.0	20.1	37.7	49.1	51.9	46.7	35.6	17.2	-4.9	-15.2
Talkeetna	2.1	5.5	10.0	23.3	34.8	45.2	49.6	46.3	37.2	24.0	10.2	3.7
Anchorage	8.7	12.0	17.6	28.6	39.0	47.3	51.7	49.6	41.5	28.6	16.0	10.3
Project Site	-26.4	-7.4	-13.4	-5.5	13.7	36.9	42.0	31.8	20.9	4.8	-8.1	-18.8
Average Temperature (°F)												
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fairbanks	-9.9	-3.0	10.5	31.2	48.8	59.9	62.1	56.5	45.1	24.6	3.3	-6.8
Talkeetna	10.9	15.8	21.8	34.0	45.8	55.5	58.7	55.5	46.3	31.9	18.3	12.1
Anchorage	15.2	19.0	25.2	36.1	47.0	54.8	58.5	56.5	48.3	34.5	21.9	16.5
Project Site	12.5	15.9	12.9	17.5	37.9	58.5	57.1	52.1	41.2	19.3	7.7	3.4

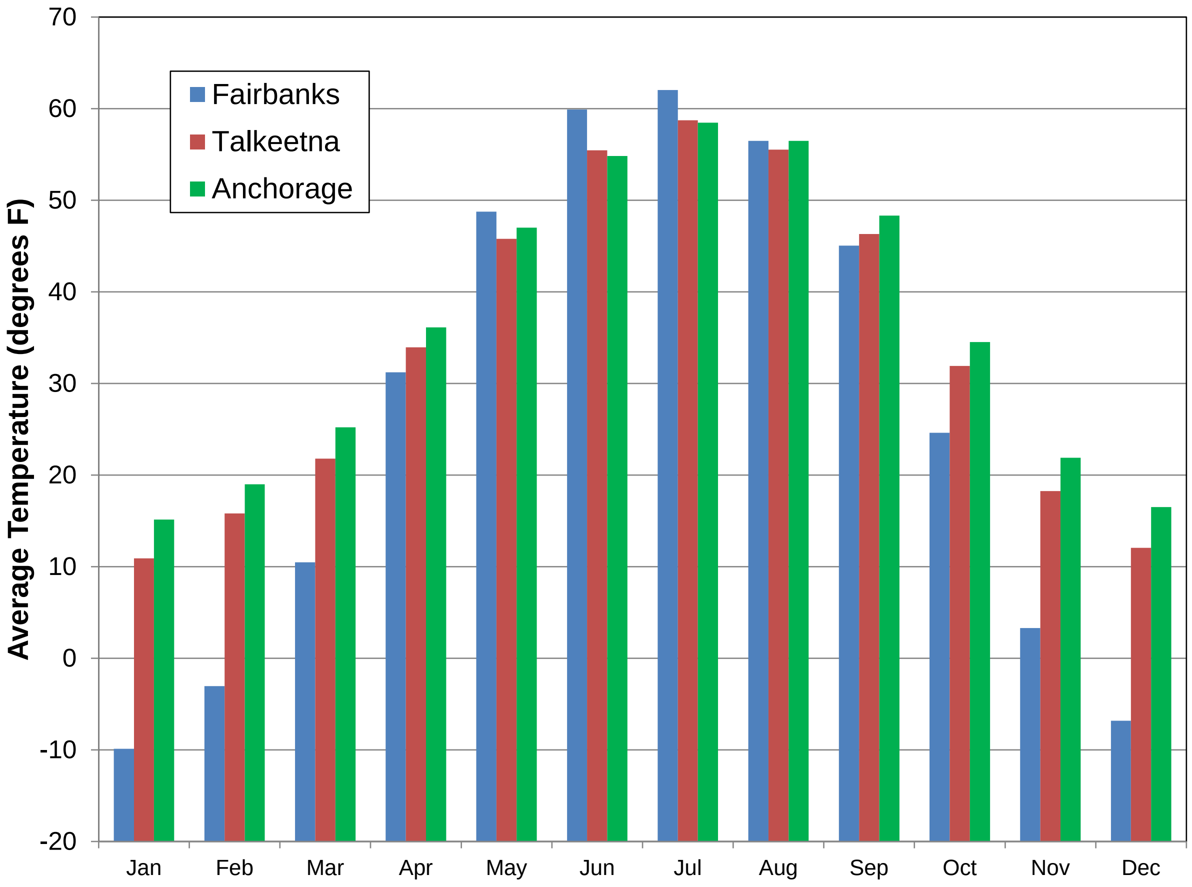


Figure 6.1-2. Average Temperatures (°F)

6.2. Hydrology

This section summarizes available existing U.S. Geological Service (USGS) hydrologic data in the Susitna River watershed, and presents statistics for estimated flow at the Watana Dam site. Included in this section are (1) a summary of the hydrologic record; (2) monthly flow frequency and flow duration; (3) Watana Dam site historical flows; (4) flood frequency; and (5) Susitna watershed flow distribution.

6.2.1. Hydrologic Record

A summary of recorded flow data in the Susitna River watershed is useful for many purposes associated with the Susitna-Watana Project. Recorded flow data is also needed to develop a long-term estimate of flow and flood frequency at the Watana Dam site for use in project design, reservoir operation and power generation studies. Fourteen gaging stations have been intermittently operated by the USGS within the Susitna River watershed between 1949 and 2013 as shown in Table 6.2-1. At the time of preparation of this report, water year 2014 was not included because the water year was still in-progress and the USGS had not yet made data available for the 2013–2014 river ice season. An additional station on the Little Susitna River, which is not a tributary of the Susitna River, was included in Table 6.2-1 due to its proximity to the Susitna River and the exceptionally long period of record for this gage.

Table 6.2-1. USGS Streamflow Gages in the Susitna Watershed

USGS Gage Number	Gage Name	Drainage Area (sq.mi)	Latitude	Longitude	Gage Datum (feet)	Available Period of Record
15290000	Little Susitna River near Palmer	62	61°42'37"	149°13'47"	917	1948 - 2013
15291000	Susitna River near Denali	950	63°06'14"	147°30'57"	2,440	1957 - 1976; 1978 - 1986; 2012
15291200	Maclaren River near Paxson	280	63°07'10"	146°31'45"	2,866	1958 - 1986
15291500	Susitna River near Cantwell	4,140	62°41'55"	147°32'42"	1,900	1961 - 1972; 1980 - 1986
15291700	Susitna River above Tsusena Creek	5,160	62°49'24"	147°36'17"	1,500	2013
15292000	Susitna River at Gold Creek	6,160	62°46'04"	149°41'28"	677	1949 - 1996; 2001 - 2013
15292400	Chulitna River near Talkeetna	2,570	62°33'31"	150°14'02"	520	1958 - 1972; 1980 - 1986
15292700	Talkeetna River near Talkeetna	1,996	62°20'49"	150°01'01"	400	1964 - 1972; 1980 - 2013
15292780	Susitna River at Sunshine	11,100	62°10'42"	150°10'30"	270	1981 - 1986; 2012 - 2013
15292800	Montana Creek near Montana	164	62°06'19"	150°03'27"	250	2005 - 2006; 2008 - 2012
15294005	Willow Creek Near Willow	166	61°46'51"	149°53'04"	350	1978 - 1993; 2001 - 2013
15294010	Deception Creek near Willow	48	61°44'52"	149°56'14"	250	1978 - 1985
15294100	Deshka River near Willow	591	61°46'05"	150°20'13"	80	1978 - 1986; 1988 - 2001
15294300	Skwentna River near Skwentna	2,250	61°52'23"	151°22'01"	200	1959 - 1982
15294345	Yentna River near Susitna Station	6,180	61°41'55"	150°39'02	80	1980 - 1986
15294350	Susitna River at Susitna Station	19,400	61°32'41"	150°30'45	40	1974 - 1993

The location of the five USGS gaging stations located in the area tributary to or just downstream of Watana Dam, along with the watershed boundaries, are shown on Figure 6.2-1.

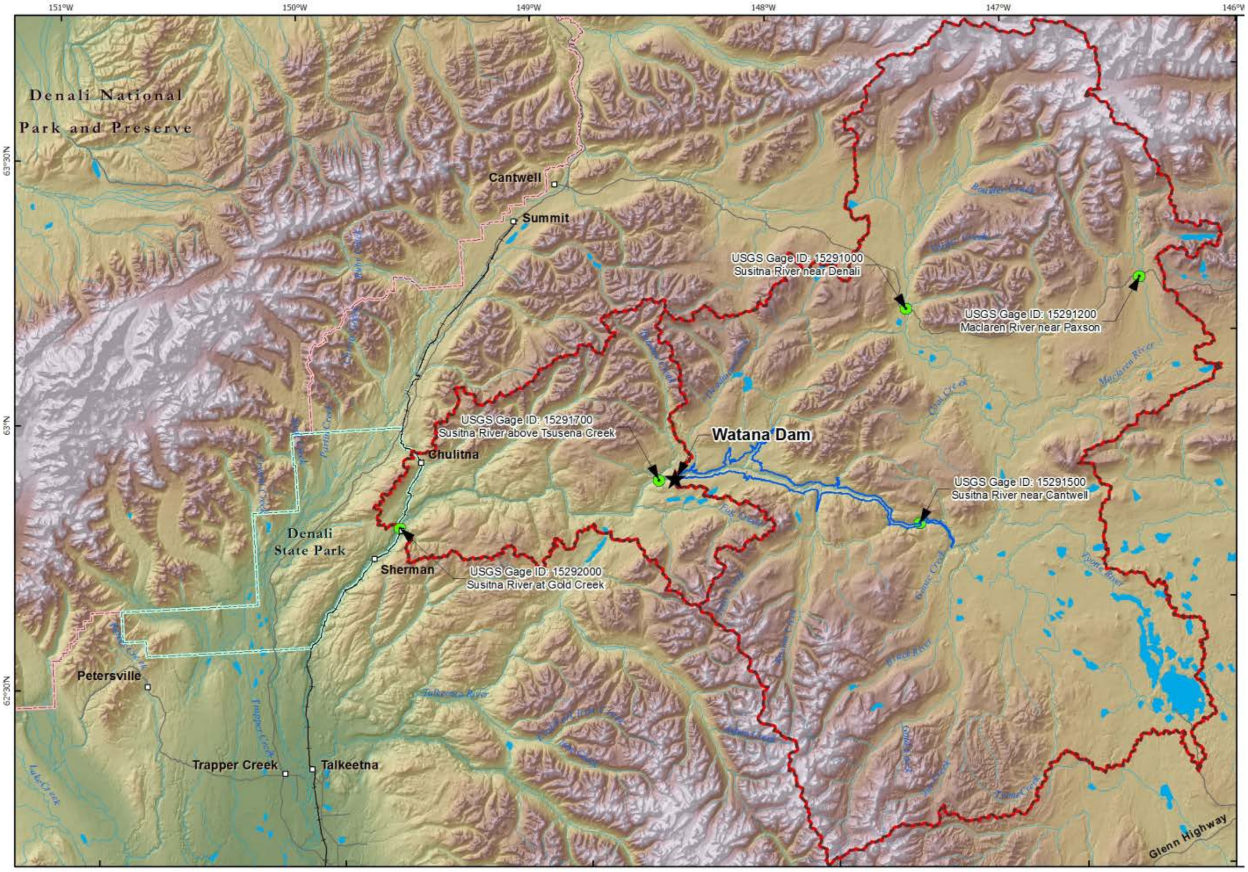


Figure 6.2-1. Susitna Watershed Boundary and USGS Gage Locations

Figure 6.2-2 shows the chronological availability of USGS flow data in the Susitna watershed. A modeled daily flow data set for the Watana Dam site was developed from the daily data at the downstream gage at Gold Creek and the upstream gage near Cantwell. The drainage area at the Watana Dam site, 5,180 square miles, is approximately halfway between the drainage area at Cantwell (4,140 square miles) and Gold Creek (6,160 square miles). The drainage areas for these sites were confirmed with geographic information system measurements. The 17 years of concurrent data at the Cantwell and Gold Creek gaging stations were used to calculate monthly scaling factors for use in estimating flows at Watana, as described below.

Figure 6.2-2 also shows an active period of flow gaging in the early 1980s, with at least four years of concurrent data at almost all sites.

Note: Data are on a calendar year basis.

Figure 6.2-2. Susitna Watershed USGS Flow Data – Chronological Availability

Within the period of record for gages in the Susitna watershed, there have been several periods of no gage-height record, some lasting for several consecutive months. The USGS has developed estimated flows for the period of no gage-height records, as is their customary practice, to provide a continuous period of record during operational years. All of the data used in hydrologic analyses for the Susitna watershed are accepted measured or estimated values published by the USGS.

Average monthly flows over the period of record for the main stem Susitna River plus the Paxson River, which is tributary to the Watana Dam site, are presented on Table 6.2-2. As shown in Table 6.2-2 and in Figure 6.2-3, flow in the Susitna River and its tributaries is highly seasonal, with peak flows in July corresponding with summer snow melt conditions, and low winter flows occurring when much precipitation is stored in the watershed as snow.

Table 6.2-2. Average Monthly Flows (cfs) at Selected USGS Gages in the Susitna Watershed

	Susitna River near Denali ($950mi^2$)	Maclaren River near Paxson ($280mi^2$)	Susitna River near Cantwell ($4,140mi^2$)	Susitna River at Gold Creek ($6,160mi^2$)	Susitna River at Sunshine ($11,100mi^2$)	Susitna River at Susitna Station ($19,400mi^2$)
January	262	105	961	1,590	4,375	8,487
February	220	90	828	1,414	3,939	7,739
March	199	82	779	1,297	3,496	7,136
April	233	89	915	1,753	3,948	10,021
May	2,135	850	7,908	14,138	27,970	64,825
June	7,279	2,894	18,230	26,417	56,472	118,479
July	9,831	3,240	17,542	23,871	66,238	130,317
August	8,159	2,548	14,918	21,365	60,972	113,051
September	3,296	1,136	7,936	13,741	35,202	74,446
October	1,181	421	3,365	6,345	16,600	39,578
November	525	192	1,575	2,679	6,787	15,966
December	339	130	1,117	1,892	4,877	9,983
Annual	2,793	981	6,340	9,805	23,864	50,417

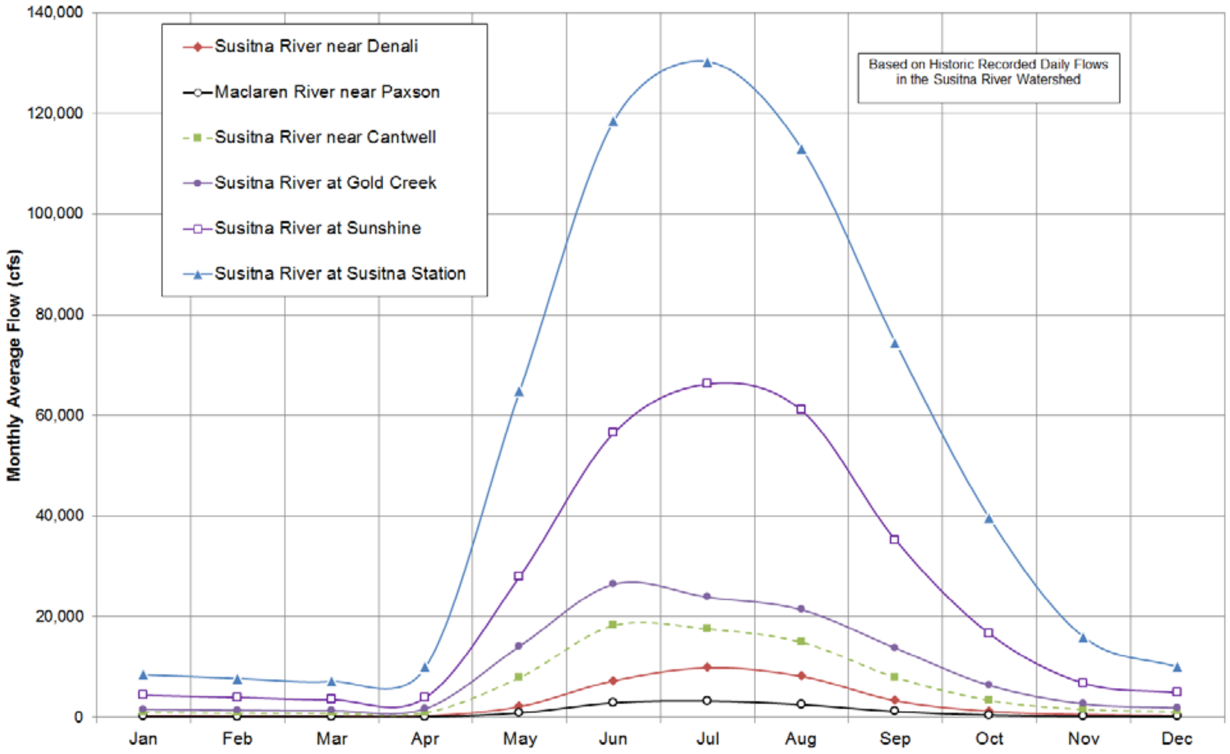


Figure 6.2-3. Average Monthly Flows in the Susitna Watershed

6.2.2. Monthly Flow Frequency and Flow Duration

The nearest long-term gaging stations upstream and downstream from Watana Dam were used to create flow frequency and flow duration plots. USGS gaging station 15291700 Susitna River above Tsusena Creek is located about two miles downstream from the Watana Dam site, but flow records began in water year 2012 so the period of record is inadequate for determining average flows or flow frequency data. Daily flow data at Cantwell and Gold Creek on the Susitna River was used; these stations are 41 river miles upstream and 47 river miles downstream respectively. Table 6.2-3 and Table 6.2-4 present monthly flow frequencies for flows in the Susitna River at Cantwell and Gold Creek, respectively. The flow frequency was calculated at five percent exceedance intervals except at the high and low flow ends where 1 percent exceedance intervals were used to provide additional definition where the flow duration values change rapidly.

Figure 6.2-4 through Figure 6.2-7 show the flow frequency and flow duration curves for these sites. The flow frequency curves demonstrate the same seasonal flow as Figure 6.2-3, with peak flows occurring in June at the middle watershed sites of Cantwell and Gold Creek.

Table 6.2-3. Flow (cfs) Frequency at USGS Gage 15291500 – Susitna River near Cantwell

% of Time Flow is Exceeded	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual (all months)
0	1,800	1,500	1,500	3,000	32,500	49,100	34,000	55,000	21,000	9,400	3,600	1,900	55,000
1	1,800	1,500	1,500	1,800	23,740	43,310	29,400	35,886	18,427	7,353	3,200	1,774	28,775
2	1,700	1,500	1,500	1,682	22,000	37,848	28,000	28,800	17,088	7,000	2,982	1,600	26,000
3	1,700	1,500	1,500	1,500	20,200	35,251	27,036	28,258	16,183	6,536	2,600	1,600	24,000
4	1,696	1,500	1,500	1,400	20,000	33,396	26,248	26,000	16,000	6,070	2,500	1,600	22,100
5	1,600	1,500	1,400	1,400	19,100	32,455	25,860	24,600	15,010	6,000	2,400	1,600	21,000
10	1,500	1,200	1,200	1,400	16,000	27,000	23,100	20,830	13,010	5,200	2,200	1,600	18,000
15	1,300	1,200	1,100	1,226	14,000	25,360	21,800	18,445	12,000	5,000	2,200	1,400	16,000
20	1,300	1,200	940	1,200	12,700	23,240	20,700	17,960	10,520	4,500	2,000	1,400	14,500
25	1,300	1,000	940	1,200	11,300	21,150	19,900	17,100	9,500	4,175	1,900	1,400	12,000
30	1,200	965	900	1,100	10,000	20,000	19,000	16,490	8,624	3,918	1,800	1,400	9,865
35	1,094	904	850	1,070	10,000	19,000	18,600	16,000	8,000	3,600	1,800	1,400	7,100
40	1,000	850	825	1,000	9,380	18,000	18,000	15,800	7,900	3,600	1,700	1,300	4,970
45	1,000	850	760	940	8,660	17,000	17,600	15,200	7,570	3,406	1,600	1,200	3,200
50	970	690	690	900	7,500	16,000	17,000	14,700	7,100	3,200	1,530	1,200	2,100
55	760	680	660	850	6,500	15,805	16,700	14,000	6,786	3,000	1,500	1,080	1,600
60	760	670	650	750	5,200	15,200	16,000	13,100	6,600	2,844	1,486	994	1,400
65	730	650	600	720	3,700	15,000	15,580	12,400	6,230	2,600	1,400	932	1,200
70	700	647	560	660	3,000	14,970	15,000	12,000	5,975	2,400	1,364	860	1,100
75	680	640	550	650	2,500	14,200	14,800	11,400	5,515	2,200	1,100	800	950
80	680	560	550	550	2,200	13,600	14,000	10,700	5,132	2,026	1,100	750	850
85	610	500	480	500	1,700	12,635	13,300	9,856	4,430	1,900	918	720	720
90	500	480	460	500	1,500	11,000	12,200	9,267	3,818	1,800	800	650	650
95	460	440	460	485	800	8,823	11,340	7,637	3,396	1,586	780	565	500
96	440	423	440	467	750	8,381	11,000	7,121	3,200	1,423	780	550	500
97	436	420	431	460	750	7,951	11,000	5,684	3,034	1,239	758	550	480
98	420	420	400	440	710	7,232	10,904	4,728	2,800	1,100	709	500	460
99	420	420	400	440	580	6,980	10,000	4,371	2,515	1,026	655	500	440
100	420	420	400	440	580	6,130	8,550	3,600	2,080	840	600	480	400

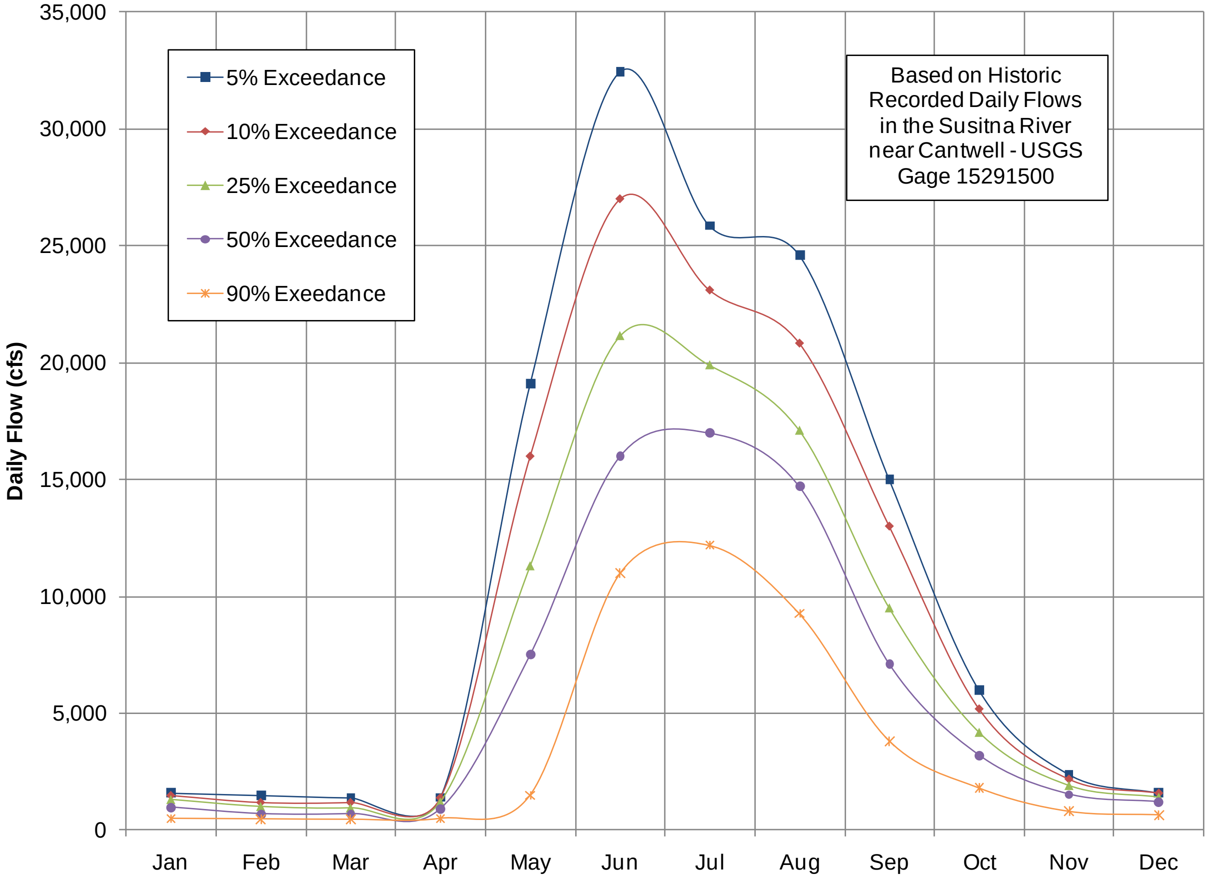


Figure 6.2-4. Susitna River Flow Frequency at Cantwell

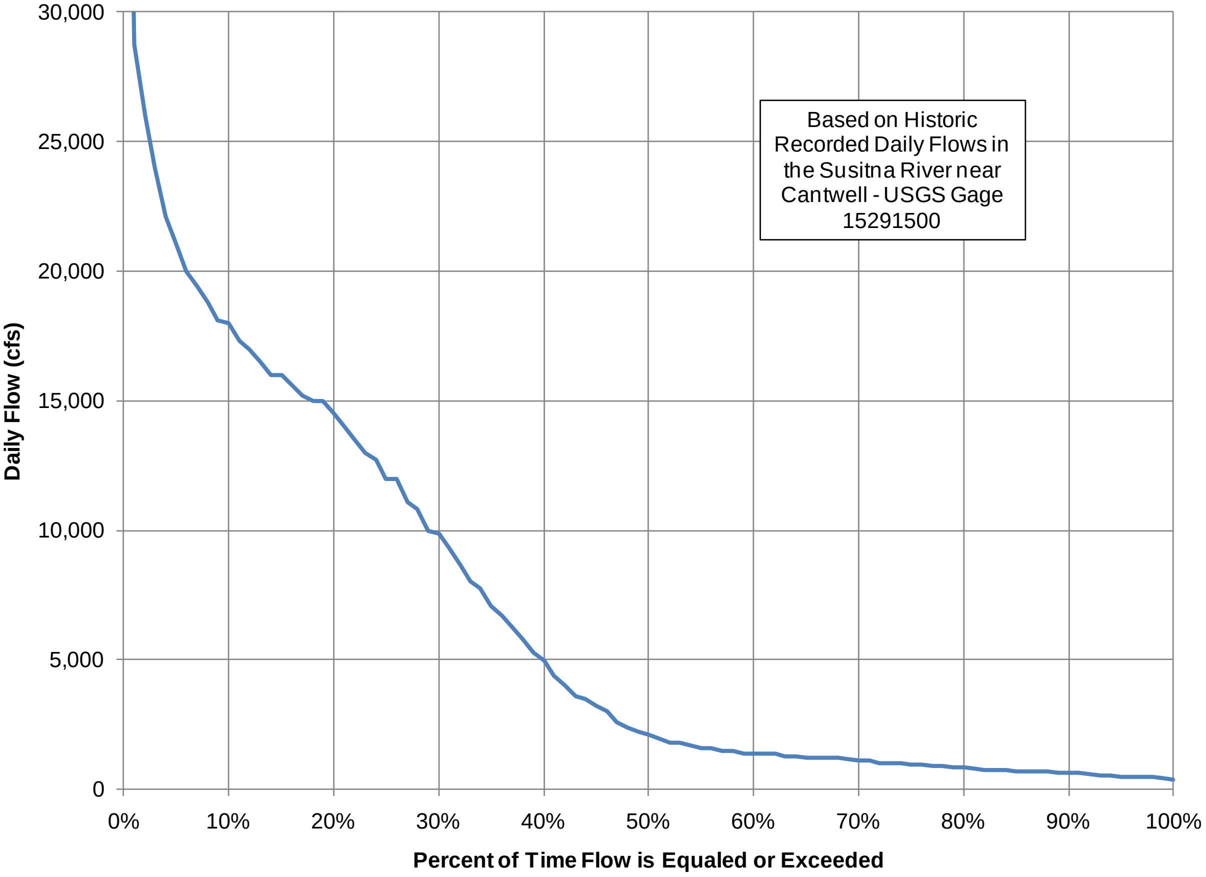


Figure 6.2-5. Susitna River Flow Duration at Cantwell

Table 6.2-4. Flow (cfs) Frequency at USGS Gage 15292000 – Susitna River at Gold Creek

% of Time Flow is Exceeded	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual (all months)
0	2,900	3,700	2,400	24,000	55,500	85,900	60,800	77,700	47,700	36,200	8,940	4,400	85,900
1	2,500	2,400	2,100	7,242	37,958	62,003	42,934	51,206	32,305	16,860	5,184	3,500	39,857
2	2,400	2,150	1,900	5,384	35,116	51,782	39,000	43,006	30,300	14,630	4,800	3,200	35,300
3	2,400	2,000	1,900	4,169	33,074	46,473	37,008	39,045	27,900	13,100	4,500	2,900	32,700
4	2,300	2,000	1,900	3,684	31,532	43,428	35,436	34,824	26,088	12,460	4,400	2,800	31,000
5	2,200	2,000	1,900	3,400	31,000	41,710	34,500	32,900	25,000	12,000	4,202	2,713	30,000
10	2,025	1,900	1,800	2,500	27,800	37,110	31,300	29,000	21,710	10,300	3,700	2,500	25,470
15	2,000	1,800	1,700	2,200	24,270	34,265	29,500	26,445	19,500	9,268	3,400	2,400	22,600
20	2,000	1,790	1,600	2,000	22,000	32,420	28,000	25,200	18,000	8,480	3,200	2,300	20,200
25	1,900	1,700	1,600	1,900	20,350	30,600	26,800	24,000	16,900	7,800	3,100	2,200	18,000
30	1,850	1,600	1,500	1,800	18,800	29,300	25,800	23,000	15,600	7,210	3,000	2,200	15,300
35	1,800	1,500	1,500	1,700	17,700	28,000	25,000	22,400	14,700	6,740	2,900	2,100	12,000
40	1,700	1,500	1,400	1,650	16,400	27,000	24,200	21,700	14,000	6,300	2,800	2,000	8,400
45	1,600	1,500	1,350	1,600	15,000	26,000	23,500	21,000	13,200	5,900	2,700	2,000	5,200
50	1,600	1,400	1,300	1,540	13,600	25,350	22,800	20,200	12,500	5,500	2,600	1,900	3,500
55	1,600	1,400	1,300	1,500	12,000	24,300	22,200	19,600	11,900	5,200	2,600	1,900	2,650
60	1,500	1,300	1,200	1,500	10,360	23,300	21,700	18,800	11,300	4,950	2,400	1,700	2,200
65	1,500	1,300	1,100	1,400	9,000	22,200	21,200	18,000	10,665	4,600	2,400	1,700	1,950
70	1,400	1,200	1,000	1,200	7,160	21,200	20,600	17,500	10,100	4,500	2,300	1,600	1,800
75	1,300	1,200	995	1,200	5,050	20,000	19,900	17,000	9,520	4,215	2,100	1,500	1,600
80	1,200	1,000	940	1,100	4,400	18,900	19,200	16,200	8,936	4,000	1,900	1,500	1,500
85	1,100	970	880	1,000	3,400	17,800	18,500	15,400	8,249	3,700	1,700	1,300	1,400
90	960	860	800	920	2,800	16,400	17,560	14,500	7,199	3,400	1,600	1,110	1,200
95	900	800	750	830	2,055	15,000	16,300	12,985	6,000	2,898	1,400	1,000	950
96	850	750	740	830	1,900	14,700	16,000	12,288	5,791	2,784	1,300	1,000	900
97	850	750	740	780	1,700	13,827	15,600	11,800	5,500	2,500	1,300	900	850
98	800	720	700	756	1,500	13,218	15,032	10,988	5,316	2,200	1,200	850	800
99	718	700	660	710	1,400	12,200	14,600	8,088	4,900	1,900	1,100	850	750
100	700	600	660	700	900	10,000	11,800	5,280	3,710	1,500	950	800	600

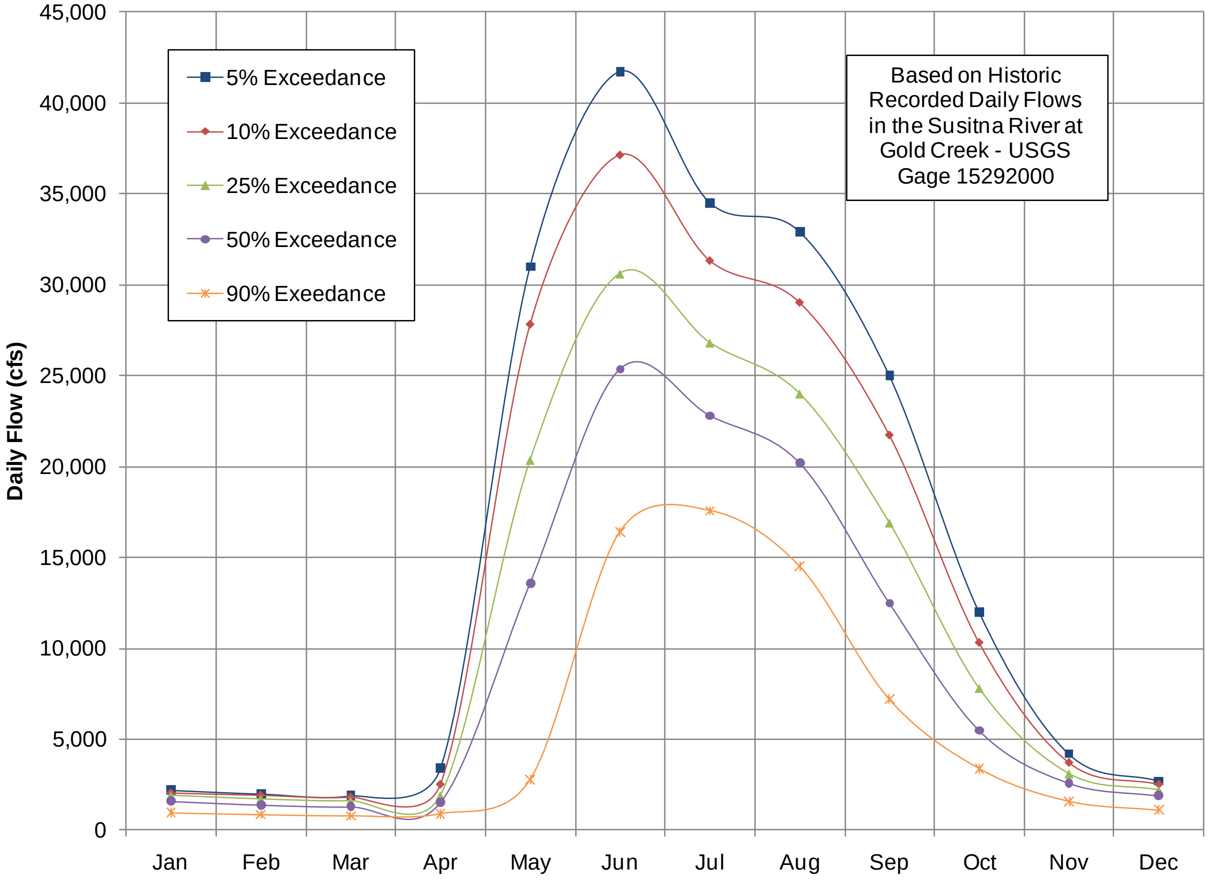


Figure 6.2-6. Susitna River Flow Frequency at Gold Creek

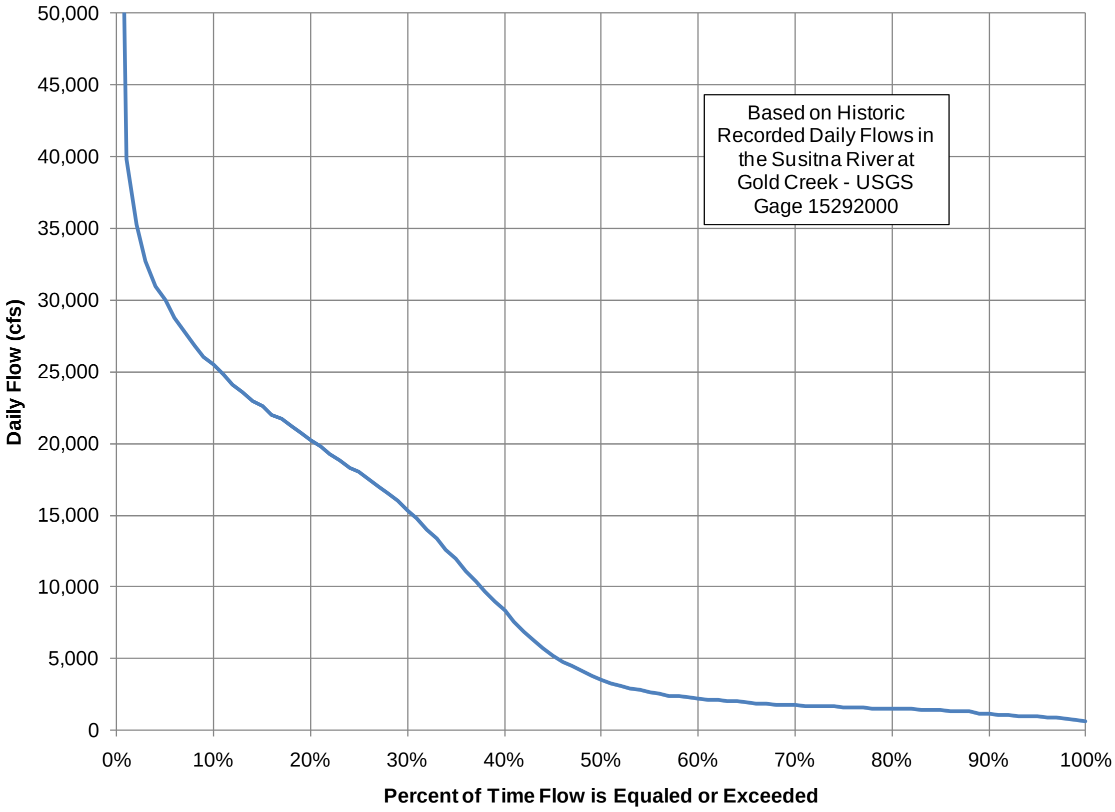


Figure 6.2-7. Flow Duration Curve for the Susitna River at Gold Creek

6.2.3. Watana Dam Site Historical Inflows

The Watana Dam site is located between USGS gage locations at Cantwell and Gold Creek. Because long-term flow data are not available for the dam site, daily flow data from Cantwell and Gold Creek were used to create a modeled historical flow data set for Watana.

For Watana Dam, the reservoir inflows are a continuous 61-year record of daily flows for Water Years 1950 through 2010. The USGS provided the basis for the continuous long-term daily flows with a Susitna River watershed record extension study (Curran 2012) that includes both recorded and correlated flows. Two of the USGS gages included in the record extension study were Susitna River at Gold Creek (USGS gage 15292000) that has a drainage area of 6,160 square miles, and Susitna River near Cantwell (USGS gage 15291500) that has a drainage area of 4,140 square miles. Watana Dam has a drainage area of 5,180 square miles, about halfway between these two USGS gages. USGS gage 15291700 Susitna River above Tsusena Creek, located two miles below the Watana Dam site, was not included in the USGS record extension study and was therefore not used in developing inflows at Watana Dam. Inflows to Watana Reservoir are based on proportioning the USGS flows based on drainage area. As shown on

Table 6.2-5, the long-term average inflow at the Watana Dam site is 8,015 cubic feet per second (cfs). The flow frequency at the Watana Dam site is presented on Table 6.2-6.

Table 6.2-5. Modeled Monthly Average Flow (cfs) at the Watana Dam Site

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1950	5,164	2,078	1,149	817	625	575	691	9,449	16,180	18,678	16,401	6,777	6,599
1951	3,113	1,037	876	763	651	587	1,295	11,586	17,169	18,646	16,234	17,550	7,495
1952	4,529	2,210	1,522	1,280	795	699	731	4,435	26,820	21,830	17,270	11,907	7,865
1953	6,697	2,825	1,360	876	651	651	1,295	15,900	22,627	16,668	17,014	12,566	8,306
1954	4,554	1,684	1,199	1,037	795	618	986	14,253	20,892	16,795	21,560	10,602	7,966
1955	4,359	2,222	1,641	1,436	1,118	876	956	7,637	24,756	22,821	21,212	11,746	8,442
1956	4,017	1,522	1,037	779	771	747	755	14,578	27,534	25,800	20,308	15,123	9,465
1957	4,720	2,458	1,719	1,360	1,199	956	956	11,328	24,990	19,270	16,950	16,339	8,551
1958	6,702	3,198	2,634	1,575	1,043	915	1,226	10,601	21,269	18,907	18,589	6,155	7,787
1959	3,900	1,725	1,209	1,157	1,043	779	997	13,194	19,282	20,688	25,674	13,943	8,691
1960	5,342	2,295	1,768	1,477	1,160	954	1,038	12,995	12,773	18,997	19,511	16,930	7,989
1961	6,362	2,418	2,169	1,971	1,404	1,449	2,133	13,638	22,784	19,841	19,479	10,148	8,701
1962	4,638	2,263	1,760	1,609	1,257	1,177	1,457	11,333	36,020	23,446	19,890	12,746	9,834
1963	5,560	2,509	1,709	1,309	1,185	884	777	15,297	20,663	28,767	21,012	10,799	9,277
1964	5,187	1,789	1,195	852	782	575	609	3,579	42,839	20,081	14,044	7,524	8,262
1965	4,759	2,368	1,070	863	773	807	1,232	10,964	21,214	23,236	17,392	16,226	8,451
1966	5,221	1,565	1,204	1,060	985	985	1,338	7,094	25,941	16,154	17,387	9,216	7,374
1967	3,270	1,202	1,122	1,102	1,031	890	850	12,556	24,715	21,989	26,106	13,670	9,096
1968	4,019	1,934	1,704	1,618	1,560	1,560	1,577	12,825	25,704	22,086	14,144	7,164	8,032
1969	3,135	1,355	754	619	608	686	1,262	9,311	13,962	14,844	7,772	4,260	4,912
1970	2,403	1,021	709	636	602	624	986	9,537	14,401	18,411	16,264	7,224	6,115
1971	3,768	2,496	1,687	1,097	777	717	814	2,857	27,613	21,125	27,445	12,190	8,588
1972	4,979	2,587	1,957	1,671	1,491	1,366	1,305	15,972	27,428	19,818	17,509	10,957	8,963
1973	3,913	1,810	1,171	956	956	795	817	6,741	22,974	15,046	16,755	7,418	6,641
1974	3,019	1,217	822	694	616	574	789	13,361	14,726	15,498	13,353	10,050	6,268
1975	3,025	1,360	1,282	1,212	1,176	1,118	1,274	12,661	26,784	22,963	14,915	13,424	8,468
1976	6,314	1,599	860	775	755	715	1,098	10,361	20,170	15,619	16,343	5,603	6,728
1977	3,132	2,133	1,932	1,464	1,294	1,199	1,344	10,439	31,366	18,902	15,870	10,367	8,311
1978	6,174	2,847	2,083	1,627	1,335	1,284	1,362	9,803	15,712	17,360	13,502	7,030	6,720
1979	3,980	2,039	1,345	1,116	1,025	956	1,158	11,429	20,429	23,937	16,892	8,823	7,812
1980	5,959	3,393	1,942	1,399	1,171	1,118	1,337	9,846	23,400	26,741	18,006	10,995	8,827
1981	6,632	3,044	1,790	1,858	1,592	1,262	1,641	14,415	16,737	27,598	30,542	11,666	9,984
1982	5,700	2,468	1,596	1,380	1,104	971	1,196	10,878	21,441	20,442	13,203	13,979	7,898
1983	5,154	2,132	1,893	1,797	1,610	1,427	1,565	11,671	20,603	18,768	20,863	11,194	8,270
1984	6,882	2,657	1,939	1,782	1,741	1,697	1,613	10,831	22,911	20,708	17,420	7,347	8,174
1985	4,257	2,384	1,799	1,479	1,273	1,298	1,517	8,440	21,226	23,295	16,433	11,700	7,966
1986	5,073	2,039	1,425	1,207	1,131	1,038	1,162	9,736	17,817	20,425	14,207	10,558	7,193
1987	10,415	2,786	1,567	1,292	1,213	1,199	1,644	10,671	19,016	24,765	17,964	10,962	8,686
1988	4,814	1,997	1,280	1,248	1,199	1,199	1,269	14,335	24,637	21,261	16,119	11,326	8,434
1989	6,262	2,429	1,602	1,602	1,441	1,441	1,715	11,292	22,163	19,554	18,497	12,695	8,433
1990	6,552	2,416	1,480	1,413	1,360	1,483	3,446	21,223	28,001	19,439	19,627	21,863	10,733
1991	5,622	1,968	1,768	1,519	1,441	1,295	1,290	4,934	21,210	17,526	15,071	10,130	7,008
1992	4,730	1,962	1,768	1,574	1,441	1,496	1,685	4,985	19,122	21,130	17,459	8,331	7,180
1993	3,546	2,200	1,634	1,493	1,404	1,311	2,042	17,252	19,421	15,957	15,458	17,589	8,310
1994	8,116	2,685	2,034	1,650	1,429	1,220	2,603	12,014	25,724	17,312	15,321	7,654	8,185
1995	3,670	2,239	1,682	1,485	1,375	1,360	2,293	14,604	20,451	21,099	15,152	15,779	8,471
1996	5,278	2,139	1,152	995	945	876	1,078	5,403	12,922	13,169	14,113	8,524	5,581
1997	2,815	1,561	1,389	1,277	1,176	1,078	1,282	7,885	15,738	20,166	20,415	11,132	7,206
1998	3,171	1,418	1,210	1,084	1,031	977	1,370	7,856	20,300	21,280	18,812	13,257	7,686
1999	6,285	2,434	1,684	1,344	1,089	917	1,087	7,662	19,026	18,902	20,946	9,273	7,603
2000	5,588	2,483	1,612	1,321	1,199	1,110	1,354	9,415	25,738	24,263	13,455	12,724	8,390
2001	6,592	2,456	1,676	1,411	1,249	1,147	1,271	7,376	25,715	18,217	18,001	8,479	7,835
2002	3,925	2,114	1,520	1,238	1,135	1,040	1,061	9,473	13,624	14,959	19,678	13,376	6,969
2003	8,973	4,380	2,084	1,324	1,802	1,207	1,750	6,553	20,125	24,139	17,450	11,110	8,452
2004	6,627	2,010	1,449	1,176	1,018	860	2,203	19,489	20,957	16,635	14,600	5,252	7,745
2005	2,663	1,387	1,288	1,149	988	832	2,112	22,327	28,455	22,160	18,157	18,893	10,079
2006	6,732	1,720	1,196	1,118	1,109	1,086	1,227	12,996	19,261	19,131	25,426	10,093	8,489
2007	8,517	2,532	1,864	1,622	1,526	1,396	1,827	14,166	16,260	17,828	15,887	11,095	7,928
2008	4,071	2,599	2,265	1,476	1,072	1,086	1,336	9,736	17,438	18,204	16,280	11,934	7,331
2009	4,494	1,238	1,037	1,106	1,037	1,070	3,701	18,949	19,105	15,977	15,233	10,242	7,812
2010	5,804	2,261	1,475	1,173	1,078	1,041	1,481	16,183	16,524	22,802	16,573	13,031	8,344
Average	5,096	2,152	1,521	1,275	1,129	1,037	1,398	11,284	21,718	20,034	17,757	11,257	8,015
Maximum	10,415	4,380	2,634	1,971	1,802	1,697	3,701	22,327	42,839	28,767	30,542	21,863	10,733
Minimum	2,403	1,021	709	619	602	574	609	2,857	12,773	13,169	7,772	4,260	4,912

Table 6.2-6. Modeled Flow (cfs) Frequency at the Watana Dam Site

% of Time Flow is Exceeded	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	2,301	2,973	1,919	19,537	40,500	72,758	49,445	66,835	39,343	29,745	7,260	3,551
1	2,031	1,935	1,697	5,838	30,947	49,630	35,464	42,415	26,363	13,075	4,265	2,825
2	2,004	1,769	1,681	4,203	28,249	41,923	32,449	35,082	24,867	11,624	3,877	2,572
3	1,929	1,694	1,604	3,228	26,424	38,456	30,822	32,017	23,030	10,706	3,643	2,334
4	1,827	1,680	1,560	2,897	25,654	35,293	29,498	28,328	21,491	10,167	3,547	2,252
5	1,791	1,602	1,522	2,659	25,005	34,128	28,709	27,058	20,623	9,749	3,400	2,170
10	1,642	1,451	1,441	2,013	22,262	30,396	26,123	23,623	17,945	8,398	2,949	1,975
15	1,602	1,441	1,360	1,692	19,510	28,170	24,690	22,279	16,112	7,479	2,744	1,916
20	1,601	1,361	1,280	1,604	17,716	26,690	23,584	20,924	14,841	6,821	2,621	1,835
25	1,521	1,320	1,201	1,519	16,419	25,202	22,646	19,897	13,811	6,301	2,509	1,768
30	1,441	1,257	1,199	1,445	14,943	24,066	21,746	19,421	12,799	5,853	2,415	1,762
35	1,396	1,199	1,153	1,374	13,975	23,138	21,031	18,813	11,999	5,392	2,346	1,709
40	1,361	1,198	1,115	1,319	12,982	22,181	20,299	18,153	11,407	5,079	2,263	1,609
45	1,309	1,185	1,042	1,280	11,846	21,359	19,783	17,626	10,698	4,734	2,177	1,589
50	1,280	1,119	1,037	1,221	10,683	20,663	19,226	16,999	10,131	4,463	2,096	1,523
55	1,257	1,118	984	1,199	9,630	19,948	18,704	16,350	9,686	4,243	2,067	1,496
60	1,199	1,040	956	1,151	7,936	19,104	18,231	15,668	9,188	3,964	1,943	1,403
65	1,165	1,037	884	1,105	6,866	18,421	17,883	14,993	8,727	3,734	1,930	1,359
70	1,118	1,021	876	1,006	5,409	17,743	17,344	14,595	8,288	3,606	1,774	1,280
75	1,060	957	807	957	4,086	16,686	16,728	14,035	7,856	3,406	1,682	1,211
80	1,037	809	779	878	3,541	15,783	16,111	13,440	7,316	3,148	1,521	1,186
85	876	773	715	798	2,783	14,859	15,661	12,801	6,840	2,916	1,393	1,118
90	795	750	644	755	2,256	13,599	14,790	12,058	5,906	2,609	1,344	981
95	756	630	595	694	1,693	12,134	13,740	10,720	4,952	2,179	1,119	875
96	684	627	587	689	1,579	11,825	13,446	10,340	4,859	2,018	1,081	796
97	656	595	587	638	1,460	11,382	13,082	9,728	4,567	1,847	1,040	769
98	641	588	555	604	1,228	10,887	12,670	9,071	4,356	1,695	1,037	737
99	618	571	533	581	1,146	10,087	12,285	6,792	3,964	1,537	924	696
100	599	476	523	557	748	8,385	10,531	4,622	3,103	1,214	798	684

The monthly flow frequency based on modeled daily flow at the Watana Dam site is presented graphically in Figure 6.2-8. Figure 6.2-9 shows the annual flow duration curve for modeled flow at the Watana Dam site.

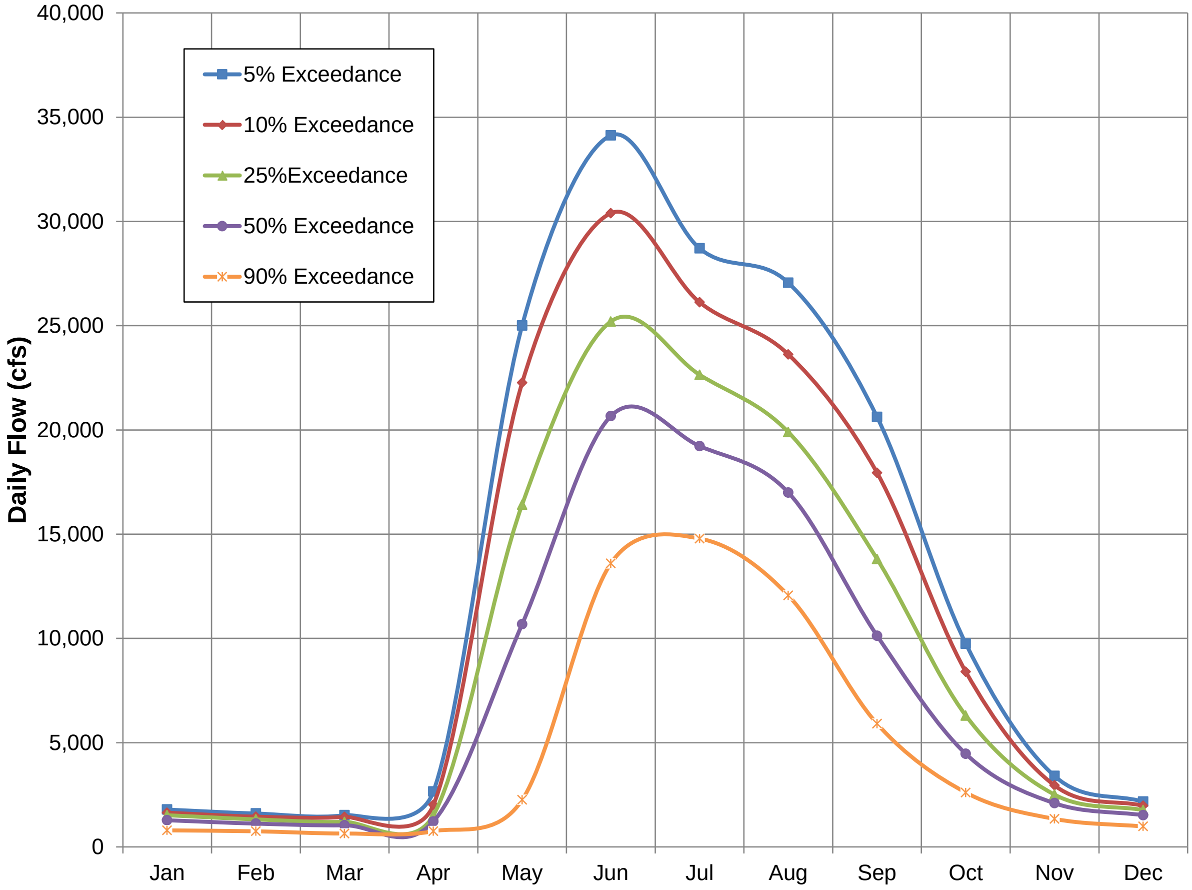


Figure 6.2-8. Modeled Susitna River Flow Frequency at Watana Dam

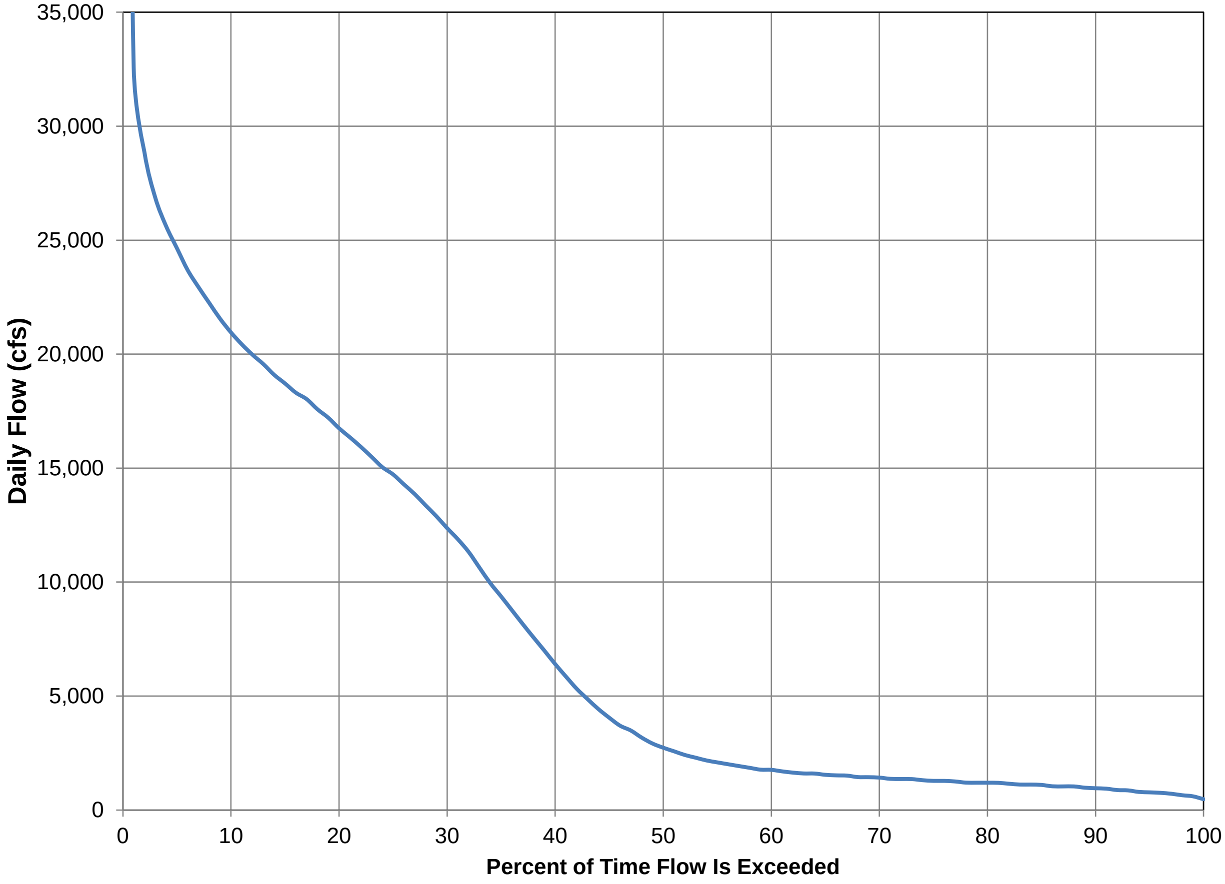


Figure 6.2-9. Modeled Susitna River Flow Duration at Watana Dam

6.2.4. Flood Frequency

Peak annual flows have been recorded by the USGS at Cantwell and at Gold Creek, as summarized in Table 6.2-7 and Table 6.2-9. Peak flow rates provided by the USGS include both average daily values and instantaneous peaks.

Peak flows for return periods up to 10,000 years were estimated for the Susitna River at Cantwell and Gold Creek. Peak flows were estimated for various return periods by fitting recorded peak flow data with a Log Pearson Type III distribution according to methods in Bulletin 17B (IACWD 1982). Estimated peak flows for the Susitna River at Cantwell and Gold Creek are presented in Table 6.2-8 and Table 6.2-10.

Table 6.2-7. Peak Annual Flows in the Susitna River at Cantwell

Date	Peak Flow (cfs)
June 23, 1961	30,400
June 15, 1962	46,800
July 18, 1963	32,000
June 08, 1964	51,200
July 13, 1965	26,000
June 06, 1966	27,000
August 14, 1967	38,800
May 22, 1968	25,000
July 15, 1969	19,300
August 01, 1970	20,500
August 10, 1971	55,000
June 17, 1972	44,700
July 29, 1980	28,500
August 14, 1981	30,900
June 21, 1982	24,100
June 04, 1983	25,800
June 16, 1984	33,400
July 03, 1985	28,200

The quality of the fit of the parameterized Log Pearson Type III distribution to the observed data is evaluated by plotting the data and the parameterized distribution together. A good fit is indicated by data points for observed annual peaks, which are close to, and randomly distributed above and below, the computed Log Pearson Type III curve. The probability values assigned to each data point, called plotting positions, and the scale of the x-axis, are selected so that the Log Pearson Type III distribution appears as a straight line when the skew value is zero.

The fitted distribution and resulting estimated peak flows at specified return periods are approximations. The ability to fit a distribution depends on the size and the variability within the sample. Confidence limits around the computed distribution curve provide a measure of the uncertainty for the predicted discharge at a specified exceedance probability.

Figure 6.2-10 and Figure 6.2-11 below show the fit Log Pearson Type III distribution as a solid line, 5 percent and 95 percent upper and lower confidence limits on the distribution as dashed lines, the observed annual peak flow data, and return periods for which peak flows were estimated in Table 6.2-9 and Table 6.2-11.

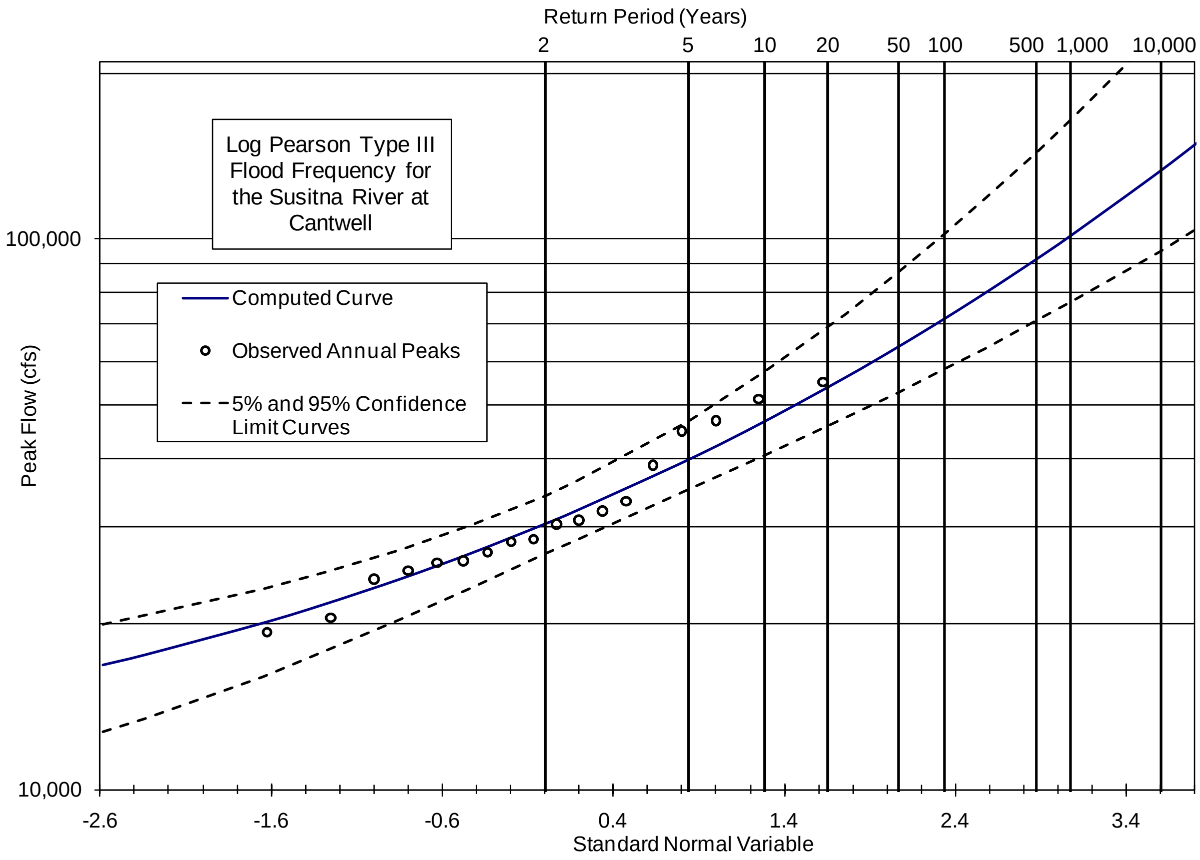


Figure 6.2-10. Log Pearson Type III Flood Frequency Plot for the Susitna River at Cantwell

Table 6.2-8. Calculated Flood Frequency for the Susitna River at Cantwell

Return Period (Years)	Flow (cfs)
2	30,300
5	39,700
10	46,600
25	56,000
50	63,600
100	71,700
200	80,200
500	91,900
1,000	101,000
10,000	133,000

Table 6.2-9. Peak Annual Flows in the Susitna River at Gold Creek

Date	Peak Flow (cfs)	Date	Peak Flow (cfs)	Date	Peak Flow (cfs)
June 21, 1950	34,000	June 30, 1970	33,400	September 15, 1990	50,300
June 8, 1951	37,400	August 10, 1971	87,400	June 23, 1991	35,300
June 17, 1952	44,700	June 17, 1972	82,600	July 19, 1992	33,300
June 7, 1953	38,400	June 16, 1973	54,100	September 3, 1993	36,300
August 4, 1954	42,400	May 29, 1974	37,200	June 22, 1994	46,600
August 26, 1955	58,100	June 3, 1975	47,300	June 25, 1995	37,800
June 9, 1956	51,700	June 12, 1976	35,700	August 26, 1996	26,100
June 8, 1957	42,200	June 15, 1977	54,300	August 1, 2001	40,200
August 3, 1958	49,600	June 23, 1978	25,000	August 23, 2002	36,200
August 25, 1959	62,300	July 16, 1979	41,300	July 28, 2003	51,700
September 13, 1960	41,900	July 29, 1980	51,900	May 8, 2004	43,400
June 23, 1961	54,000	July 12, 1981	64,900	June 19, 2005	50,200
June 15, 1962	80,600	June 21, 1982	37,900	August 20, 2006	59,800
July 18, 1963	49,000	June 3, 1983	37,300	May 28, 2007	30,800
June 7, 1964	90,700	June 17, 1984	59,100	July 30, 2008	34,400
June 28, 1965	43,600	May 28, 1985	40,400	May 5, 2009	40,400
June 6, 1966	63,600	June 18, 1986	29,100	July 22, 2010	37,400
August 15, 1967	80,200	July 31, 1987	47,300	May 29, 2011	46,300
May 22, 1968	41,800	June 16, 1988	43,600	September 21, 2012	72,000
May 25, 1969	28,400	June 15, 1989	46,800	June 1, 2013	90,500

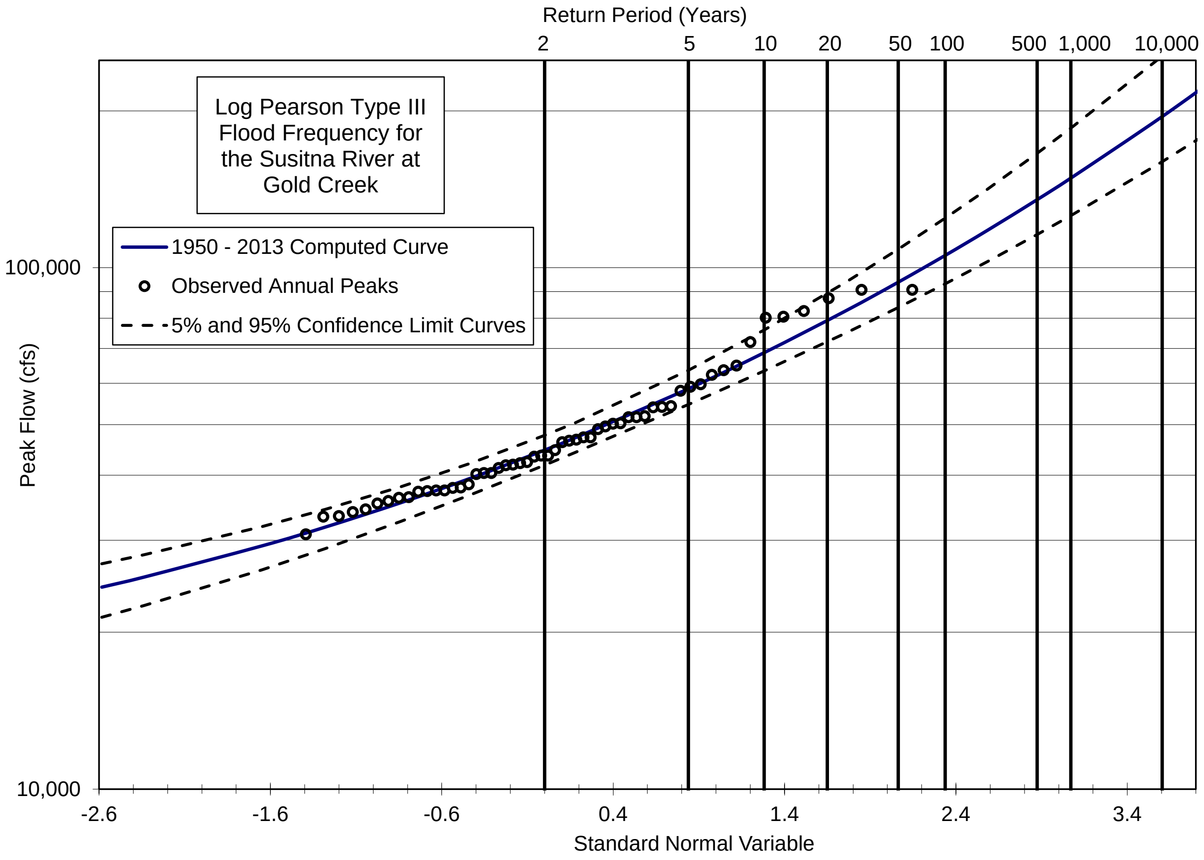


Figure 6.2-11. Log Pearson Type III Flood Frequency Plot for the Susitna River at Gold Creek

Table 6.2-10. Calculated Flood Frequency for the Susitna River at Gold Creek

Return Period (Years)	Flow (cfs)
2	44,700
5	58,600
10	68,700
25	82,700
50	93,800
100	106,000
200	118,000
500	135,000
1,000	149,000
10,000	195,000

Peak flows were estimated for return periods up to 1,000 years at the Watana Dam site by transposing peak flow analysis results at Gold Creek to Watana according to the following equation:

$$Q_{Watana} = Q_{Gold\ Creek} \times \left(\frac{A_{Watana}}{A_{Gold\ Creek}}\right)^{0.86}$$

where A is the drainage area for each site. Peak flows are frequently adjusted from a gaged to an ungaged location by the ratio of the square root of the drainage areas. A USGS publication on the *Flood Characteristics of Alaskan Streams* (Water Resources Investigations 78-129, indicates that the exponent of the drainage area ratio should be at about the selected 0.86 value. The flood frequency values for Watana Dam presented in Table 6.2-11 can also be used to develop the construction diversion floods.

Table 6.2-11. Estimated Peak Annual Flows in the Susitna River at Watana Dam

Return Period (Years)	Flow (cfs)
2	38,500
5	50,500
10	59,200
20	68,300
25	71,300
50	80,800
100	91,300
500	116,300
1,000	128,400

6.2.5. Probable Maximum Precipitation / Probable Maximum Flood

Estimates of Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) for the project are discussed in Section 9.

6.2.6. Susitna Watershed Flow Distribution

Future reservoir development and alteration of the current flow regime, including lower summer flows, higher winter flows, and dampening of peak flows, resulting from reservoir regulation may affect downstream habitat, and therefore, is of interest. The potential magnitude of this impact can be preliminarily evaluated by comparing flow in the river at the Watana Dam site to flow at downstream locations. Gages in the lower Susitna River watershed were used to determine the average monthly and annual flow distribution for the river. Figure 6.2-12 presents the annual average flow distribution, and Table 6.2-12 presents the average monthly flow at gaging stations, as a percent of the flow at Susitna Station, the furthest downstream gaging station. Flows at the Watana Dam site account for between 15 to 20 percent of the total flow in the river as measured at the Susitna Station USGS gage.

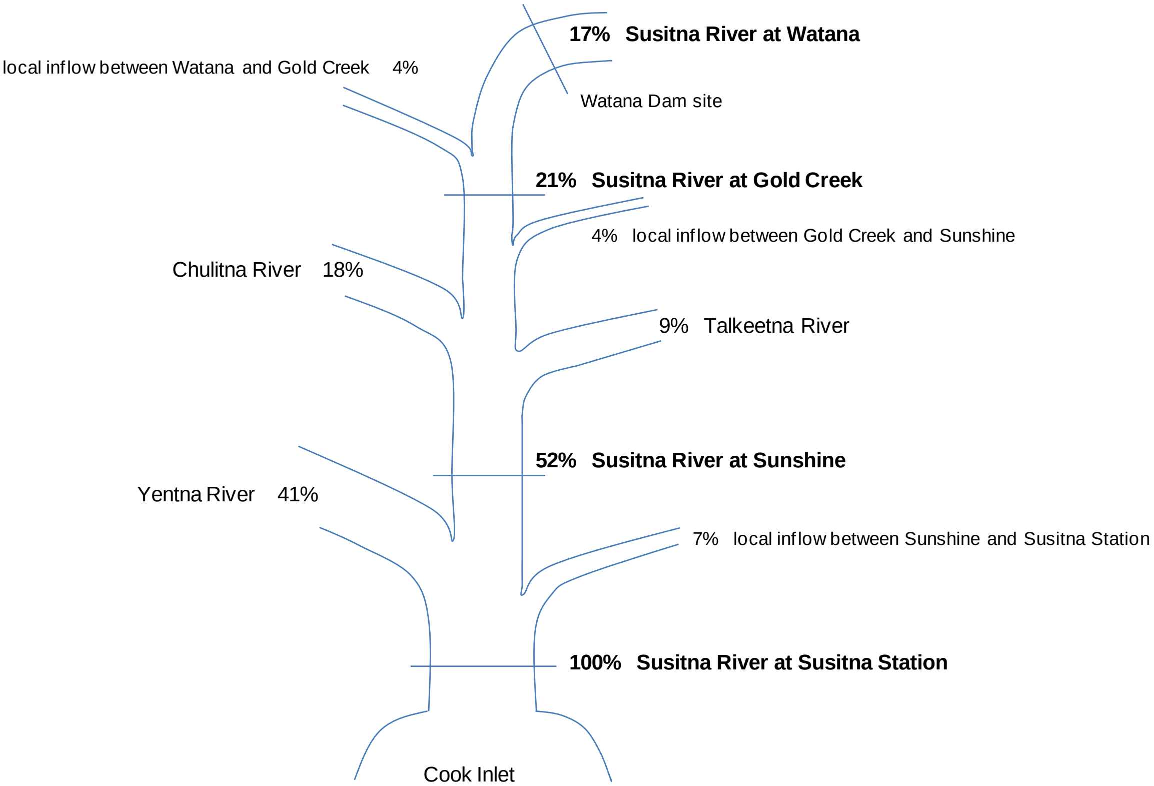


Figure 6.2-12. Average Annual Flow Distribution for the Susitna River

Table 6.2-12. Percent Contribution of Flow at Susitna River Watershed USGS Gage Stations to Flow at the Susitna Station USGS Gage

	Drainage Area (sq.mi.)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Susitna River at Watana	5,180	**20**	**19**	**21**	**18**	**20**	**20**	**18**	**16**	**15**	**14**	**15**	**18**	**17**
local inflow [a]	980	5	5	5	4	5	4	3	3	4	4	3	4	4
Susitna River at Gold Creek	6,160	**24**	**24**	**26**	**22**	**25**	**24**	**21**	**19**	**19**	**18**	**18**	**22**	**21**
Chulitna River near Talkeetna	2,570	20	16	17	14	13	17	21	20	17	16	16	19	18
Talkeetna River near Talkeetna	1,996	9	8	8	7	8	10	9	9	9	8	7	9	9
local inflow [a]	374	2	7	7	6	6	5	3	4	3	1	1	0	4
Susitna River at Sunshine	11,100	**55**	**56**	**57**	**50**	**51**	**56**	**53**	**52**	**48**	**43**	**42**	**50**	**52**
Yentna River near Susitna Station	6,180	38	38	40	45	42	44	44	44	37	34	32	35	41
local inflow [a]	2,120	6	6	3	6	6	1	3	4	15	23	26	15	7
Susitna River at Susitna Station	19,400	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

[a] Percent of flow attributed to local inflow is equal to the increase in flow between gaged locations on the Susitna River.

The percent contribution values presented in Table 6.2-12 were calculated from monthly averages for the four years of concurrent data, from 1982 to 1985, available for the Susitna River at Gold Creek, Sunshine, and Susitna Station, and for the Chulitna, Talkeetna, and Yentna Rivers. Local inflow between gaging locations in Figure 6.2-12 and Table 6.2-12 was calculated as the difference in flow between gaging stations. The drainage area contributing to local inflow was similarly assumed to be the difference in drainage area for gaged sites.

6.2.7. Hydrologic Change

Climate change can modify the expected energy from hydroelectric projects like the Susitna-Watana Project due to altered seasonal and annual reservoir inflow regimes. In comparison with projected future temperature changes, future changes in runoff patterns are considered to be significantly less certain.

Preliminary hydrology studies conducted to date indicates that there has been no historic trend in annual flows. Figure 6.2-13 plots the annual Susitna Reservoir inflows presented on Table 6.2-5. The lack of historic trend is indicated by the trendline, which is essentially horizontal. There has been an observed seasonal trend toward earlier snow and glacier melt runoff in the Susitna River basin. Analysis of the long-term record of annual average flows at Gold Creek indicates that there is no statistically significant trend.

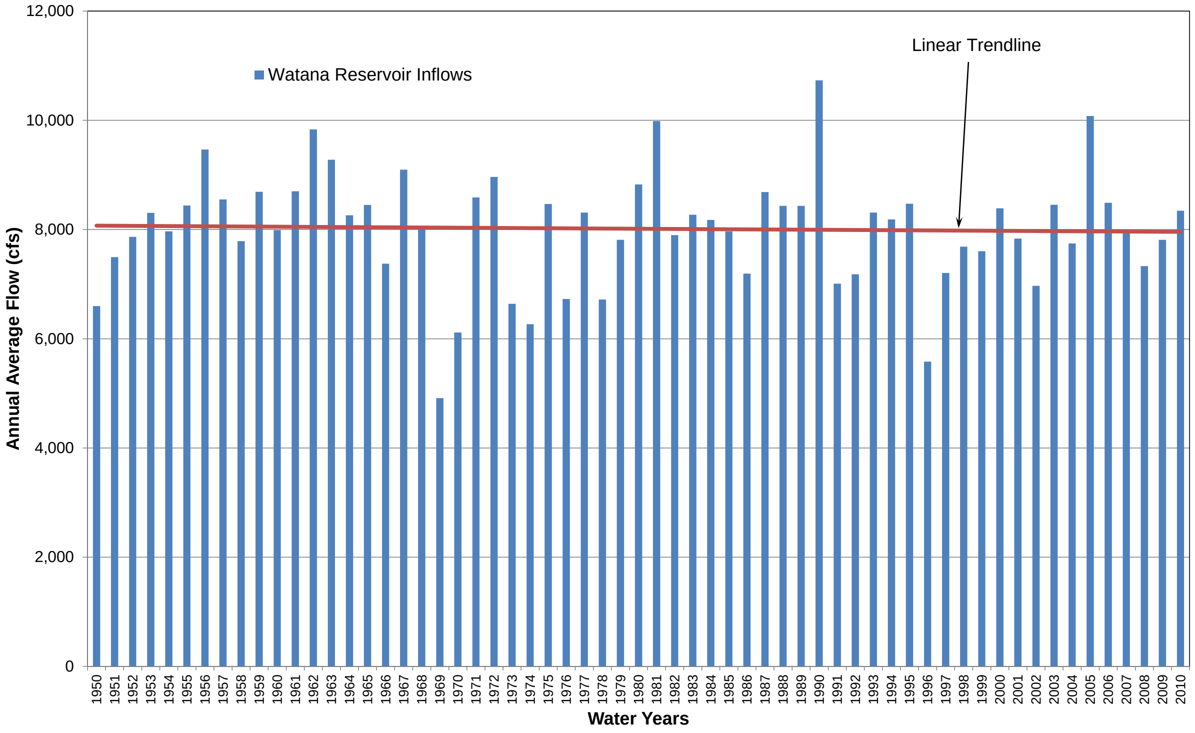


Figure 6.2-13. Watana Reservoir Annual Inflows and Trendline

Statistically significant streamflow trends are most prevalent and consistently upward during the cool season months. This is likely due to more precipitation falling as rain rather than snow, and more frequent periods of snowmelt during the cool months. The month of April, as shown on Figure 6.2-14, has the most pronounced upward trend that is also due to an earlier onset of significant snowmelt in recent years. There is a consistent trend toward decreasing runoff in the months of June, as shown in Figure 6.2-15, through August. The net effect is that the increasing flows in some months and decreasing flow in other months balance out such that total annual flows remain approximately the same. Projecting the continued historic monthly trends to the year 2050 will result in a changed monthly flow distribution. The shape and relative magnitude of projected changes in monthly flows at Watana Dam are very similar to those that are expected to occur for the snowmelt runoff dominated Columbia River (Climate Impacts Group 2009). If the seasonal shift of flow continues to occur without any change in average annual flow, it would result in a small increase of a few percent in the available winter energy from the project.

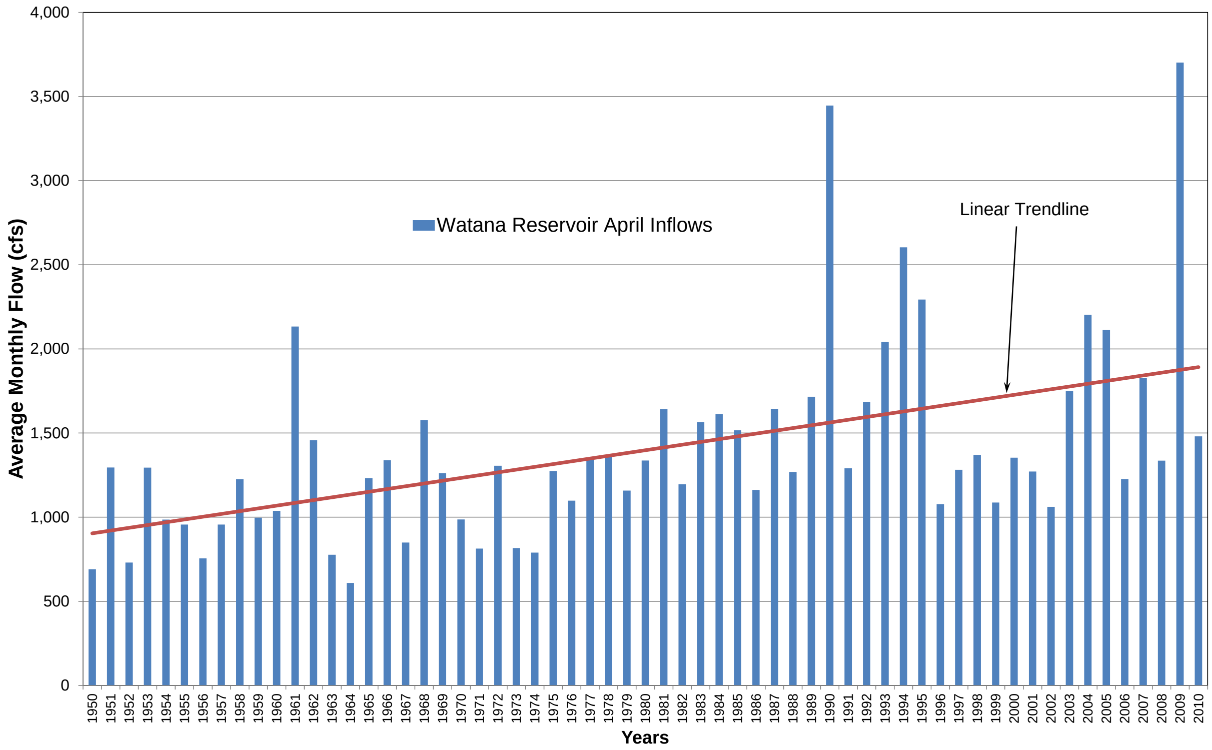


Figure 6.2-14. Example Month with Trend toward Increasing Flows – April

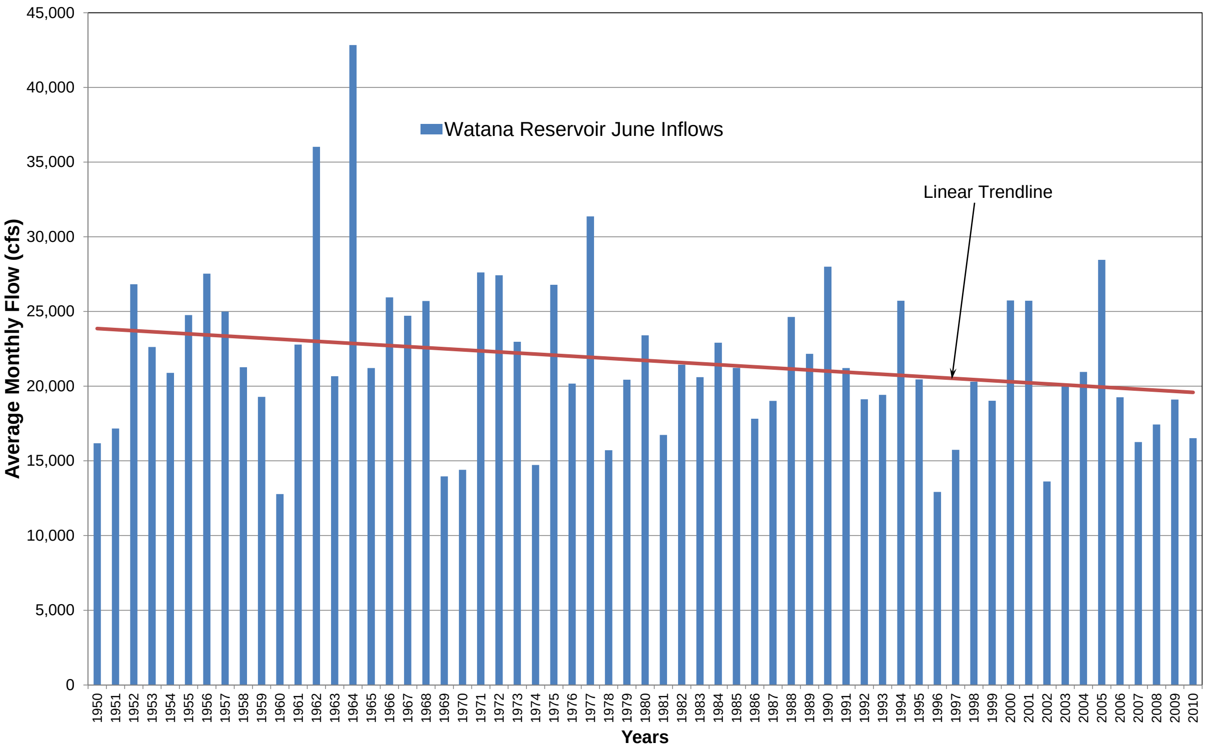


Figure 6.2-15. Example Month with Trend toward Decreasing Inflows – June

Two potentially significant additional hydrologic changes should also be noted. Over the past decades, many glaciers have been in retreat worldwide and in Alaska. Glacier volume loss has been a component of Susitna River flow that cannot be sustained indefinitely. Using downstream Susitna River data published in a recent study (Neal et al. 2010), approximately 5.8 percent of the flow near the mouth of the Susitna River could be estimated as glacier volume loss. The second potentially significant additional hydrologic change is an anticipated general trend toward increasing precipitation and runoff in the region of the Susitna watershed. Using information developed by the Intergovernmental Panel on Climate Change (IPCC 2007), average runoff in the region of the Susitna watershed is projected to increase by about 10 percent by 2050 in comparison to 1990. Because clear evidence of the opposing effects of glacier volume loss and increasing average annual runoff are not apparent in the historic runoff record, neither was included in the hydrology and power studies performed thus far.

The hydrologic change studies performed to date have been directed at determining whether the available historic hydrologic record provides a hydrologic change signal of sufficient magnitude that would warrant inclusion in the current reservoir sizing and project operation studies. Only a seasonal shift in flow timing that could result in a small increase in winter energy was found. Among the proposed studies submitted by AEA to the Federal Energy Regulatory Commission (FERC) in the Revised Study Plan is a Glacier and Runoff Changes Study. This study (performed by others) will quantitatively evaluate the effects of projected changes in precipitation and temperature on watershed hydrology over the next 100 years in the Upper Susitna River Segment basin. The Glacier and Runoff Changes Study (scheduled for completion in 2015) will be performed in greater detail than the preliminary hydrologic change studies that have been performed to date. Depending on the timing and extent to which results of the Glacier and Runoff Changes Study become available, they could be incorporated as a sensitivity analysis in the reservoir operation and power feasibility studies.

Due to substantial uncertainty in determining any potential climate change effects on extreme flood runoff, the lack of guidelines for incorporating potential climate change into the PMF studies, and due to the already conservative nature of assumptions and procedures used in determining the PMF, climate change was not explicitly included as a parameter in the PMF study.

6.3. Geology

Geologic studies and investigations have been performed to develop an understanding of the regional and site geology, hydrogeology, tectonics, and seismic conditions associated with the project. The summarized results, interpretations, and conclusions from studies are described in this section.

An understanding of the project geology forms the basis for developing the geotechnical design of the project. The geotechnical design includes characterizing the rock mass conditions and rock structure; evaluating construction materials; identifying geotechnical design and construction considerations; identifying areas of risk and uncertainty; and recommending additional investigations and studies to collect additional information. The geotechnical design is discussed further in Section 10.3 of this Feasibility Report.

6.3.1. Sources of Information

Geologic and geotechnical field investigation programs have been performed during a number of phases over the last nearly 60 years. Field work in the area was initiated by the U.S. Bureau of Reclamation (USBR) in the late 1950s, but were not followed until field programs were conducted in the 1970s and 1980s (USACE 1975, 1979; Acres 1982a, 1982b; Woodward Clyde Consultants 1980, 1982; and Harza-Ebasco 1983, 1984) and more recently (2011–2014) in support of the engineering feasibility study. Site investigations are ongoing and additional investigations are still planned for the future. These will acquire additional data to improve characterization of dam site geologic and geotechnical conditions, reduce uncertainties in interpretations, and support the feasibility study and associated FERC study plans.

6.3.1.1. Previous Studies and Investigations

To date, site investigations have focused on characterizing the dam site, quarry and borrow areas, and relict channel areas using aerial photointerpretation, geologic mapping, drilling and in situ testing, geotechnical instrumentation monitoring, test pits, and geophysical surveys. Packer testing for determining rock mass permeability was performed, and instrumentation, piezometers and thermistors were installed in most boreholes to assess hydrogeological and ground temperature conditions in the soil and bedrock. Soil and rock samples were collected for laboratory testing to assess material properties. As the studies advanced, investigations were increasingly targeted at geologic conditions in certain locations (e.g., relict channels) or assessment of the conditions associated with specific project features (e.g., thickness of alluvium in river channel along dam centerline) or proposed project structures.

The site investigations were originally developed and implemented based on a proposed 885-ft. high embankment dam with an underground powerhouse complex on the right abutment. Thus, the type of dam, areal extent of the dam footprint, and general arrangement differed from that which is proposed in the current engineering feasibility study.

6.3.1.1.1. Scope of Work of Previous Studies

Table 6.3-1 summarizes the studies that have been performed at the Watana dam site prior to the commencement of the present engineering feasibility study. For locations of the investigations at the dam site, refer to Drawings 01-01GT001, 01-01GT002, and 01-01GT005, as well as the original reports of the investigations.

Table 6.3-1. Summary of Previous Site Investigations

Dates	Lead Investigator	Studies Performed
1957 to 1958	USBR	▪ Limited geologic reconnaissance mapping.
1975	USACE	▪ 22,500 ft. of seismic refraction survey lines.
1978	USACE	▪ Geologic mapping. ▪ 47,665 ft. of seismic refraction survey lines. ▪ Rock core drilling: 28 vertical and inclined boreholes, left and right abutments, and river bottom, relict channel area. ▪ 27 test pits and 24 auger borings for materials investigations. ▪ Laboratory testing of borrow materials. ▪ Instrumentation: 10 open-well piezometers, 13 temperature logging casings installed in boreholes.
1980-1981	Acres (Alaska Power Authority)	▪ Geologic mapping including aerial reconnaissance. ▪ Reservoir area aerial photo interpretation; terrain unit mapping. ▪ Preliminary assessment of reservoir slope stability. ▪ 100,000 ft. of seismic refraction survey (includes Watana and Devil's Canyon). ▪ Soil borings and sampling, Borrow D (14), Borrow E.

Dates	Lead Investigator	Studies Performed
		▪ Rock core drilling – 8,000 ft. and geologic logging for holes in left and right abutments, and relict channel area. ▪ Packer or water pressure testing. ▪ Test pits, and bulk sampling for materials investigations. ▪ Downhole geophysical logging in two boreholes for temperature, caliper, resistivity, and sonic velocity. ▪ Laboratory testing of soils and rock material characterization and shear strength (discontinuities). ▪ Instrumentation installation and monitoring: pneumatic piezometers with thermistor strings.
1982 Supplement to 1980-1981 Study	Acres (Alaska Power Authority)	▪ Reconnaissance geologic mapping along Susitna River, Fog Creek, Deadman Creek, and Tsusena Creek, and Watana Creek. ▪ Geologic mapping at dam site including focus on potential fracture, shear, and alteration zones. Detailed mapping of abutments including "geologic features" GF1 and GF7 . ▪ Soil borings (16) – 2,300 ft. in Borrow Site D and Watana relict channel with split-spoon sampling and undisturbed sampling. Permeability testing and instrumentation installation. ▪ Reservoir mapping by aerial photo interpretation. ▪ Seismic refraction surveys: – 21,400 ft., Watana dam site abutments; – 26,000 ft., Watana relict channel/Borrow Site D; – 45,000 ft., Fog Lakes relict channel. ▪ Laboratory testing, soils – on site lab. ▪ Freeze-thaw and aggregate testing. ▪ Instrumentation installation pneumatic and stand-pipe piezometers and thermistors, and monitoring.
1983	Harza-Ebasco (Alaska Power Authority)	▪ Winter program. ▪ Geophysical surveys, river channel: – Ground penetrating radar, 8,490 ft., 14 profiles; – Seismic refraction, 8,785 ft., 10 profiles. ▪ Downhole geophysical surveys: gamma logging, 22 river borings and 8 relict channel borings. ▪ Becker drilling: – 14 boreholes and 1,927 ft. of drilling in Watana relict channel plus water well; – 43 boreholes and 3,710 ft. of drilling in the river channel. ▪ Constant head hydraulic conductivity tests in river overburden. ▪ Water pressure tests in rock. ▪ Laboratory testing of soils. ▪ Instrumentation installation, pneumatic piezometers and thermal probes, and monitoring.
1984	Harza-Ebasco (Alaska Power Authority)	▪ Geologic mapping at dam site include with focus on fracture, shear, and alteration zones; in area of geologic features GF1 and GF7. ▪ Rock core drilling, 11 boreholes and 4,370 ft. of drilling in area of GF1, downstream portal, and underground powerhouse. Evaluation of the persistence of shearing/faulting and seepage potential associated with "geologic feature" GF1, and the degree of fracturing/shearing in the downstream portal underground powerhouse areas. ▪ Constant and falling head tests in soil. ▪ Water pressure tests in rock.

Dates	Lead Investigator	Studies Performed
		▪ Downhole geophysical logging using gamma gamma, neutron, and natural gamma. ▪ Borehole alignment surveys. ▪ Laboratory testing of soils. ▪ Instrumentation installation, pneumatic and open standpipe piezometers; and monitoring. ▪ Groundwater sampling.

6.3.1.1.2. Results and Conclusions of Previous Studies

The significant findings from the geologic investigations performed during the 1970s and 1980s, pertinent to the general arrangement and dam type in this engineering feasibility report, are summarized below. In some cases, the results and conclusions below have been modified slightly or simplified from what was included in the original reports, to reflect knowledge gained from the subsequent studies. Reference should be made to the original reports for results and conclusions from the individual investigations and for additional details from each study.

1. Bedrock at the dam site is generally fresh to slightly weathered, hard to very hard, diorite to quartz diorite, with local widely spaced felsic and andesite dikes and veins. Andesite porphyry is found downstream of the dam and on the upper left abutment (the location of proposed Quarry A).

   a. The contact between the andesite and diorite is generally highly fractured, weathered, and poor rock quality. It is less than 10 ft. wide.
   b. The rock is fractured, sheared and hydrothermally altered.
   c. Beneath the river channel, bedrock ranges from altered to fresh, hard, diorite. Areas of moderately to closely fractured rock were encountered as were a few shear zones containing fine-grained gouge.
   d. Water takes from pressure testing within these zones were low.

2. Subsurface investigations indicate that rock quality is suitable for large underground facilities (right abutment).

3. Overburden on the dam abutments is generally 10 to 20 ft. thick consisting of talus, till and alluvium but locally may reach depths of 50 ft. (upstream of the dam axis on the left abutment).

4. Alluvium in the river channel consists of well-graded coarse-grained gravels, sandy gravels, and gravelly sands with cobbles and boulders ranging in thickness from 40 to 80 ft., but may be locally 140 ft. thick.

   a. The bedrock channel shape is generally symmetric about the river centerline. The channel bottom is nearly flat with the exception of two pronounced depressions upstream of the dam axis.
   b. The bedrock in the river channel ranges from altered to fresh, hard, diorite. Areas of moderately to closely fractured rock were encountered as were a few shear zones containing fine-grained gouge. Water takes from pressure testing within these zones were low.

5. Localized fracture, shear, and altered zones have been mapped within the dam site and are generally less than 10 ft. wide.

   a. Two major and two minor joint sets were identified: a) strike 320 (azimuth), dip near vertical; b) strike 045 to 080, dip near vertical; c) strike 340 to 030, dip 40° to 60° west; d) strike 080, low dip angle.
   b. Fractures are closely spaced on the surface and more widely spaced at depth. Healed fractures are common.
   c. Some fractures have clay gouge seams and slickensides.

6. No evidence of major faulting was found.

7. The groundwater table at the dam site tends to follow the topography. The groundwater in the right abutment is 40 to 280 ft. deep. Groundwater on the left abutment is complicated by permafrost, and artesian conditions were encountered below the permafrost.

8. Permafrost on the left abutment appears continuous and ranges from about 200 to 300 ft. thick. At lower elevations of the right abutment, local permafrost was encountered to depths of 50 to 60 ft. Ice was found in cores DH84-3 and DH84-8, and ice blocked hole DH84-6 after it was completed.

9. Two prominent “fracture / shear zones” were mapped in exposures upstream (GF1) and downstream of the dam site (GF7). The GF1 and GF7 features are considered unsuitable rock for construction of surface or underground works and should be avoided (they are remote from the current proposed dam location.

10. Drilling investigations of the GF1 feature above the rock outcrop encountered no evidence of major shearing or faulting that would lead to significant seepage or erosion under filled reservoir conditions. Groundwater levels in the area of GF1 are high indicating low transmissibility.

11. A relict channel was identified above the right abutment between the Susitna River and Tsusena Creek. Glacial, fluvial, and lacustrine deposits fill the channel and are as much as 450 ft. thick (El. 1800 ft.). The average hydraulic gradient from maximum pool (El. 2185 ft.) to Tsusena Creek is about nine percent.

12. Potentially suitable borrow materials were identified near the dam site for aggregates (Quarry A, B), rockfill (Borrow E, I, J), filters, and impervious (Borrow D, H) materials.

6.3.1.2. Investigations and Studies for this Feasibility Report

Site investigations and studies were performed from 2011 to 2014 to support the development of the engineering feasibility and licensing studies. They supplemented the earlier geologic investigations and interpretations conducted in the 1970s and 1980s and included evaluation of previous results and interpretations. The latest site investigations and studies are incomplete and this report therefore reflects only the information acquired prior to the release of this report. Additional investigations and studies are planned – in particular (but not limited to) the excavation of adits, together with associated in situ testing.

The most significant difference between the previous engineering arrangements and that documented in this report is that the current proposed arrangement includes a curved RCC dam instead of a zoned embankment dam as previously proposed. The engineering feasibility study of the new arrangement required that all available geologic information and interpretations be re-examined with emphasis given to foundation characterization and the associated structural properties of the bedrock.

Investigations included re-examination and improved characterization of previously identified geologic structures in the dam site area that could conceivably influence dam type selection and design of rigid concrete structures. They also included characterizing a new potential construction material source, Quarry M, and performing a site-specific seismic hazard analysis for the project to update previous studies performed by Woodward Clyde Consultants in the 1980s. Site investigation methods included analysis of LiDAR data, geologic mapping, drilling and in situ testing, instrumentation installation and monitoring, and laboratory testing. In addition, analysis of LiDAR data and geologic mapping were performed on a regional basis, including the reservoir area, to support both the site-specific seismic hazard analysis and the soils and geological studies required for FERC licensing. For locations of the drilling and mapping investigations at the dam site area, reference should be made to Drawing 01-01GT001 and Drawing 01-01GT002.

As part of the latest site investigations program, new methods not available in the 1980s were used to collect additional types of information and improve interpretations. Newly acquired LiDAR data (Drawing 01-01GT002) were used to create detailed ground surface maps that enabled geomorphic evaluations and facilitated more focused geologic mapping. For the drilling programs, downhole televiewer logging was used to supplement available information on discontinuity orientations. Additionally, geotechnical instrumentation, which included data loggers, was installed to measure and record piezometric levels and ground temperatures to assess hydrogeological and ground temperature (permafrost) conditions. Laboratory testing was also conducted focusing on the engineering properties of the rock and aggregate sources.

Table 6.3-2 summarizes the studies performed between 2011 and 2014 at the Watana dam site in support of this feasibility study. The Geotechnical Data Report is attached as Appendix B1 and contains details of the geotechnical investigations performed in support of this engineering feasibility study.

Table 6.3-2. Summary of 2011 to 2014 Site Investigations

Dates	Studies Performed
2011	▪ Rock core drilling, 3 boreholes, 600 ft. at Quarry A. ▪ Water pressure testing in rock. ▪ Instrumentation installation, open standpipe piezometers. ▪ Laboratory testing and petrographic analysis of rock core and bulk samples. ▪ Microseismic monitoring stations established (4).
2012	▪ Geologic mapping of the dam site, Quarry M and surrounding areas using LiDAR base map. ▪ Rock core drilling, 8 boreholes, 2,355 ft. at the dam site. ▪ Water pressure testing in rock. ▪ Downhole optical and acoustic televiewer logging in 4 boreholes. ▪ Instrumentation installation for groundwater levels and ground temperature. Instrumentation monitoring. ▪ Laboratory testing and petrographic analysis of rock core samples; engineering properties of rock and construction aggregates. ▪ LiDAR digital imagery evaluation for updating terrain unit maps, lineament analysis, and preliminary assessment of reservoir area slope conditions. ▪ Microseismic monitoring stations expanded (total 8).
2014	▪ Geologic mapping of the dam site and surrounding areas. ▪ Rock core drilling, 4 boreholes, 1,750 ft. of drilling at the dam site. ▪ Water pressure testing in rock. ▪ Continuous downhole optical and acoustic televiewer logging in all boreholes. ▪ Laboratory testing of rock core samples. ▪ Instrumentation installation for groundwater levels and ground temperature. Instrumentation monitoring. ▪ Crustal seismic source evaluation. ▪ Microseismic station network monitoring.

6.3.1.2.1. 2012 Drilling and Testing

The 2012 drilling and testing program focused on the evaluation of conditions in the dam footprint and Quarry M. Eight boreholes were cored using HQ3-wireline methods. Three boreholes were advanced in the left abutment, two boreholes were advanced in the right abutment and three boreholes were advanced in Quarry M. Water pressure testing was conducted at regular intervals in each of the boreholes. Selected boreholes were surveyed using either downhole optical or acoustic televiewer logging. Geotechnical instrumentation including piezometers and thermistors were installed in selected boreholes. Laboratory testing was conducted on selected rock core samples and bulk surface samples collected from the talus slopes on the left abutment.

Because prior to 2012, few explorations had been conducted in the left abutment of the dam footprint, cored drill holes were made at DH12-1, DH12-2 and DH12-8 to improve the understanding of the left side. DH12-1 and DH12-2 were drilled in the upper portion of the left abutment to depths of about 300 and 200 ft., respectively. Both of these drill holes were inclined at approximately 20 degrees from vertical to the northeast. Rock conditions encountered in DH12-1 and DH12-2 were observed to consist primarily of fresh, strong to very strong diorite with occasional zones of weathering. Weathered zones were generally five feet thick or less, with highly weathered portions limited to less than one to two feet thick. DH12-8, oriented to the south and 30 degrees from vertical, was advanced to approximately 350 ft. in the lower left abutment near river level. DH12-8 also encountered mostly fresh, strong to very strong, diorite with weathered zones approximately five feet wide or less.

Previous interpretations of the earlier site investigations postulated the presence of multiple geologic features (GFs) that transect the dam footprint. Therefore, new drill holes DH12-3 and DH12-4 targeted geologic features GF4A and GF4B (per Acres nomenclature) and GF5, respectively. Drill hole DH12-3 was drilled to a depth of about 400 ft. in the area of feature GF4B. DH12-3 trends southwest and is inclined 30 degrees from vertical. To investigate GF5, DH12-4 was advanced 350 ft. trending west-southwest and 20 degrees from vertical. Both DH12-3 and DH12-4 encountered closely spaced discontinuities over large portions of these holes. Discontinuities were commonly stained with iron oxide nearer to the surface and tended to be healed at depth. While zones of highly weathered rock and shear zones were encountered in these boreholes, they were generally three to five feet thick or less. Prominent, wide shear zones or thick zones of heavily altered rock were absent in the holes.

Boreholes DH12-5, DH12-6 and DH12-7 were drilled within the proposed Quarry M, located upstream of the left abutment, specifically to verify the suitability of the area as a source for the production of concrete aggregate. DH12-5 was drilled to a depth of about 250 ft. and inclined

20 degrees from vertical toward the northwest. In general, DH12-5 encountered fresh, strong to very strong diorite over the length of the hole. Localized zones of moderately weathered rock were observed to be typically three to four feet wide or less. DH12-6 was drilled near the mapped location of GF4 (Acres 1982a; 1982b), on the upper south bank. This hole was advanced approximately 350 ft. and inclined 10 degrees from vertical toward the east. DH12-6 encountered closely fractured rock over significant portions of the hole. A large percentage of this core is moderately to slightly weathered; however, several zones of highly to completely weathered rock up to 14 ft. thick (apparent thickness) were encountered. DH12-7 was drilled near the mapped locations of GF2 and GF3. This borehole was drilled to a depth of 150 ft. and was inclined 10 degrees from vertical toward the east-northeast. DH12-7 encountered significant zones of completely or highly weathered rock up to approximately 18 ft. wide (apparent width). A 5-foot wide (apparent width) shear zone was noted at a depth of 118.5 ft.

Lugeon values were determined over regular intervals in the 2012 drilling program using a five-step water pressure test procedure in accordance with the recommendations presented by Houlsby (1976). Test results varied widely from zero to greater than 100 Lugeons (1 Lugeon ≈ $1.3\text{x}10^{-5}$ cm/sec for N- and H- sized holes). Hydraulic conductivity was typically highest near the ground surface where open discontinuities were encountered with greater frequency and decreased with depth.

Downhole televiewer surveys were conducted in drill holes DH12-3, DH12-4, DH12-6, and DH12-8. Optical televiewers were used to survey DH12-3 and DH12-4 since groundwater levels were relatively deep. An acoustic televiewer was used to survey DH12-6 and DH12-8 due to cloudy water in the hole, which made conditions for optical methods less suitable. The televiewer surveys were also limited in some places by unstable hole conditions, particularly in DH12-6 where caving conditions were encountered, limiting the survey between the depths of 289.5 ft. and 347 ft. Unstable hole conditions also precluded televiewer surveys above a depth of 62 ft. in DH12-3.

New geotechnical instrumentation was installed in each new borehole. Vibrating wire piezometers were installed in DH12-1 through DH12-6 and DH12-8. Thermistor strings and temperature acquisition cables were installed in all holes with the exception of DH12-5 and DH12-7. Piezometers and thermistor strings are equipped with data loggers programed to record measurements at regular intervals. A 1½-inch diameter PVC standpipe piezometer was installed in DH12-7.

The 2012 laboratory testing program consisted of tests to measure rock strength, seismic modulus, and properties of aggregates. Rock strength tests included 11 uniaxial compression strength (UCS) tests, nine point load index tests, five Brazilian tensile strength tests, and five direct shear tests of discontinuities. The testing indicated that fresh to slightly weathered rock has an average UCS of over 26,500 psi. One test conducted on moderately weathered rock resulted in a UCS of about 7,600 psi. Brazilian tensile strength tests were conducted on slightly weathered to fresh samples, yielding an average value of approximately 2,200 psi. Direct shear strength tests were conducted on various discontinuities including iron-stained joints, calcite-coated joints, and saw-cut surfaces.

6.3.1.2.2. 2014 Drilling and Testing

The 2014 exploration and testing program included investigation of conditions beneath the bed of the Susitna River and previously mapped geologic features on the right abutment. Drill holes DH14-9b and DH14-10 were drilled beneath the Susitna River in opposing directions to explore the presence/absence of any significant geologic structure in the river bed parallel to the Susitna River at the dam site. Drill holes DH14-11and DH14-12 targeted postulated geologic features GF4 and GF5 (per Acres 1982 terminology) on the lower to middle sections of the right abutment. All holes were drilled using HQ3-wireline drilling methods. Water pressure testing and downhole logging were performed in all holes, and a laboratory testing program was completed.

It had been postulated that a significant geologic feature could potentially be present below the Susitna River at the location of the dam. If present, such a feature would present a significant engineering challenge to the project, and could conceivably require re-examination of the choice of dam type. Combined, holes DH14-9b and DH14-10 were drilled across the width of the river in opposing directions with the intent intersecting any significant geologic structure, if present. DH14-9b was drilled to a depth of 683 ft. from the right abutment inclined 30 degrees from vertical toward the south. DH14-10, located approximately 300 downstream of the dam axis on the southern bank of the river, was drilled to a depth of 692 ft. and inclined 30 degrees from vertical toward the north. In general, DH14-9b and DH14-10 encountered slightly weathered, strong to very strong diorite with occasional zones of alteration. Alteration zones were typically comprised of moderately weathered, medium strong diorite and were about five feet thick or less; however, some altered diorite zones were up to about 14 ft. thick. While small shears with one to two inches of clay gouge were encountered, no significant geologic structures were observed in either hole. This provides subsurface evidence in support of interpretations made from geologic mapping that the existence of a through-going fault in the thalweg of the river at the dam site is improbable.

Drill hole DH14-11, located about 230 ft. downstream of DH12-4, was drilled in a northeast direction to further improve the understanding of conditions within the dam footprint along the postulated geologic feature GF5. DH14-11 was drilled to a depth of approximately 197 ft. and was inclined 30 degrees from vertical toward the northeast. Rock encountered in DH14-11 primarily consisted of fresh to slightly weathered, strong to very strong diorite. Zones of closely fractured rock were common throughout much of the borehole. These fractured zones were more common in the upper portions of the hole. Altered diorite zones two to five feet thick were encountered in the upper 105 ft. of the exploration. Three zones of completely to highly weathered rock where encountered that ranged from about an inch to two feet thick.

Drill hole DH14-12 targeted a fracture and shear zone previously mapped by Acres (1982). This feature was mapped parallel to GF5 and approximately 300 ft. downstream of the dam axis on the right abutment. DH14-12 was drilled to a depth of 175 ft. and was inclined 30 degrees from vertical toward the northeast. Bedrock encountered in DH14-12 typically consisted of slightly weathered, strong diorite with occasional zones of altered diorite. Approximately six zones of altered diorite were encountered ranging in thickness from 0.5 to 11 ft. (apparent thickness). A shear zone having 1-inch of gouge was encountered at a depth of about 76 ft. A second shear zone containing about 20 inches of gouge was encountered at a depth of 110.0 ft. within an approximately 5-foot wide zone of altered rock.

Lugeon values were determined over regular intervals in the 2014 boreholes using a five-step water pressure test procedure in accordance with the recommendations presented by Houlsby (1976). Test results varied widely from zero to about 70 Lugeons. Tests typically indicated very low to very high permeability, with few intermediate test results. High test values commonly coincided with open jointing or fracture zones near the ground surface, or discrete fractures or fracture zones at depth. Test values indicated that permeability generally decreases with depth.

Each of the four 2014 boreholes were surveyed using both optical and acoustic downhole televiewers. Because the groundwater surface was encountered above the bedrock elevation in explorations DH14-9b and DH14-10, both were surveyed over their entire length using both optical and acoustic televiewers. Optical televiewer surveys were conducted over the entire length of DH14-11 and DH14-12; however, acoustic televiewer surveys were limited in these two holes by relatively deep groundwater levels. Accordingly, acoustic surveys were conducted below a depth of approximately 34 ft. in DH14-11 and about 95 ft. in DH14-12.

The 2014 laboratory testing consisted of UCS, Brazilian tensile strength, and direct shear testing. In contrast to the 2012 program, the 2014 program focused on testing samples of poor, weathered, or altered character. Eight UCS tests were conducted. Tests conducted on moderately weathered rock had an average UCS of about 9,500 psi. Two tests conducted on slightly weathered to fresh rock had an average UCS of about 19,000 psi. One test conducted on moderately to highly weathered rock had UCS of about 1,600 psi. Brazilian tensile strength tests were conducted on two moderately weathered samples, which had strengths of about 420 and

860 psi. Eight direct shear strength tests were conducted on various discontinuities including calcite coated joints or joints with slickensides.

6.3.1.2.3. Regional Mapping

Regional mapping was done to develop a better understanding of the geologic and structural relationships in the area at the dam site and surrounding areas and to evaluate the potential impacts of local faulting on the dam and other critical structures.

Existing regional geologic mapping depicting both the dam site and the general vicinity within 5 to 10 miles has been developed by Csejtey et al. (1978), Acres (1982b), and Wilson et al. (2009). The existing maps were developed at a variety of scales, using various methods and level of detail, and for multiple purposes; therefore, there is inconsistency in the local completeness and accuracy of geologic mapping which has led to several areas of general disagreement across the maps. The emphasis of most prior mapping in the region was directed to reconnaissance level bedrock framework and mineral resource evaluations. Along the Susitna River, much of Wilson’s (2009) map is a compilation of Csejtey’s (1978) work, and several prominent outcrops in the area were not recognized. Previous dam site-specific geologic mapping was, by definition, highly focused and of limited aerial extent.

Geologic observations made during this recent study included examination of prominent outcrops that seem to have been un-recognized in previous mapping. The regional mapping is intended to indicate confirmation or disagreement with existing mapping, and to provide a level of transparency as to where outcrops are present or absent, and from which locations outcrop-based interpretations are possible.

Field investigations identified and inspected a number of exposures to collect structural (strike and dip) information, and to understand the distribution and deformation of rocks in the site area and vicinity. The data was collected along an east-west transect along the Susitna River, and a north-south transect along Watana Creek. Bedding attitudes were collected using a Brunton compass set to 19 degrees declination and GPS-enabled ruggedized laptop for location. Additional bedding attitude data were compiled from existing data sources including Army Corps of Engineers (USACE) (1979), Acres (1982b) and Woodward Clyde Consultants (1982).

Strike and dip data were collected from outcrop locations and a small number of observation points were made from the air. Long extents of the south side of the Susitna River had no outcrop or exposures because of vegetation and soil cover. Good exposures on the south side of the Susitna River generally were located at the confluence of tributary creeks, and seemingly erosion-resistant Cretaceous rocks. However, the field traverses along the Susitna River and

Watana Creek provides somewhat limited structural insight because they capture only a one-dimensional traverse characterization of a three-dimensional volume.

6.3.1.2.4. Recent Dam Site Geologic Mapping

Mapping was performed at the dam site to evaluate and update the interpretations from earlier studies, to fill information gaps, and to improve characterization of bedrock conditions at the dam site – to a level that could support the assumptions made during the structural analysis of the proposed dam.

The original geologic mapping was performed at the dam site beginning in the late 1970s and continued during the 1980s, during which time the distribution of geologic materials was defined and the orientations and character of rock discontinuities were measured at outcrops. In addition, the mapping efforts in the dam site area, combined with information from the contemporaneous drilling and geophysical explorations, identified eight geologic features (GF1 to GF8).

The objective of the mapping at the dam site has been to evaluate the previous work and to update specifically the characterization of the geologic features identified by Acres (1982a, 1982b) and the geologic interpretation of the site that was developed during the earlier studies. In addition, the recent mapping efforts attempted to fill information gaps identified during previous studies, or further define structural features that affect the design of a concrete gravity structure. Specifically, the objectives of the dam site mapping included:

1. Interpret the site geology and structure using the newly acquired LiDAR digital imagery.
2. Field locate geologic features previously identified as well as new features, most particularly those that may be encountered in the dam foundation. Update the locations of these features using new topographic (LiDAR) mapping and sections as well as the geologic descriptions.
3. Identify rock outcrops throughout the dam site area and provide the following at each outcrop:
    a. Rock type, weathering/alteration, strength
    b. Orientations of rock discontinuities.
    c. Descriptions of discontinuities in accordance with criteria established by the International Society of Rock Mechanics (Barton and Choubey 1977). Assessments of discontinuities include persistence, aperture, fillings and stains, surface shape and roughness, larger scale roughness (Joint Roughness Coefficient [JRC]), and spacing.

   d. Estimate the Geologic Strength Index (GSI) of the rock mass in outcrop considering rock structure and joint surface conditions.
   e. Estimate the typical size of blocks bound by the joint sets.

4. Evaluate discrepancies between orientations of discontinuities in outcrop and downhole logs. Downhole televiewer logging performed in 2012 and 2014 indicated an overabundance of shallow dipping joints compared with observations made during geologic mapping of rock outcrops. Mapping indicated the dominant geologic structure is steeply inclined joints trending in the northwest-southeast and northeast-southwest directions, which is consistent with the interpretations from the 1980s.

5. Identify rock types in outcrops and update locations of geologic contacts as appropriate.

Geologic mapping of rock outcrops was performed on the north and south banks (right and left abutments) of the river beginning about 2,000 ft. upstream of the dam axis near geologic feature GF1 and extended to about 1,500 ft. downstream of the dam near GF7. Measurements and observations of structure and geologic features were made at outcrops distributed on both banks of the river; however, greater effort was focused on geologic structure anticipated to appear within the dam foundation.

Navigating was managed using GPS (Trimble GEO7X) equipped with ArcGIS preloaded with maps that included topography, slopes angles, geologic maps, etc., to facilitate navigation and interpretations. The locations of outcrops (designated as OC 1 to OC 118), observation points (designated as BS 1 to BS 37), and geologic structures were recorded by GPS and numbered sequentially are shown on Drawing 01-01GT002.

To obtain representative measurements, outcrops distributed throughout the site and on both abutments up to the proposed reservoir rim were mapped. At each outcrop, the orientations of the prominent joint sets were measured and characterized following ISRM criteria. In addition, the rock type, weathering or alteration condition, color, strength, block dimensions, and an estimate of the GSI were recorded. This information is used to estimate the engineering properties of the joints and rock mass needed for design analyses.

Observations (BS 1 to BS 37) were recorded at locations of geologic interest (e.g., gullies, shear zones) that did not necessitate or allow for measurement of all joints or a full assessment of the rock outcrop.

Field measurements were recorded on data sheets and field notebooks, which were compiled into spreadsheets. Rock discontinuity data were input into DIPS (Rocscience, Inc.) software to identify orientations of the prominent joint sets. After identifying which set each joint belonged to, the joints were grouped so that the ISRM criteria could be developed for each joint set.

The geologic features and structure that had been mapped during previous studies were re mapped and characterized. Many of the geologic features and prominent structures are associated with topographic features such as gullies instead of being observed directly in outcrop. In the absence of direct observation, the surface and geologic conditions were described and measurements of discontinuities were made at the nearest outcrops to constrain the possible location and orientation of the structure. The mapping information, combined with information from the recent drilling investigations and downhole logging, has been combined to constrain the locations of prominent geologic structures and to update the descriptions of geologic features.

6.3.2. Regional Geologic Setting

6.3.2.1. Physiographic Provinces

The Project is located in the south-central region of Alaska where three principal physiographic provinces exist: the Copper River Basin, the Susitna Basin, and the Talkeetna Mountains as shown in Figure 6.3-1. The Copper River Basin is an intermontane basin surrounded by the Alaska, Talkeetna, Chugach, and Wrangell mountains. It is characterized by flat-lying to hummocky topography and is overlain by extensive glacial, glacio-fluvial, and glacial-lacustrine deposits. The Susitna Basin is a north-south trending feature and is the principal deposition center for alluvium transported by numerous major river systems originating in the surrounding mountains. The Susitna River source is in the ranges north of the Copper River Basin and it flows from there westward through the northwestern Copper River Basin and through the Talkeetna Mountains in a deeply incised canyon. Downstream, sediments from the Susitna River contribute to alluvial deposition in the Lower Susitna Basin. The dam site is located within the Talkeetna Mountains province. The Talkeetna Mountains are an elevated area that lies between the Copper River and Susitna Basins, with glaciated peaks between 6,500 ft. and 9,800 ft. in elevation as shown in Figure 6.3-1.

Figure 6.3-1. Major Physiographic Provinces

6.3.2.2. Regional Tectonic Setting and History

The tectonic evolution of south-central Alaska is defined by plate convergence, with Mesozoic (i.e., Jurassic-Cretaceous) collisions of the Wrangellia composite terrane followed by later Cenozoic collision of the Yakutat terrane. The Wrangellia terrane generally consists of late Triassic flood basalts; the Peninsular terrane consists of Jurassic arc volcanics, metasediments, and plutons. The two terranes originated well south (~30° latitude) of their current position. Together, the Wrangellia and Peninsular terranes are referred to as the Wrangellia composite terrane (Figure 6.3-2 and Figure 6.3-3), and likely were sutured together in the Late Jurassic (Csejtey et al. 1978). The composite terrane, in turn, was accreted onto North America in the mid- to late-Cretaceous when the southern plate margin of North America was roughly along the position of the Denali fault. Between the converging terrane and North America was a marine basin (Kahiltna basin) that accumulated Jurassic-Cretaceous sedimentation shed from the southeast direction (Kalbas et al. 2007). The northeast striking Talkeetna fault is the principal eastern terrane-bounding structure in the region, separating the Jurassic-Cretaceous sediments (i.e., Kahiltna assemblage deposits) on the northwest from the Wrangellia terrane metavolcanics to the southeast (Figure 6.3-2 and Figure 6.3-3). Thus, in terms of terrane accretion, the region of crust south of the Denali fault and northeast of the Talkeetna fault is a large suture zone that narrows to the east, reflecting oblique plate convergence and the long-term closing of the Kahiltna basin. The rocks that formed in the Kahiltna Basin have been uplifted through the Cenozoic, making up much of the Alaska Range and northwestern Talkeetna Mountains and forming a structural inversion. Essentially, formerly low-lying areas (i.e., basins) have now become high topography (i.e. mountains) as a result of plate convergence and mountain-building uplift along generally northeast trending folds and thrust faults.

Jurassic plutonism from melting of the oceanic subducting slab formed the batholitic complex of the southeastern Talkeetna Mountains (Nelson 2009) by intruding into the Peninsular terrane (Figure 6.3-3, map unit TKg). Subsequent uplift initiated northeast-directed sedimentation within proto-Kahiltna Basin in what is now the northeastern Talkeetna Mountains (Kalbas et al. 2007). Kahiltna Basin sediments continued to accumulate during the Cretaceous as westward sediment transport on fluvial, shallow marine and submarine fan depositional environments. The Kahiltna assemblage is about 3 to 5 km thick, and consists of turbidite sequences, chert, mudstone, sandstone, and greywackes that comprise eight distinct lithofacies (Kalbas et al. 2007). Progression in the understanding of the relationships between the terrane units and tectonics has allowed a deeper understanding about the Kahiltna Basin rocks and their significance as a recorder of long-term tectonic deformation, in contrast to previous interpretations that generalized the complex stratigraphic unit as “argillite” or “flysch”.

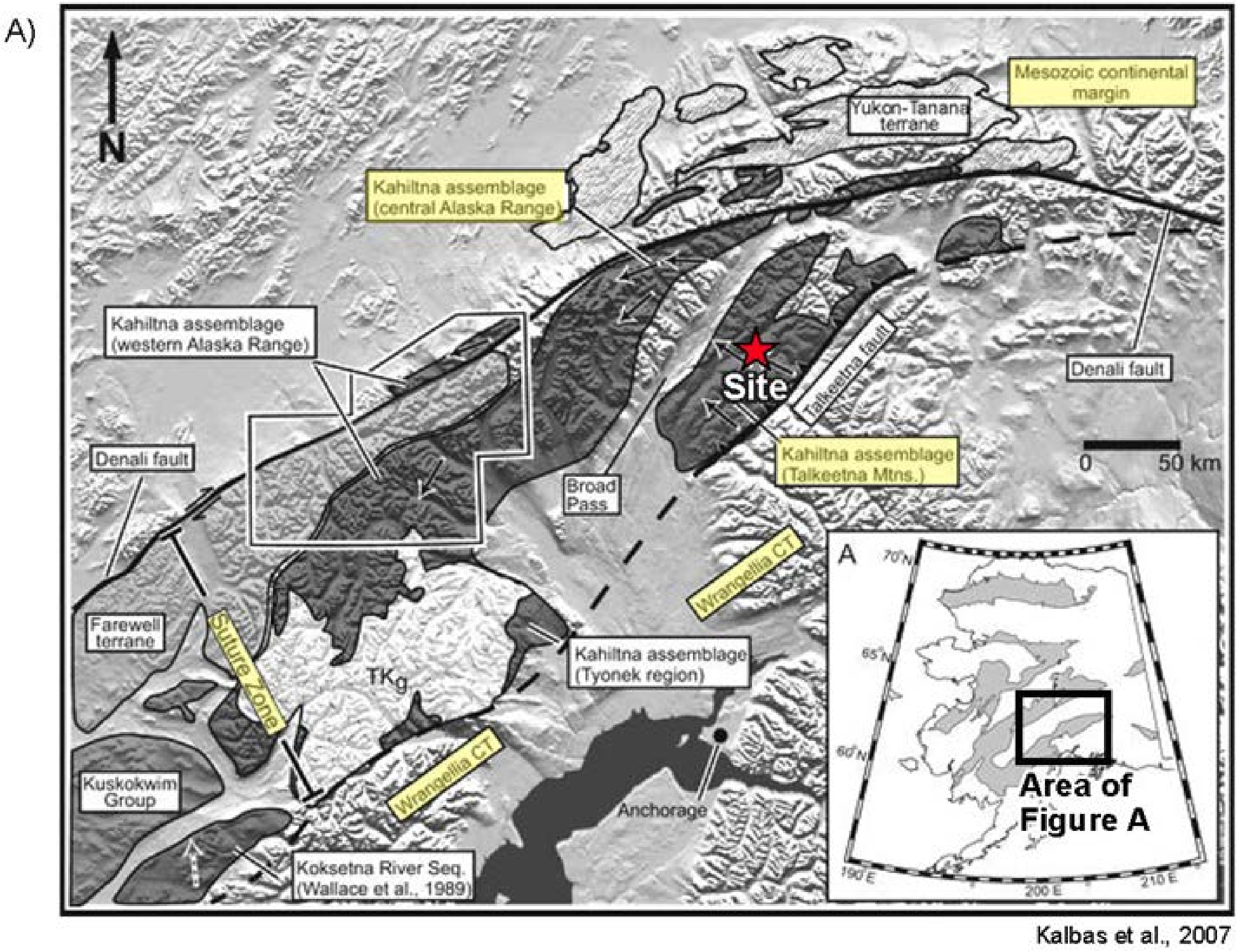
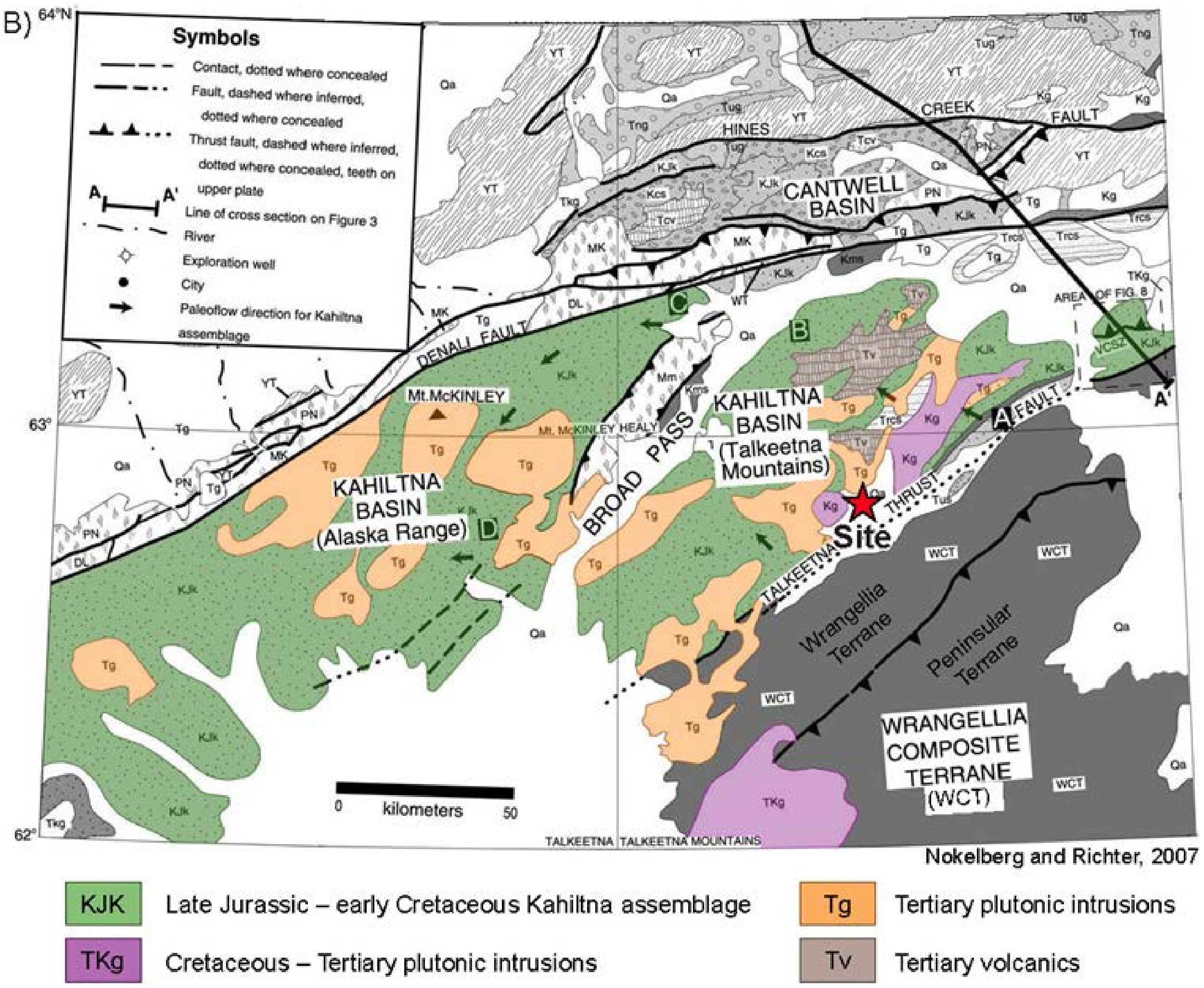


Figure 6.3-2. Regional Tectonic Terranes and Basins – Part 1 of 2 (Fugro 2014)



Nokelberg and Richter, 2007

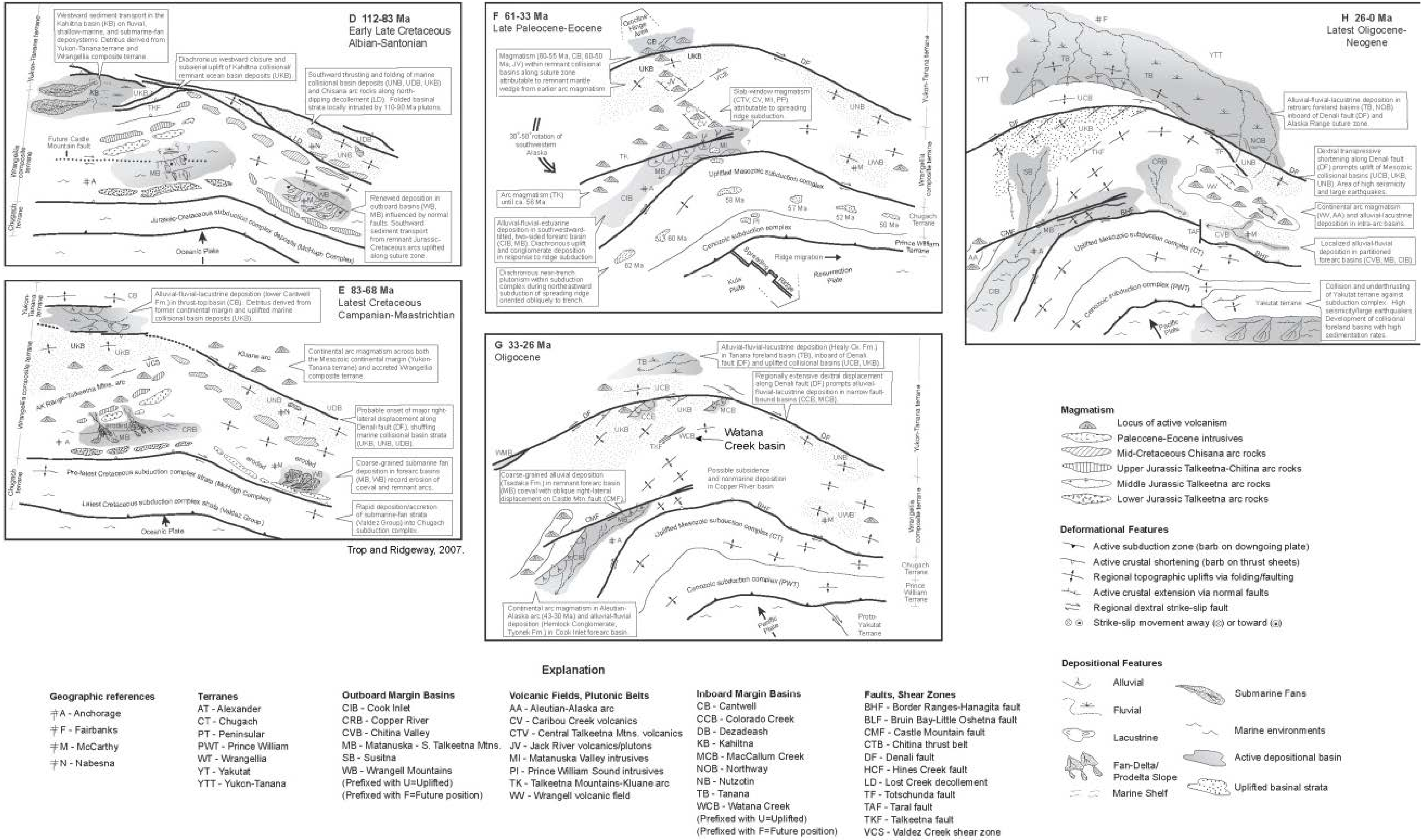
Figure 6.3-3. Regional Tectonic Terranes and Basins Part 2 of 2 (Fugro 2014)

Oblique subduction of an oceanic spreading center during Paleocene to early Eocene initiated magmatism and formation of short-lived northwest trending extensional (normal) faults shown in Figure 6.3-4 (from Ridgeway and Trop 2007). Included in these volcanics are the Cantwell and Jack River volcanic fields dated at 55 to 60 Ma, and 50 to 56 Ma, respectively shown in Figure 6.3-5 (from Cole et el, 2007). To the southeast, volcanic flows that overlie and cap the Talkeetna fault are dated at 50 Ma (Csejtey et al. 1978). Thus, Tertiary magmatic intrusions punctuate both the Kahiltna Basin assemblage, the Wrangellia composite terrane, and the Talkeetna fault (Figure 6.3-3).

Regional crustal rotation of southern Alaska took place sometime in the early to mid-Tertiary, with rotation of 30 to 50 degrees in the counterclockwise direction accommodated by the dextral Denali and Castle Mountain faults to the north and south, respectively. Consequently, regional transpressive deformation occurred during middle Eocene to Oligocene time, generating narrow fault-bounded basins along major strike slip faults as well as northeast trending folds (Trop and Ridgeway 2007). The Watana Creek basin probably was formed during this time as the Talkeetna fault re-activated as a strike slip structure from the changing crustal stress orientations (Figure 6.3-4 and Figure 6.3-5).

Post-Eocene tectonic growth of southern Alaska is controlled by the oblique collision of the Yakutat terrane, probably 15 to 10 Ma, with construction of continental magmatic arcs (i.e., the Wrangell volcanic field) from subduction of the Yakutat microplate, and development of large coastal mountain ranges (e.g., St. Elias Mountains). The collision of the Yakutat microplate is considered to have substantial influence on the deformation and counterclockwise rotation in the interior of south-central Alaska (Haeussler 2008). Subduction of the Pacific plate continued beneath North America from Eocene onwards, with growth of the Aleutian Islands from three main pulses of arc-wide magmatism occurring at 38 to 29 Ma, 16 to 11 Ma, and 6 to 0 Ma (Jicha et al. 2006).

Since the latest Cenozoic through today, south-central Alaska has experienced rapid rates of tectonic deformation driven by the obliquely convergent northwestward motion of the Pacific Plate relative to the North American Plate. In this region, the Pacific Plate is converging with North American Plate at a rate of 54 mm/yr. (2.1 in/yr.) at a slightly oblique angle (DeMets and Dixon 1999; Carver and Plafker 2008). Consequently, rates and magnitudes of seismicity are also accordingly high. In southern and southeastern Alaska, the oblique convergent plate motion is accommodated by subduction of the Pacific Plate along the Alaska-Aleutian megathrust trench, and dextral (right-lateral) transform faulting along the Queen Charlotte and Fairweather fault zones. Transpressional deformation primarily is accommodated by dextral slip along the Denali and Castle Mountain faults, as well as by horizontal crustal shortening to the north of the Denali fault.



D 112-83 Ma
Early Late Cretaceous
Albian-Santonian

Westward sediment transport in the Kahiltna basin (KB) on fluvial, shallow-marine, and submarine-fan deposystems. Detritus derived from Yukon-Tanana terrane and Wrangellia composite terrane.

Diachronous westward closure and subaerial uplift of Kahiltna collisional remnant ocean basin deposits (UKB).

Southward thrusting and folding of marine collisional basin deposits (UNB, UDB, UKB) and Chisana arc rocks along north-dipping decollement (LD). Folded basinal strata locally intruded by 110-90 Ma plutons.

Renewed deposition in outboard basins (WB, MB) influenced by normal faults. Southward sediment transport from remnant Jurassic-Cretaceous arcs uplifted along suture zone.

E 83-68 Ma
Latest Cretaceous
Campanian-Maastrichtian

Alluvial-fluvial-lacustrine deposition (lower Cantwell Fm.) in thrust-top basin (CB). Detritus derived from former continental margin and uplifted marine collisional basin deposits (UKB).

Continental arc magmatism across both the Mesozoic continental margin (Yukon-Tanana terrane) and accreted Wrangellia composite terrane.

Probable onset of major right-lateral displacement along Denali fault (DF), shuffling marine collisional basin strata (UKB, UNB, UDB).

Coarse-grained submarine fan deposition in forearc basins (MB, WB) record erosion of coeval and remnant arcs.

Rapid deposition/accretion of submarine-fan strata (Valdez Group) into Chugach subduction complex.

Trop and Ridgeway, 2007.

F 61-33 Ma
Late Paleocene-Eocene

Magmatism (60-55 Ma, CB; 60-50 Ma, JV) within remnant collisional basins along suture zone attributable to remnant mantle wedge from earlier arc magmatism.

Slab-window magmatism (CTV, CV, MI, PF) attributable to spreading ridge subduction.

Arc magmatism (TK) until ca. 56 Ma

Alluvial-fluvial-estuarine deposition in southwestward-tilted, two-sided forearc basin (CIB, MB). Diachronous uplift and conglomerate deposition in response to ridge subduction.

Diachronous near-trench plutonism within subduction complex during northeastward subduction of spreading ridge oriented obliquely to trench.

G 33-26 Ma
Oligocene

Alluvial-fluvial-lacustrine deposition (Healy Cr. Fm.) in Tanana foreland basin (TB), inboard of Denali fault (DF) and uplifted collisional basins (UCB, UKB).

Regionally extensive dextral displacement along Denali fault (DF) prompts alluvial-fluvial-lacustrine deposition in narrow fault-bound basins (CCB, MCB).

Coarse-grained alluvial deposition (Tsadaka Fm.) in remnant forearc basin (MB) coeval with oblique right-lateral displacement on Castle Mtn. fault (CMF).

Possible subsidence and nonmarine deposition in Copper River basin

Continental arc magmatism in Aleutian-Alaska arc (43-30 Ma) and alluvial-fluvial deposition (Hemlock Conglomerate, Tyonek Fm.) in Cook Inlet forearc basin.

H 26-0 Ma
Latest Oligocene-Neogene

Alluvial-fluvial-lacustrine deposition in retroarc foreland basins (TB, NOB) inboard of Denali fault (DF) and Alaska Range suture zone.

Dextral transpressive shortening along Denali fault (DF) prompts uplift of Mesozoic collisional basins (UCB, UKB, UNB). Area of high seismicity and large earthquakes.

Continental arc magmatism (WV, AA) and alluvial-lacustrine deposition in intra-arc basins.

Localized alluvial-fluvial deposition in partitioned forearc basins (CVB, MB, CIB).

Collision and underthrusting of Yakutat terrane against subduction complex. High seismicity/large earthquakes. Development of collisional foreland basins with high sedimentation rates.

Magmatism
Locus of active volcanism
Paleocene-Eocene intrusives
Mid-Cretaceous Chisana arc rocks
Upper Jurassic Talkeetna-Chitina arc rocks
Middle Jurassic Talkeetna arc rocks
Lower Jurassic Talkeetna arc rocks

Deformational Features
Active subduction zone (barb on downgoing plate)
Active crustal shortening (barb on thrust sheets)
Regional topographic uplifts via folding/faulting
Active crustal extension via normal faults
Regional dextral strike-slip fault
⊗ ⊙ Strike-slip movement away (⊗) or toward (⊙)

Depositional Features
Alluvial
Fluvial
Lacustrine
Fan-Delta/ Prodelta Slope
Marine Shelf
Submarine Fans
Marine environments
Active depositional basin
Uplifted basinal strata

Explanation

Geographic references
╪A - Anchorage
╪F - Fairbanks
╪M - McCarthy
╪N - Nabesna

Terranes
AT - Alexander
CT - Chugach
PT - Peninsular
PWT - Prince William
WT - Wrangellia
YT - Yakutat
YTT - Yukon-Tanana

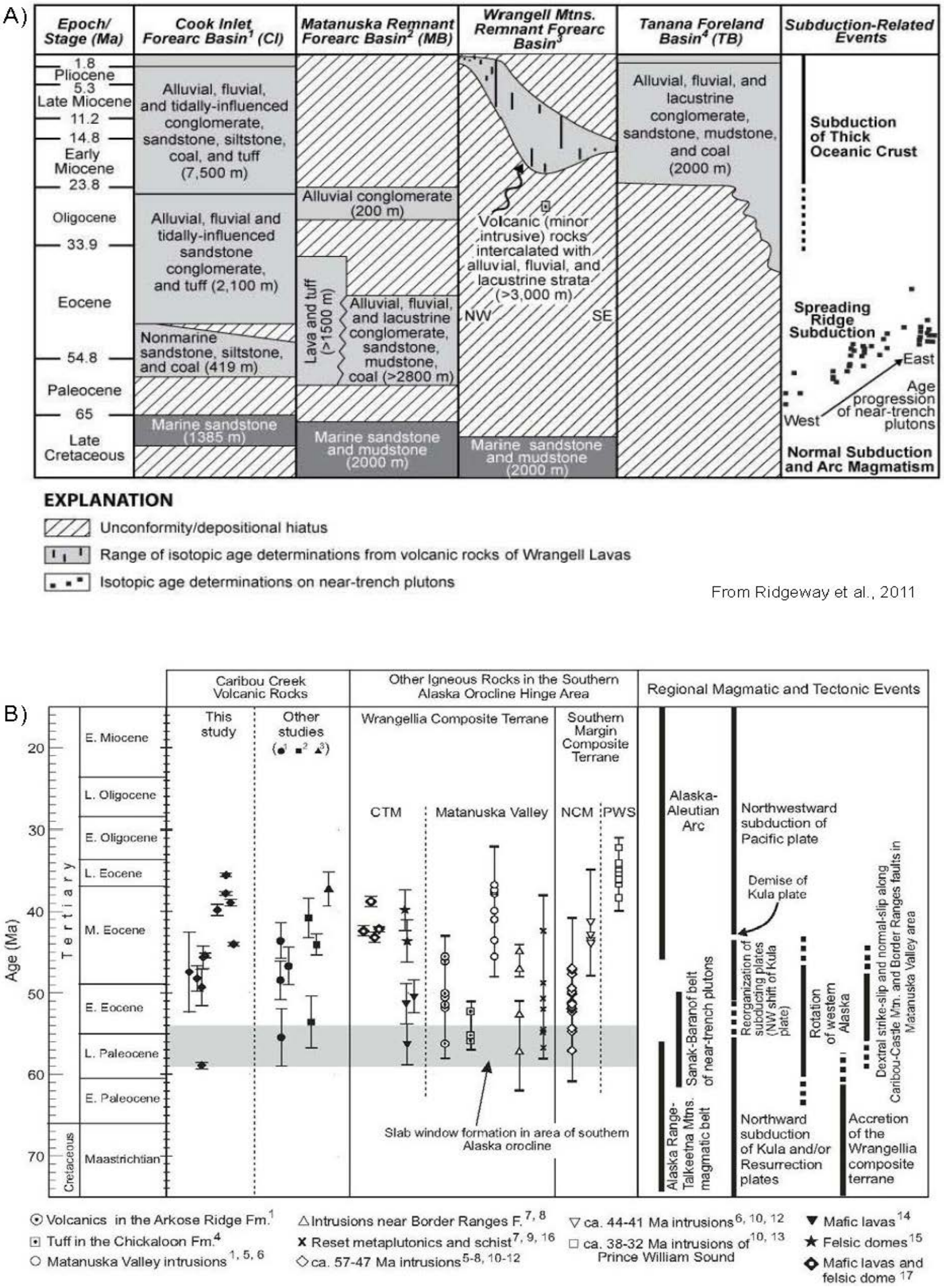
Outboard Margin Basins
CIB - Cook Inlet
CRB - Copper River
CVB - Chitina Valley
MB - Matanuska - S. Talkeetna Mtns.
SB - Susitna
WB - Wrangell Mountains
(Prefixed with U=Uplifted)
(Prefixed with F=Future position)

Volcanic Fields, Plutonic Belts
AA - Aleutian-Alaska arc
CV - Caribou Creek volcanics
CTV - Central Talkeetna Mtns. volcanics
JV - Jack River volcanics/plutons
MI - Matanuska Valley intrusives
PI - Prince William Sound intrusives
TK - Talkeetna Mountains-Kluane arc
WV - Wrangell volcanic field

Inboard Margin Basins
CB - Cantwell
CCB - Colorado Creek
DB - Dezadeash
KB - Kahiltna
MCB - MacCallum Creek
NOB - Northway
NB - Nutzotin
TB - Tanana
WCB - Watana Creek
(Prefixed with U=Uplifted)
(Prefixed with F=Future position)

Faults, Shear Zones
BHF - Border Ranges-Hanagita fault
BLF - Bruin Bay-Little Oshetna fault
CMF - Castle Mountain fault
CTB - Chitina thrust belt
DF - Denali fault
HCF - Hines Creek fault
LD - Lost Creek decollement
TF - Totschunda fault
TAF - Taral fault
TKF - Talkeetna fault
VCS - Valdez Creek shear zone

Figure 6.3-4. Schematic Evolution of South-Central Alaska (Fugro 2014)



Age-event diagram showing radiometric ages of volcanic rocks in the Caribou Creek volcanic field.

Figure 6.3-5. Correlations of Cenozoic Tectonic, Magmatic, and Sedimentary Events in South-Central Alaska (Fugro 2014)

The regional magmatism described above directly forms the rocks that make up the dam site though plutonic intrusions and volcanism. Multiple ages of early Cenozoic (i.e., Tertiary) volcanics intruded the Kahiltna formation, as well as the Wrangellia Terrain rocks and the Talkeetna suture zone (i.e., Wilson 2009). The rocks present at the dam site range in mineralogical composition and texture, including diorite intrusions, andesite, and felsic dikes and, to a lesser extent, mafic volcanic extrusive rocks (Acres 1982b). Previous geologic mapping reveals that the volcanic rocks have a complex field relationship at the dam site with intrusive and extrusive rocks often occurring proximal to each other with gradational contacts. A range of mineralogical variability within intrusional bodies is relatively common (USACE 1979). Review of rock core drilled for the project (Golder 2013, MWH 2014) as well as inspection of field outcrops confirms the complexity of the igneous history. Both andesite and diorite rocks include a wide range of textures on compositions. In some instances, diorite bodies locally are cut by felsic dikes. In both outcrop and core samples, inclusions of diorite have been observed within the andesite. No dikes were found cutting the andesite, suggesting it is the youngest volcanic unit at the site based on these cross cutting relationships (Acres 1982a; p. 6-7). The intrusions likely occurred sometime between 50 to 60 Ma, the field observations and relationships confirm multiple ages (or, episodes) of volcanism, intrusion, or flows of which the specific chronology has yet to be defined. Mapping by Csejtey et al. (1978) suggests that the dam site rocks could be of the order of 58 Ma; however, these dates were not collected on rock at the dam site. Rock samples were collected during 2014 field investigations to submit for absolute dating purposes to establish site geochronology.

6.3.2.3. Regional Structure

The geologic mapping transect along the Susitna River, extending through the Watana dam site area, suggests that the site area lies within a relatively coherent crustal block of Kahiltna assemblage sedimentary rocks which are overall gently tilted to the northwest, moderately folded, and intruded by multiple early to mid-Tertiary plutonic and volcanic rocks (Figure 6.3-6 and Figure 6.3-7). Field observations and mapping along the Susitna River, several kilometers upstream and downstream of the Watana dam site – discussed in the Interim Crustal Source Evaluation which forms Appendix B – have not disclosed any major faults, either parallel to or crossing the Susitna River downstream of the structures, associated with the Talkeetna fault and Watana Creek basin. The Watana dam site area lies within an area of Tertiary intrusive rocks. Kahiltna assemblage rocks and additional intrusive rocks downstream of the Watana dam site near the confluence of the Tsusena Creek and Susitna River appear structurally congruent, with an apparent absence of major cross-cutting structure or extensive penetrative deformation. There are likewise no significant expressions of vertical uplift or tectonics along the Susitna River transect, downstream of the Talkeetna fault and Watana Creek basin.

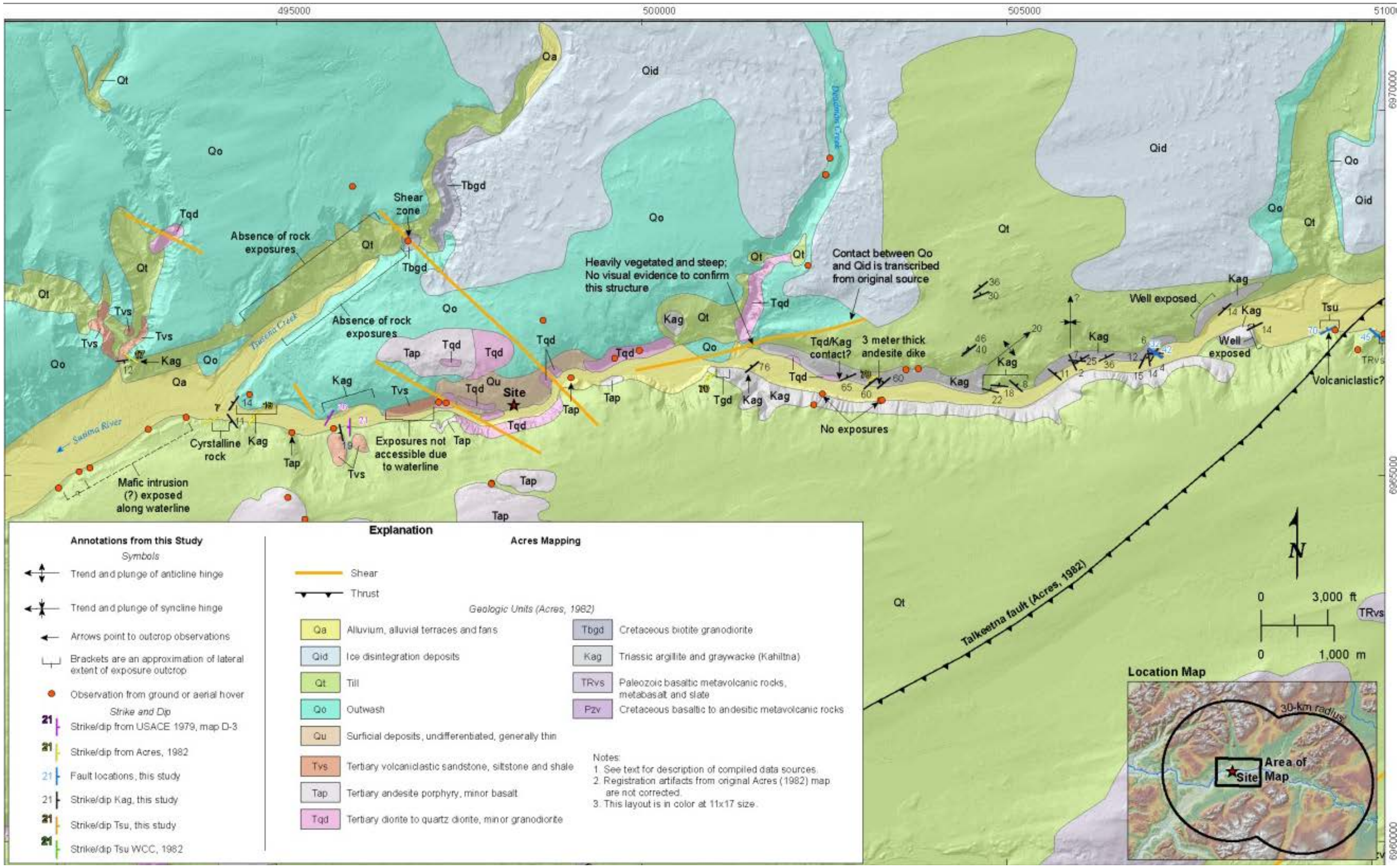


Figure 6.3-6. Acres Geologic Map Updated With Observations from 2014 (Fugro 2014)

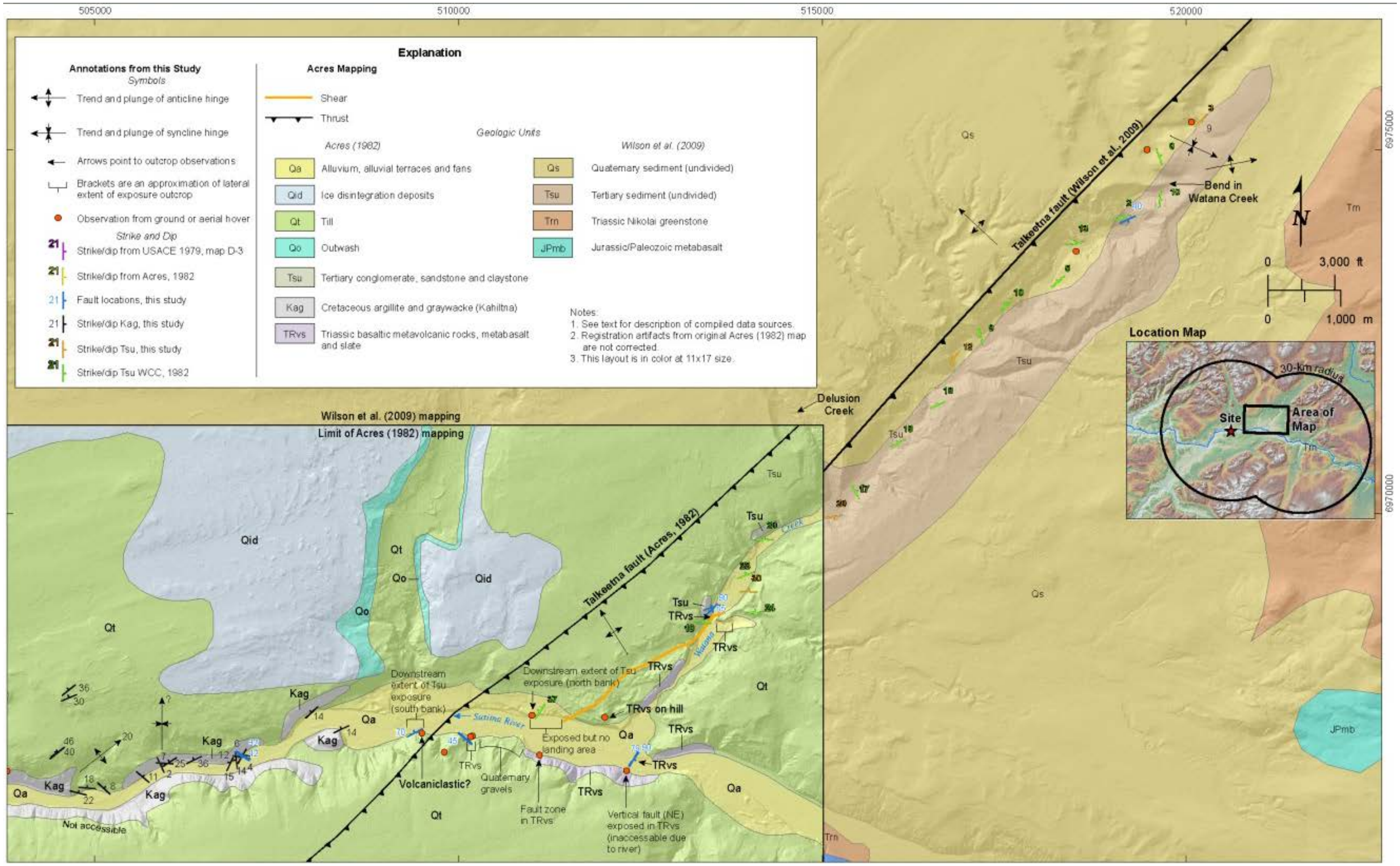


Figure 6.3-7. Acres Geologic Map Updated With Observations from 2014 (Fugro 2014)

6.3.2.4. Seismotectonics

South-central Alaska experiences significant tectonic deformation and seismicity driven by the oblique convergent northwest motion of the Pacific Plate relative to the North American Plate. The Talkeetna Mountains formed as a direct result of the convergence of these plates as the Pacific Plate was subducted below the North American Plate as shown in Figure 6.3-8.

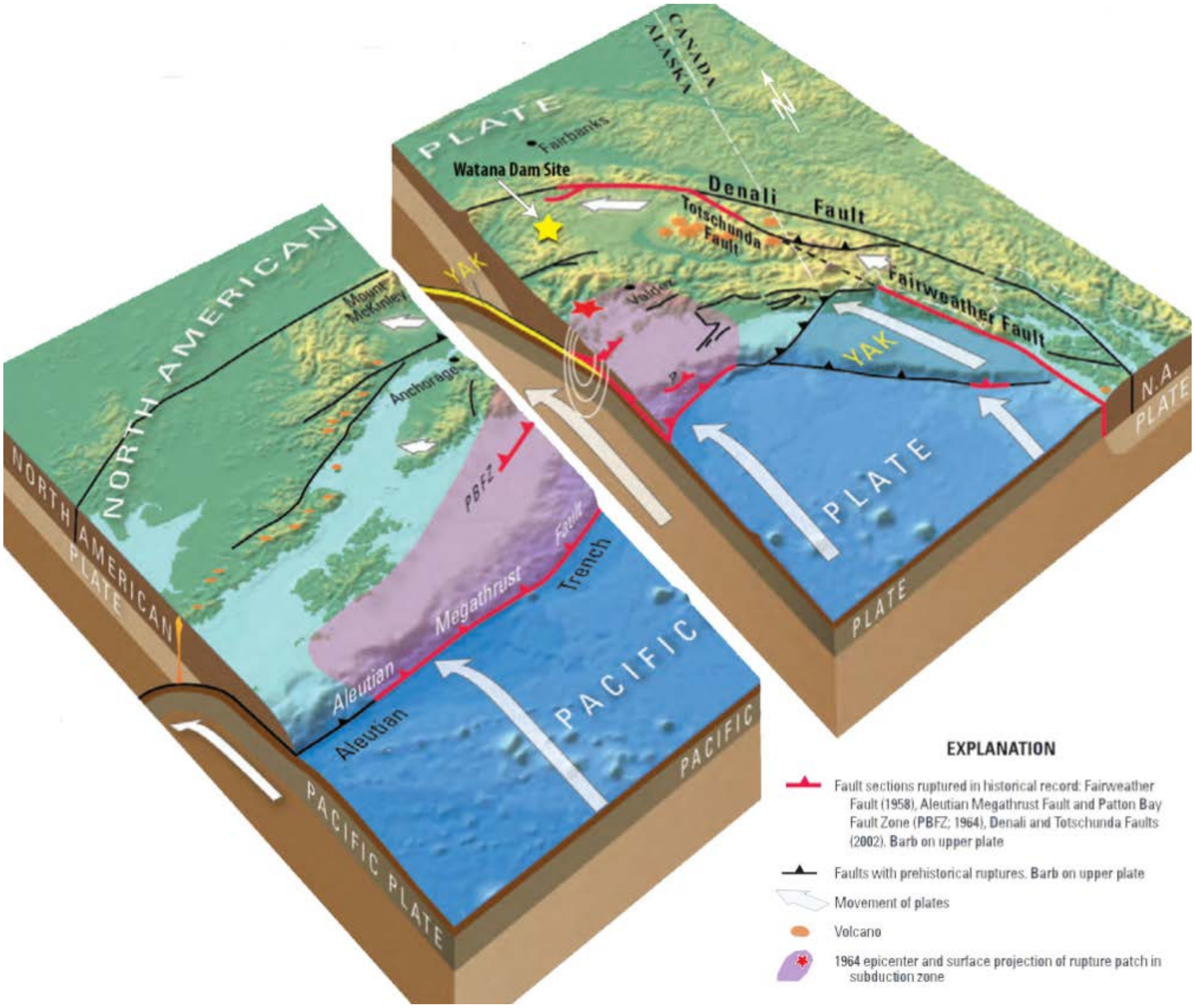


Figure 6.3-8. Tectonic Setting of South-Central Alaska During the 1964 Earthquake (modified from Brocher et al. 2014)

The Alaska-Aleutian subduction zone is one of the longest and most tectonically active plate boundaries in the world. It extends for nearly 2,500 miles (4,000 km) from south-central Alaska to the Kamchatka peninsula, and has produced some of the world’s strongest earthquakes – such as the 1964 magnitude (M) 9.2 Great Alaskan (or Good Friday) earthquake. The subduction zone has three tectonic regimes: continental subduction in the east, an island arc along the central Aleutian volcanic chain, and oblique subduction and transform tectonics in the west (Nishenko and Jacob 1990). The eastern continental subduction zone, in the vicinity of Prince William Sound, is significant in the evaluation of the seismic hazards at the Watana Dam site. In this region, the Pacific Plate is converging with the North American Plate at a rate of 54 millimeters (mm)/year (2.1 inches/year) at a slightly oblique angle (DeMets and Dixon 1999; Carver and Plafker 2008).

It has been recognized that the Alaska-Aleutian subduction zone is segmented in central Alaska, and may be broken into independent fragments (e.g., Ratchkovski and Hansen 2002). In addition, it has been recognized that the Alaskan-Aleutian subduction zone’s eastern termination lies within 100 km northeast of the Susitna-Watana site (Fuis et al. 2008). The precise location and geometric character of the slab edge are not well determined. Ruppert and Hansen (2002), define three major sections of the slab, which they termed the McKinley, Kenai, and Kodiak Blocks. The dam site is located within the McKinley Block as shown in Figure 6.3-9. A schematic of the subducting slab, which has a shallow dip (Carver and Plafker 2008) and a typical forearc basin is shown on Figure 6.3-8. The slab thickness of 12.3 km, as shown in Figure 6.3-10, is based on observed seismicity. In this area, the slab is considerably thinner than the in central Alaska, where the slab is approximately 50 km thick.

Further south, transform motion along the eastern edge of the subducting slab is accommodated by the Fairweather and Queen Charlotte (not shown) fault zones on Figure 6.3-8.

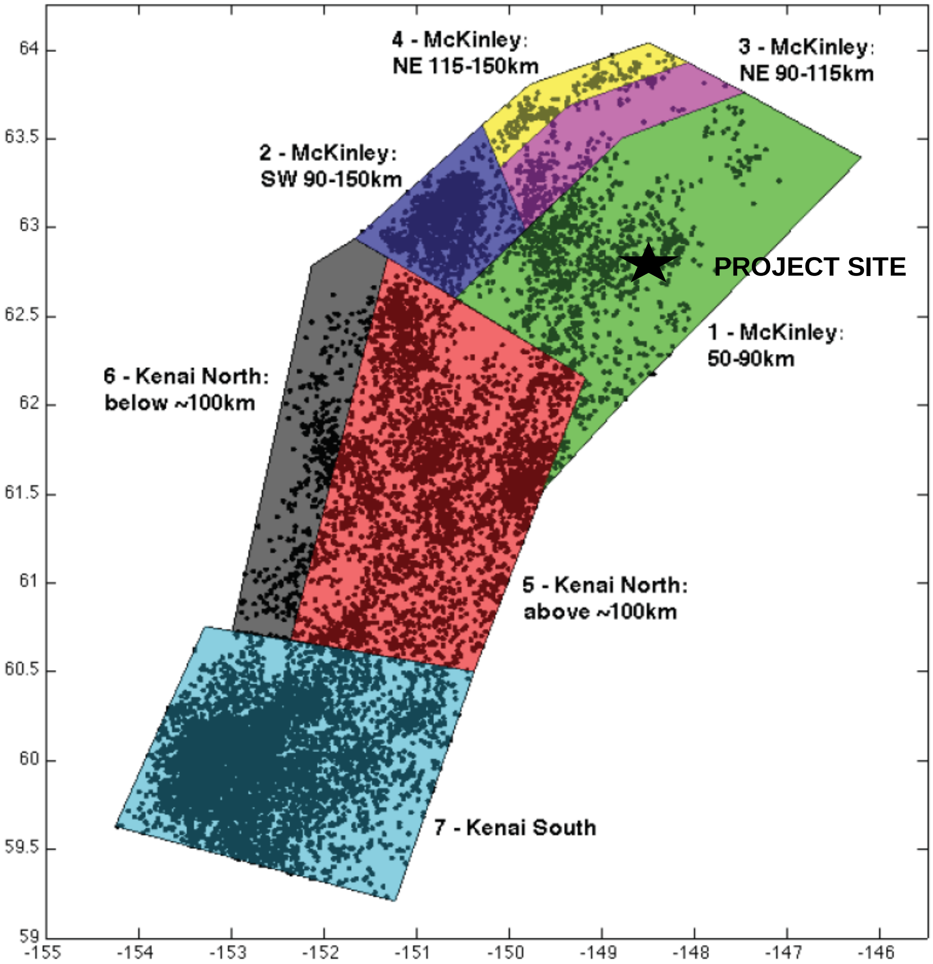


Figure 6.3-9. Map View of Slab Planes (Fugro 2013)

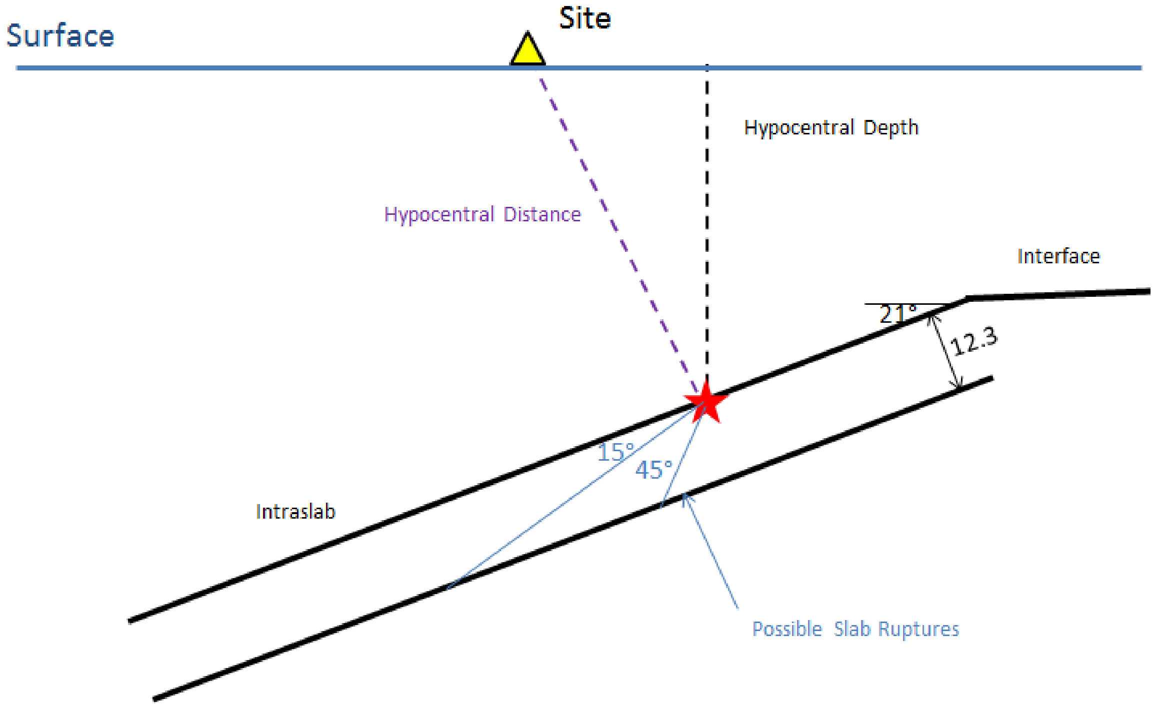


Figure 6.3-10. Schematic Showing Subducting Slab Geometry (Fugro 2013).

The dam site is located within a distinct geologic domain referred to as the Talkeetna block. The Talkeetna block is bounded by the Denali fault system to the north, the Castle Mountain fault to the south, the Wrangell Mountains to the east and the northern Aleutians and Tordrillo Mountains volcanic ranges to the west (Figure 6.3-1). Major stress is released along the Denali and Castle Mountains bounding faults during earthquakes resulting in movement (i.e., strain). However, it is less clear how stress and strain are accommodated to the east and west. There is a relative absence of large historical earthquakes within the Talkeetna block as well as a lack of mapped faults with documented Quaternary displacement (Koehler 2013; Koehler et al. 2012, 2013). The absence of earthquakes and mapped Quaternary faults within the block implies that the block is behaving rigidly with little to no internal deformation.

The Talkeetna suture zone is the proposed term by Glen et al. (2007) which refers to the Talkeetna thrust fault labeled in Figure 6.3-11. They describe the Talkeetna suture zone as a deep crustal structure bonding the northwestern edge of the Wrangellia Terrane.

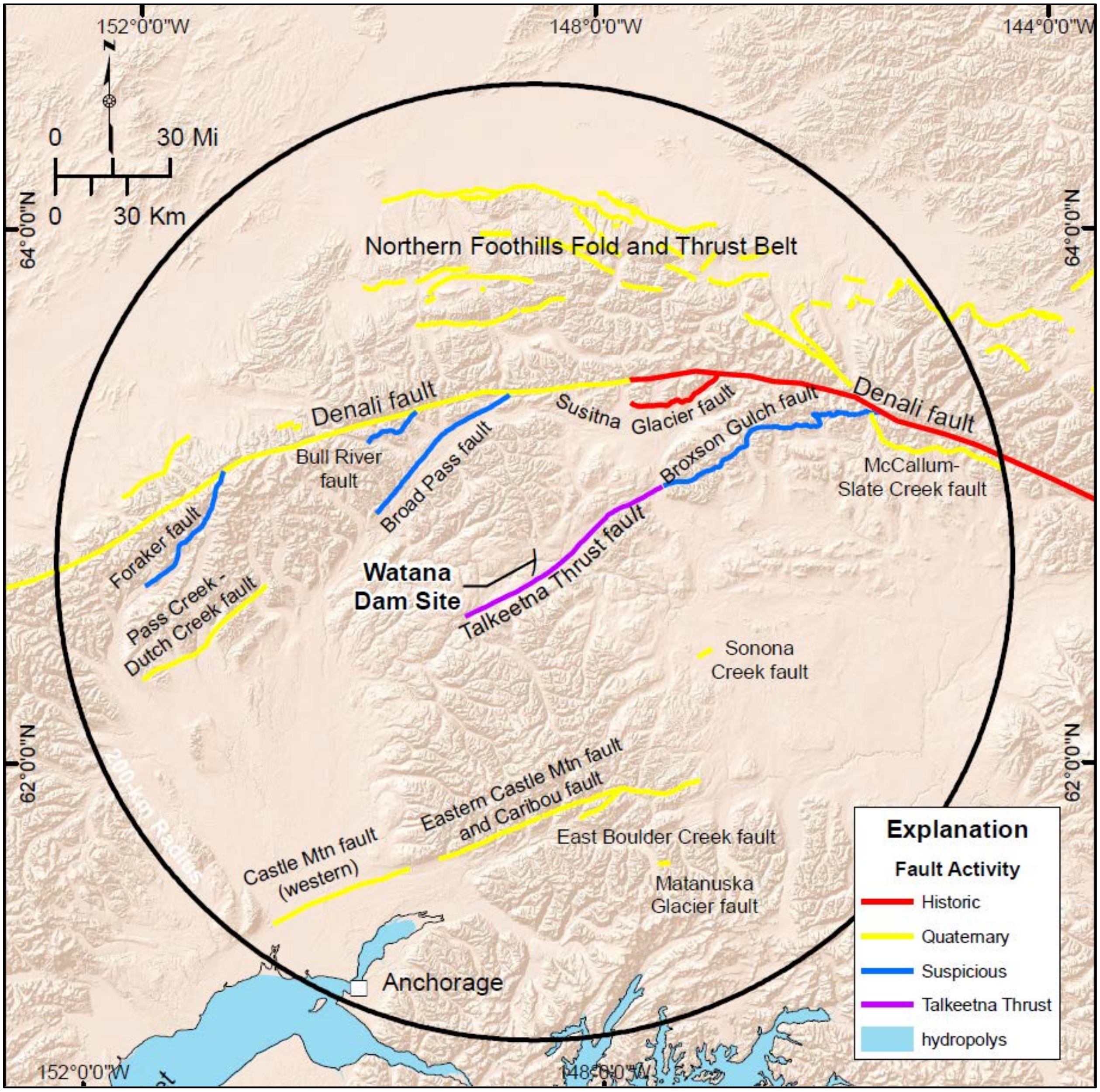


Figure 6.3-11. South-Central Alaska Regional Faults (Fugro 2012)

The Denali fault predominantly shows right-lateral, strike-slip fault motion; in plan view has an arcuate shape and defines the northern margin of the Talkeetna block as shown in Figure 6.3-1.

The Denali fault has been a major structural component of Alaska since it formed during the Late Jurassic to early Cretaceous Period (Ridgway et al. 2002). Offsets of 56 Ma metamorphic and intrusive rocks suggests at least 249 mi (400 km) of total right lateral displacement (Nokleberg et al. 1985). Offset is also constrained in the Denali region where the 38 million year old

Mt. Foraker pluton is displaced 24 mi (38 km) from the McGonagal Pluton (Reed and Lamphere 1974).

In 2002, movement on the Denali fault produced an M 7.9 earthquake, the largest strike-slip earthquake to occur in North America in almost 150 years (Eberhart-Phillips et al. 2003). Detailed studies of offset glacial features along the fault following the earthquake have demonstrated a westward decrease in the Quaternary slip rate along the fault (Matmon et al. 2006; Meriaux et al. 2009), as shown in Figure 6.3-12.

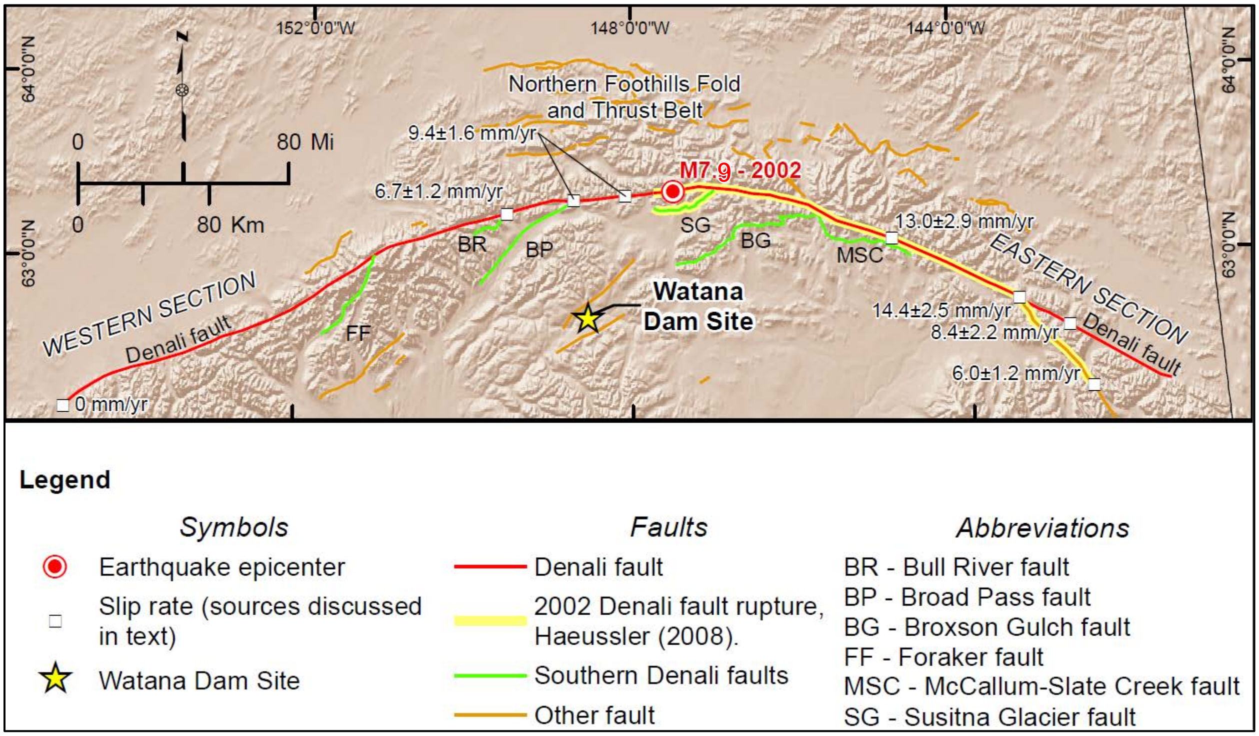


Figure 6.3-12. Denali Fault Characterization

Along the north and south sides of the Denali fault lie two zones of deformation. To the north is the Northern Foothills Fold and Thrust Belt (NFFTB), a zone of variably dipping, but generally Quaternary thrust faults and folds that accommodates transpressional deformation along the north side of the Alaska Range (Figure 6.3-12). The westward reduction in Denali fault slip rate is considered to be predominantly the result of strain partitioning onto the NFFTB (Haeussler 2008; Meriaux et al. 2009).

The other zone of deformation adjacent to the Denali fault lies south of the fault where several thrust faults splay from the Denali fault's central section as shown on Figure 6.3-12. Most of these faults are recognized as Tertiary terrane-bounding features in which Mesozoic or Paleozoic rocks are thrust over Tertiary sediments and volcanics (Haeussler 2008). Rupture along the previously unmapped Susitna Glacier thrust fault during the 2002 Denali fault earthquake highlighted the potential for seismogenic activity in this area, in contrast to the relatively sparse mapping of Quaternary faults south of the Denali fault. This concept is well expressed in the Neotectonic Map of Alaska fault explanatory note (Plafker et al. 1994).

The Castle Mountain fault defines the southern margin of the Talkeetna block. This fault is described by some as a dextral oblique strike-slip fault whose western segment is defined by a 39 mi (62 km) long Holocene fault scarp. Recent field and LiDAR-based geomorphic observations by Koehler et al. 2014, support the inference that the Castle Mountain fault is a high angle oblique reverse fault. The eastern section is primarily evident in bedrock, and there is no indication of Holocene surface rupture as shown in Figure 6.3-13. Paleoseismic studies, by Haeussler et al. (2002), on the western section demonstrate four earthquakes on the fault in the past 2,800 years, with a recurrence interval of approximately 700 years. More recent work by Koehler et al. (2014), suggest only two earthquakes in the Holocene indicating that the recurrence interval could be longer than previously thought. Despite the apparent lack of Holocene surface rupture on the eastern section, this section of the fault is spatially associated with historic seismicity as high as M 5.7 (Lahr et al. 1986).

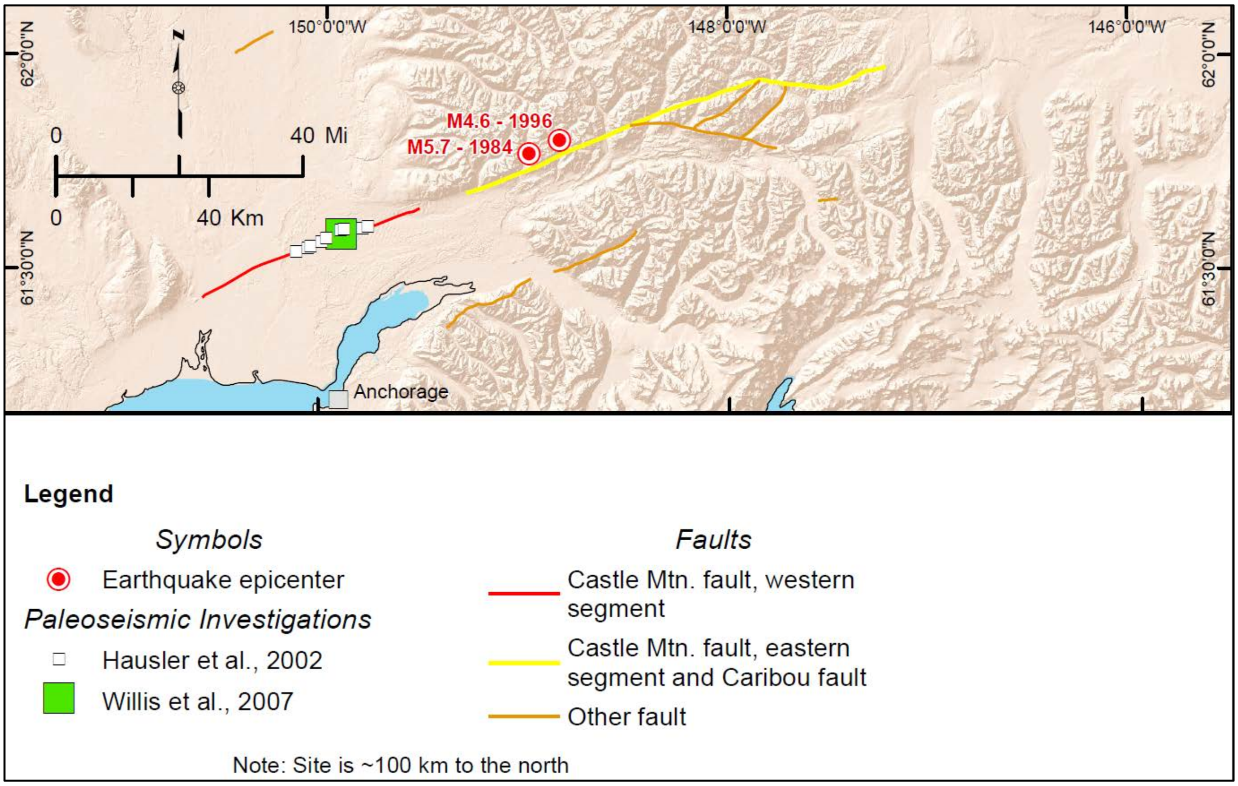


Figure 6.3-13. Castle Mountain Fault Characterization

6.3.2.5. Quaternary Geology

A period of cyclic climatic cooling during the Quaternary Period resulted in repeated glaciation of southern Alaska. Unlike the north side of the Alaska Range, which is characterized by alpine type glaciations, the Susitna Basin experienced coalescing piedmont glaciers that originated from both the Alaska Range and the Talkeetna Mountains, which merged and filled the upper basin area shown on Figure 6.3-14 (Wahrhaftig 1965; Hamilton 1994; Kaufman et al. 2011). The repeated glaciations have carved the Talkeetna Mountains into the ridges, peaks, and broad glacial plateaus that are observed today. Post-glacial uplift has induced down cutting of streams and rivers, resulting in the 500 to 700 foot deep V-shaped canyons such as Devil Canyon and Vee Canyon on the middle and upper Susitna River.

At least three periods of glaciation have been delineated for the region based on the glacial stratigraphy. During the most recent period (i.e., Late Wisconsinan), glaciers filled the adjoining lowland basins and spread onto the continental shelf. Waning ice masses formed ice barriers that blocked the drainage of glacial meltwater and produced proglacial lakes as shown in Figure 6.3-14. As a consequence of the repeated glaciation and ice-damming, the Susitna and Copper River basins are covered by varying thicknesses of till and lacustrine deposits. Many of the distinct landforms found within the project area are a direct result of this glaciation and/or the presence of ice-dammed lakes.

The Project area is located within the zone of discontinuous permafrost. Within this region, numerous isolated pockets of permafrost are found in fine-grained deposits (e.g. glacio-lacustrine sediments) and bedrock while coarse-grained deposits are generally permafrost free – or at least free of appreciable ice. It is believed that permafrost in this region is a relatively “warm” permafrost (near 0°C) and is evidenced by the presence of frozen ground in the scarps of recent shallow landslide deposits in the area and borehole ground temperature readings that are one or two degrees below freezing in some locations at the proposed dam site.

The rock temperatures below freezing are particularly found in boreholes in the north-facing slopes of the left abutment, in which it is reasonable to assume that discontinuities, joints and fractures, could be ice-filled.

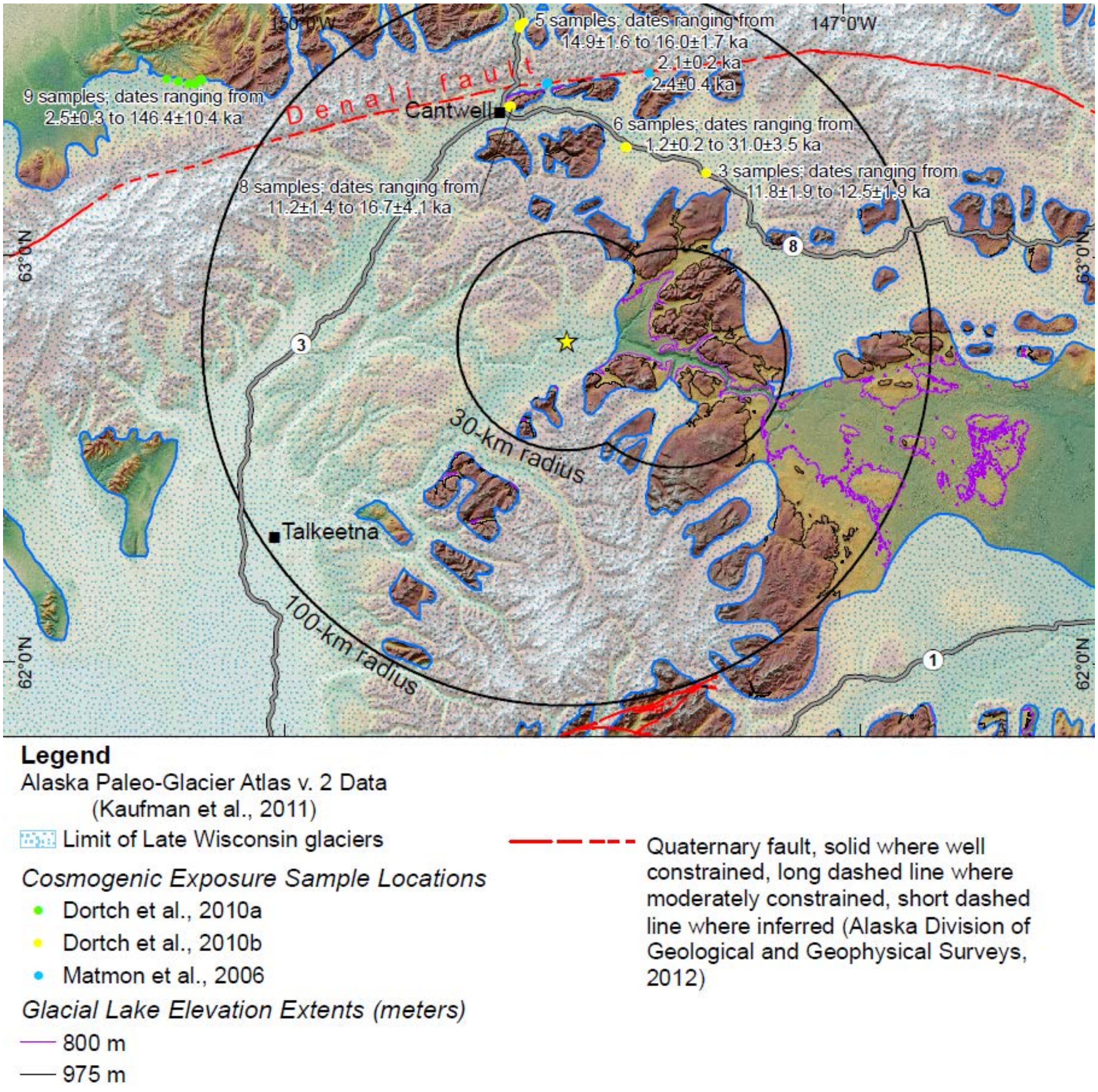


Figure 6.3-14. Late Wisconsin Glacial Limits and Age Control (Kaufman et al. 2011)

6.3.3. Seismic Hazard

A Site-Specific Seismic Hazard Analysis (SSSHA) has been performed for the Project, but is, at time of writing, incomplete. The seismic sources associated with the subduction zone (interface and intraslab) are expected to drive the Project seismic design criteria, and additional analyses on the intraslab are included in Deterministic Ground Motions for Slab events, which forms Appendix B7. However, finalization of the crustal seismic source studies – including additional

V_{S30} measurements, focal mechanism assessments based on additional seismic monitoring and update of the SSSHA, as required by the FERC Study Plan 16.6 – remains to be completed.

The derivation of seismic design criteria from the results of the preliminary SSSHA is described in Section 10 of this report.

6.3.3.1. Seismic Sources

During the 1980s studies, a site-specific seismic hazard investigation of the regional tectonics, and an evaluation of the seismic hazards, using both deterministic and probabilistic approaches, was performed. Between 2012 and 2014, the seismic studies were updated under FERC Study Plan 16.6 to characterize the seismic sources and to define and estimate the ground motion hazard. New geologic and seismic hazard information has been collected from field investigations, and long-term seismic monitoring. This information has been used together with the current research regarding large earthquake events, and the new ground motion prediction equation developed since the 1980s studies – most recently for subduction zone earthquakes.

The updated seismic source model for the region includes structural elements that are relatively consistent with previous studies, such as the Denali Fault, Castle Mountain Fault, subduction-related sources, and “background” sources. New data and observations from tectonic, geologic, paleoseismic, and seismologic studies, as well as data from recent large earthquakes, are being incorporated into the new source model. The new seismic source model also considers the potential implications of newly recognized zones of distributed tectonic deformation within the region; potentially active structures within the Talkeetna block; time-dependent scenarios for the subduction interface to consider the effects of the Great Alaskan 1964 earthquake; and time-dependent scenarios for the Denali Fault based on the 2002 earthquake. Stress accumulation and release in the form of strain, appears to be occurring primarily along the margins of the Talkeetna block, as there is an absence of major historical earthquakes within the block, as well as an absence of faults with recent displacement. Studies of selected faults and lineaments in the 1980s did not indicate that there would be potential seismic sources that could cause surface rupture through the dam site (Woodward Clyde 1982).

The original seismic source characterization and ground motion studies have been updated to account for interface and intraslab earthquakes, the recent M 7.9 Denali earthquake originating on the Susitna Glacier fault in November 2002 (Eberhart-Phillips et al. 2003) about 59 miles from the dam site; potential faults defining a postulated Fog Lakes graben (Glen et al. 2007a, 2007b); and a 10,000-year return period earthquake for the background source. The Fog Lake graben is a poorly documented structure, but it is included because of its proximity to the dam site. The Fog Lake graben structure was also included in the preliminary seismic hazard analysis as a sensitivity test for the potential reactivation of existing structures within the vicinity of the Talkeetna thrust lineament region near the dam site.

6.3.3.2. *Surface Faulting Identification*

Recent earthquakes in the region have demonstrated the potential for fault rupture on poorly or uncharacterized fault strands close to the Denali system. For this reason, it is important to understand the occurrence of identified fault strands and the potential for coseismic movement along features near the dam site, and particularly in the foundation. A comprehensive understanding of the stress regime in the vicinity of the dam site will endorse the interpretation that there is low potential for coseismic movement.

Active or potentially active faults near the dam site include the Talkeetna Thrust fault. Other local postulated features include the "Watana lineament", a northwest trending geologic feature GF1, and several other identified geologic features. Study of these geologic features started in the 1980s and continued through 2014. It has been concluded that these local features are not tectonic faults or major shear zones, nor show evidence of recent movement. It has also been concluded that there is a lack of geologic evidence supporting fault activity.

The Talkeetna thrust/suture zone is a terrane bounding structure associated with continental accretion in the late Cretaceous and early Tertiary periods. The Talkeetna thrust fault (i.e. Csejtey et al. 1982; Nokelberg et al. 1994) has been questioned by Glen (2007a, 2007b) who have interpreted that the structure is a deep crustal suture that branches upward into a 12 mile zone of Tertiary or younger faults.

The feature known as the "Watana lineament" has been postulated, manifesting itself as a series of east-west trending linear segments of the Susitna River. It was identified from high-altitude land satellite and Side-Looking Airborne Radar imagery by Gedney and Shapiro (1975). The feature has been the focus of study because of its potential manifestation at the dam site. Locations along the postulated feature have been examined, and angled boreholes have been drilled at the Watana dam site, beginning with investigations by the USACE (1979) and Acres (1982a) and most recently in 2014 to investigate further the geologic conditions beneath the Susitna River. No evidence has been found in any of these studies to corroborate existence of a continuous lineament or pattern of lineaments suggestive of faulting. All the short surface lineaments examined that might form part of a more extensive lineament have been interpreted to be of glacial origin, or related to surface processes such as slumping.

As described earlier, upstream of the proposed dam site, on the north bank, a prominent cliff exposure of northwest trending rock ridges and gullies is present. This geologic feature (GF1) approximately coincides and subparallels the western margin of a buried valley that follows a morphological depression in the topography that extends between the Susitna River and Tsusena Creek. GF1 was initially interpreted as a two-mile-long fault without “recent” displacement (Woodward-Clyde 1982). However, the subsequent field investigations, geologic mapping and drilling have led to a reinterpretation and the conclusion that GF1 is a zone of closely spaced fractures, some with slickensides and clay infilling suggestive of minor shearing and alteration separated by ribs of sound bedrock but with no evidence of “major faulting” (Harza-Ebasco 1984).

6.3.3.3. Ground Motion Estimates

The seismic source evaluation and preliminary probabilistic seismic hazard analysis provide a basis for selecting the critical seismic sources for a deterministic evaluation. The critical sources include the subduction interface and intraslab, Fog Lake graben, and background seismicity. Other faults capable of large magnitude events were included in the deterministic assessment, including the Denali and the Pass Creek – Dutch Creek faults. These two faults have a small contribution to the overall hazard, due to the distance from each of these faults to the project site. Appendix B3 contains the Interim Crustal Seismic Source Evaluation with details of the seismic source evaluation.

The median peak ground acceleration (PGA) values computed for the sources are shown in Table 6.3-3. The deterministic results assumed an input shear wave velocity in the upper 30 km of the crust (defined as V_{S30}) equal to 3,610 ft./s (1,100m/s), except where noted. Initial probabilistic analyses were performed prior to field testing for shear wave velocity. In 2013, the V_{S30} was assumed to be 3,610 ft./s (1,100m/s), and the deterministic results reflect this revision.

The results indicate that the ground motions for the intraslab sources are the more significant, and the crustal sources are less significant.

For the probabilistic evaluation, ground motion prediction equations (GMPE) are used to transform magnitude, distance and other ground motion-related parameters into ground motion amplitude distributions for a wide range of vibration frequencies. Three types of GMPEs were used for this study: crustal, interface, and intraslab sources. Based on the results of this probabilistic study, the PGA hazard is dominated by intraslab sources for all return periods. Complete details are contained in Appendix B2.

Table 6.3-3. Ground Motions – Deterministic Results

Source	MCE (Mw)	Rupture Distance[3] (miles)	Ground Motion Prediction Equations[4] (weight)	Median PGA (g)
Interface (interplate)[1]	9.2	49	ZH06 [0.25] AM09 [0.25] BCH11 [0.50]	0.26
Intraslab (intraplate)[2]	7.5	31	ZH06 [0.25] AB03 [0.25] BCH11 [0.50]	0.33
	8.0			0.56
Denali fault – entire fault	7.9	44	BA08 [0.25] CY08 [0.25] CB08 [0.25] AS08 [0.25]	0.095[5]
Castle Mtn. fault – entire fault	7.6	62		-
Fog Lake north	7.0	4		0.29
Crustal seismicity (10,000 yr. return period)[4]	6.5	9		0.275[5]

Notes:

Source Appendix B2 and Fugro (2013) for deterministic analysis results.

1. Interface events also called interplate or megathrust events. Interface events normally occur at depths up to 40 km, which is the depth at which some of the largest magnitude events have been recorded.
2. Intraslab events are deeper events, often referred to as intraplate events can be attributed to the subduction at depths greater than about 40 to 60 km.
3. Rupture Distance is defined as the closest distance to the fault plane.
4. Based on weighted magnitude-distance-epsilon deaggregation for SAB Central source and 10,000-yr. return period.
5. V_{S30}=800m/s, from initial probabilistic analyses in Appendix B2. A V_{S30} equal to 1100 m/s would slightly decrease the PGA for the crustal seismicity and the Denali fault.

6.3.3.4. Microseismic Network

To monitor seismicity in the region of the dam, the Susitna-Watana Seismic Network was established in August-September 2012 so that seismic activity in the vicinity of the Project – over an area of some 5,700 square miles could be captured. The first group of stations installed consisted of four seismograph stations (WAT1 to WAT4) within 20 mi of the dam site, with station spacing of 10 mi to 20 mi. In August 2013, three additional seismograph stations were installed (WAT5 to WAT7), which expanded coverage and reduced station spacing within 32 mi of the proposed dam site as shown on as shown on Drawing 01-01GT008.

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 seismograph at the proposed dam site (WAT1).

Data recorded by the seismic network is processed by the Alaska Earthquake Center (AEC), which monitors seismic activity from more than 400 seismograph stations throughout Alaska and neighboring regions. Data is 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. The addition of the Susitna-Watana Seismic Network has increased the event detection capabilities in the Project area; has increased the completeness of the data; has improved precision of hypocentral location precision; and overall has provided a clearer picture of seismicity within the Project area.

During the period from November 16, 2012, through December 31, 2013, 1,136 earthquakes were recorded with an epicenter located within the Susitna-Watana Seismic Network project area (Fugro 2014). The Susitna-Watana Seismic Network has recorded only low magnitude events since its initiation on November 16, 2012: an average of 2.8 events per day (1.1 crustal events per day and 1.7 intraslab events per day). As shown on Figure 6.3-15, 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 were less than M 3.8; the intraslab events were less than M 4.0.

Plotting the source locations attained by the microseismic network as a function of depth and taking a cross-section in the north-northwest to south-southeast direction, allows the boundaries of the crustal events and the boundary of the subducting plate to be defined as shown in Figure 6.3-16. The information collected by the network has increased confidence in the determination of Project design events and seismic design criteria, which are described in detail in Section 10.7.

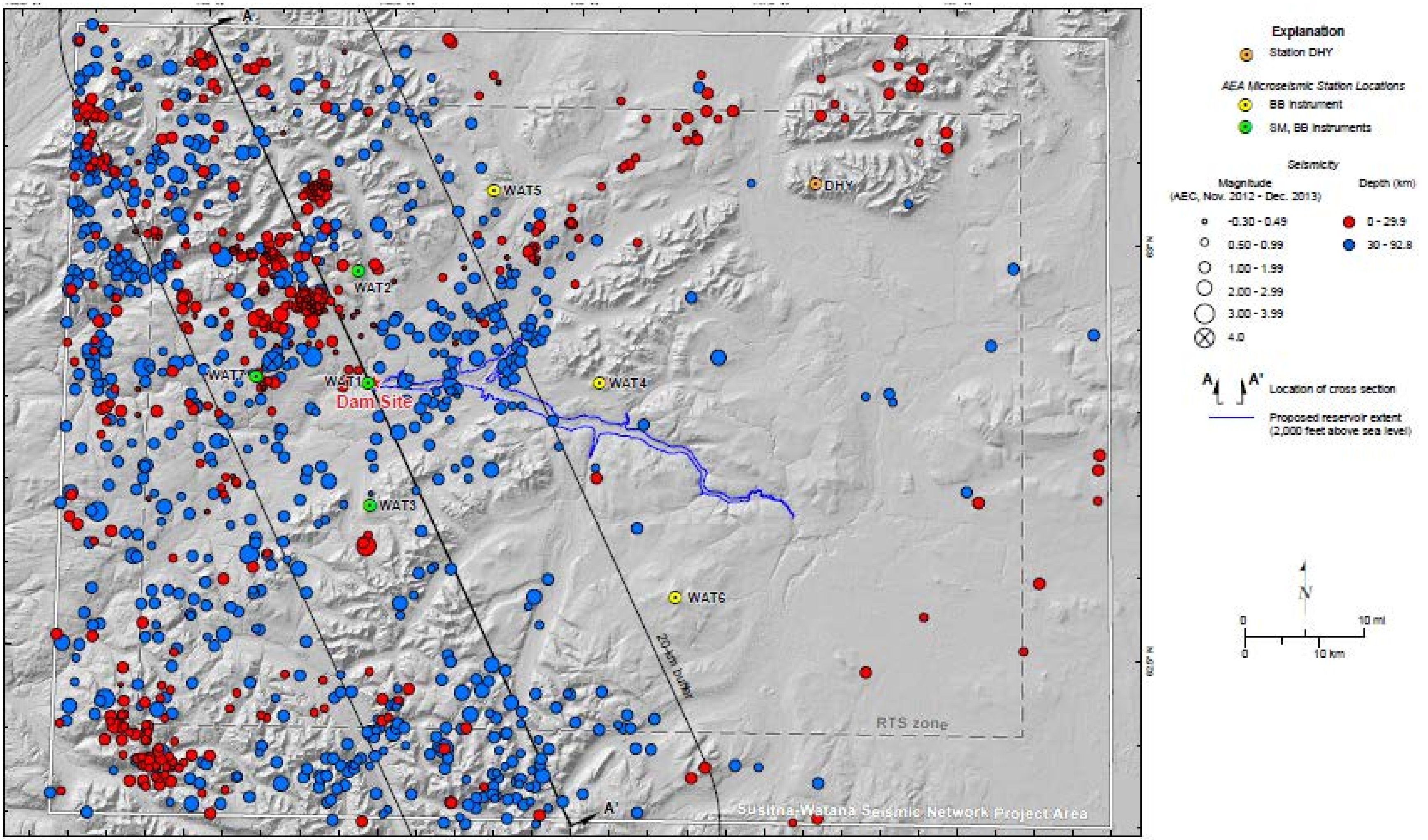
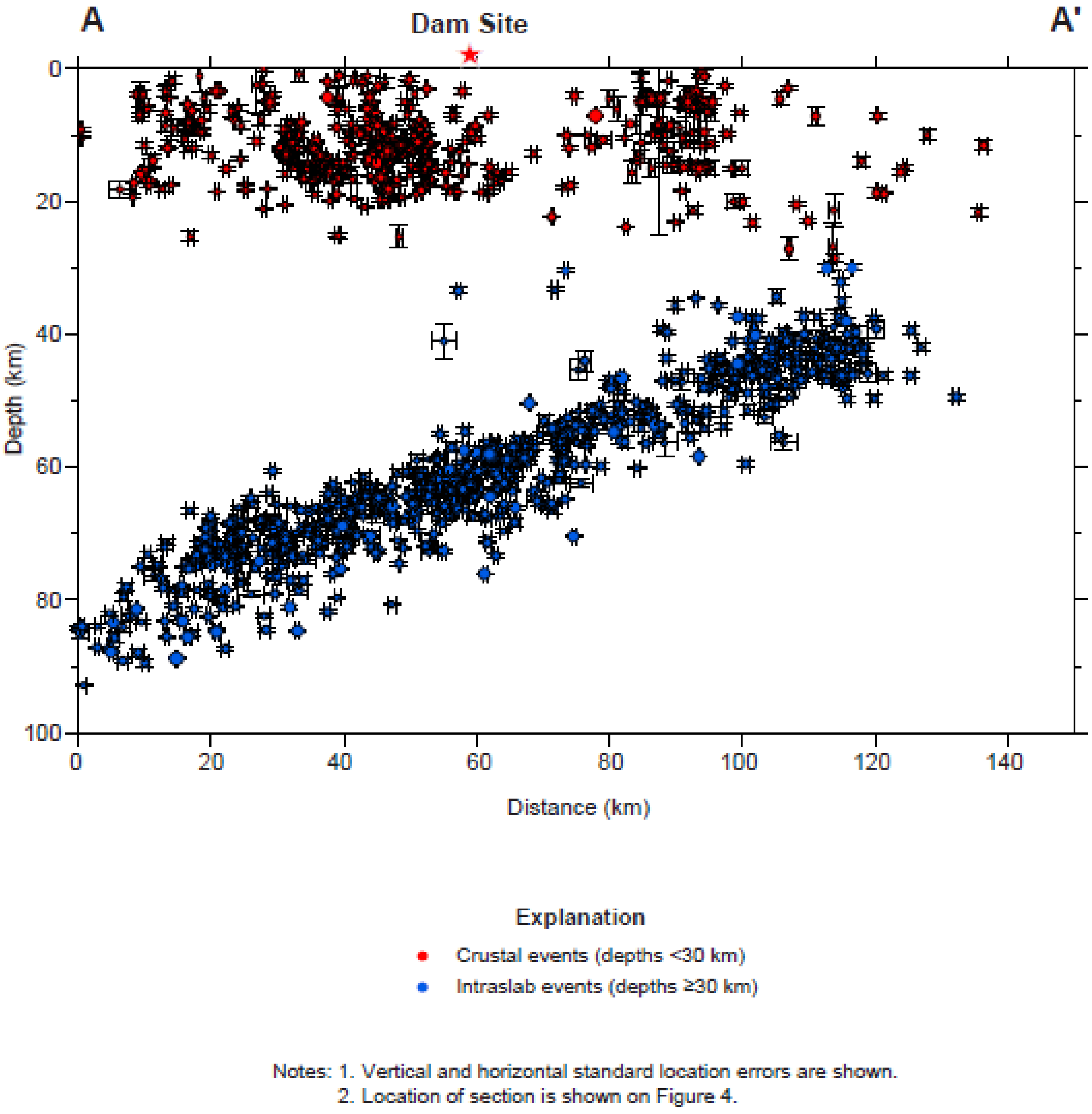


Figure 6.3-15. Seismicity within the Susitna-Watana Seismic Network Project Area, November 16, 2012 to December 31, 2013 (Fugro 2014)



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

Figure 6.3-16. Seismicity Section A-A', November 16, 2012 to December 31, 2013 (Fugro 2014)

6.3.3.5. Reservoir Triggered Seismicity

Reservoir-triggered seismicity has been described as earthquake events that are triggered by the filling of a reservoir, or by water-level changes or fluctuations during operation of the reservoir. It is believed that reservoir triggered seismicity (RTS) primarily represents the release of pre-existing tectonic strain, with the reservoir being a perturbing influence (Yeats et al. 1997; USCOLD 1997; ICOLD 2008). Thus, the reservoir does not cause or induce the seismicity, it merely triggers the release of the accumulated, naturally occurring tectonic strain that already existed.

At reservoirs where RTS has been suspected, the maximum reported earthquake magnitudes for RTS events are primarily less than M 6.0, and typically less than M 4.0, and often below the range felt by the public.

The most significant aspect of the RTS record is that of the verified RTS cases large enough to be potentially damaging. Of recorded instances of RTS, just four events have exceeded M 6.0 and only 13 events were in the range M 5.0 to M 5.9 (USCOLD 1997; Yeats et al. 1997). The largest reported RTS earthquake was the 1967, magnitude M 6.5, Koyna, India event. The other three events were Hsinfengkiang (China 1962) M 6.1, Kariba (Zambia 1963) M 6.0, and Kremasta (Greece 1966) M 6.3.

For this Project, the reservoir depth, reservoir volume, existing tectonic stress state, rock type underlying the reservoir, and the rate of filling were considered when evaluating the probability of RTS. The Project reservoir will have characteristics that might make it somewhat susceptible to RTS, in that the maximum reservoir depth is greater than 575 ft. (175 meters), and it is within an active tectonic region.

As described above, the Talkeetna Block is bordered by the Denali Fault to the north, and the Castle Mountain Fault to the south, and the Wadati-Benioff Zone (Intraslab) lies at a depth of approximately 50 km below the site based upon the focal depth of recent earthquakes, Figure 6.3-16. These distant sources do not lie within the zone potentially influenced by reservoir filling, and thus RTS is unlikely to occur on them.

Studies performed in the 1980s estimated the probability of RTS for the Project to be between 30 percent and 95 percent, with an event up to M 6.0 (WCC 1982). Recalculations performed during the present studies indicate that the reservoir has a potential for producing an RTS event up to M 6.5, but the probability of an RTS event is between 16 to 46 percent. Any event would most likely occur within 10 years of initial filling.

RTS has been considered in the derivation of the seismic design parameters for the Project, and will be further updated during detailed design. However, triggered seismicity requires the presence of a causative fault. A seismic hazard assessment requires that all faults be identified; hence, any fault identified during the seismic hazard assessment would likely cover those with the potential for RTS.

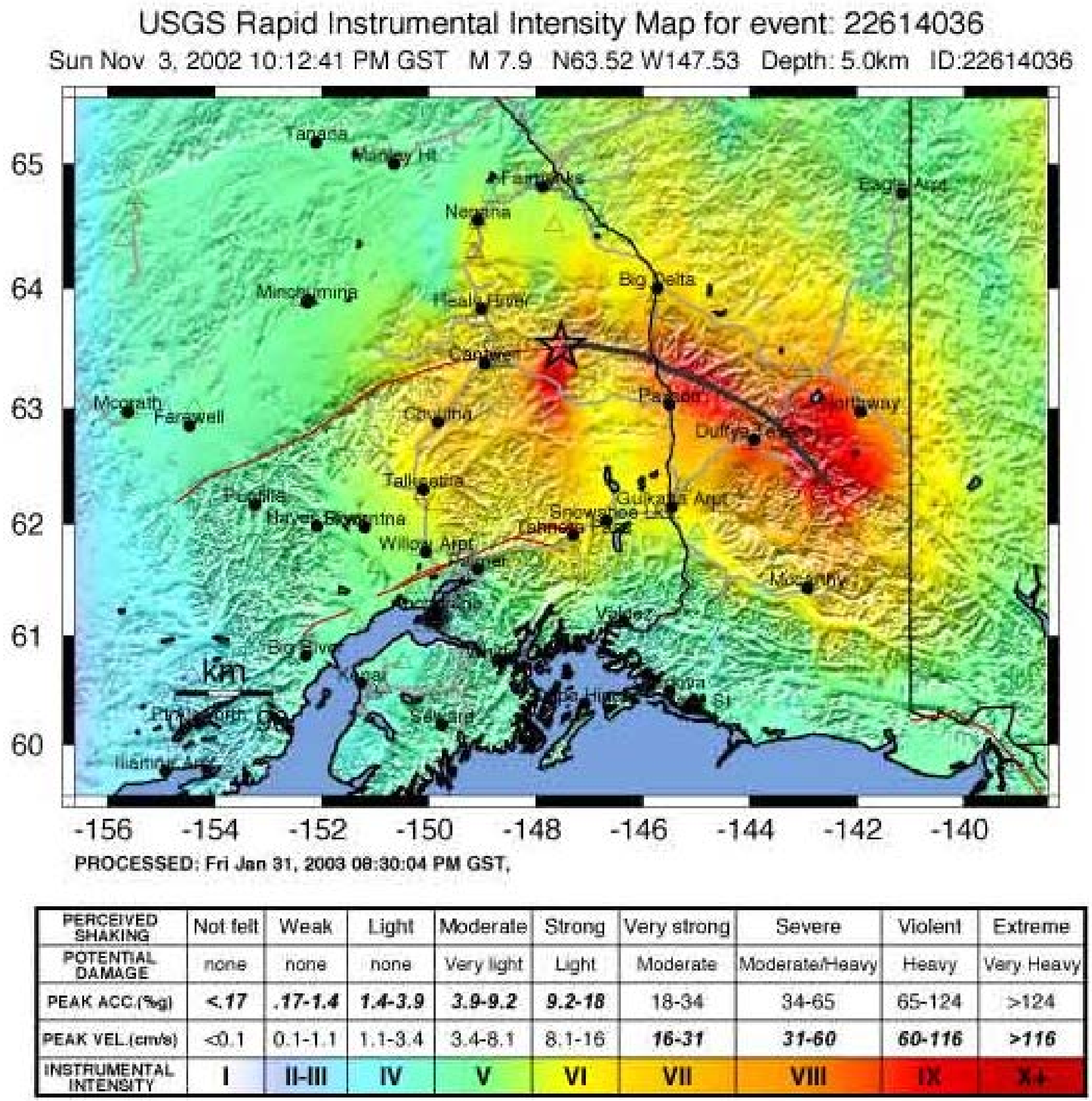
For completeness the present studies have also considered the potential effects of RTS on the nearest populated area, the town of Talkeetna, which is about 62 miles (100 km) from the site. Using the RTS event of M 6.5 and GMPE, deterministic methods were used to estimate the peak ground accelerations (PGA). The calculation estimates a PGA in Talkeetna of 0.02g for the median and 0.04g for the 84th percentile (+1 standard deviation). The inputs to calculate this hypothetical event are shown in Table 6.3-4.

Table 6.3-4. Deterministic Input Parameters

CASE	Crustal
Magnitude	6.5
R_{RUP} (km)	100 (R_{JB}=100)
V_{S30} (m/s)	760
Type of faulting	Strike-slip
Dip (degrees)	90
Seismogenic Depth (km)	20
Width (km)	20
PGA(g) [percentile]	0.02[50th] 0.04[84th]
Ground Motion Prediction Equation [weight]	BA08 [0.25] CY08 [0.25] CB08 [0.25] AS08 [0.25]

Notes:
Acronyms: BA08= Boore and Atkinson 2008; CY08=Chiou and Youngs 2008; CB08=Campbell and Bozorgnia 2008; AS08=Abrahamson and Silva 2008

For comparison, the Shake Map for the 2002 Denali earthquake (Figure 6.3-17; USGS) was reviewed and indicates the peak ground acceleration in Talkeetna were light and ranged between about 0.09g to 0.18g. Based on the above analysis it is considered that the maximum RTS event would expose the nearest town of Talkeetna to ground shaking substantially less than that experienced during the 2002 Denali event.



USGS Rapid Instrumental Intensity Map for event: 22614036
Sun Nov 3, 2002 10:12:41 PM GST M 7.9 N63.52 W147.53 Depth: 5.0km ID:22614036

PROCESSED: Fri Jan 31, 2003 08:30:04 PM GST,

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 6.3-17. USGS Shake Map for 2002 Denali Earthquake (USGS)

6.3.4. Site Geology

The Project site has been the subject of study primarily since the 1970s having undergone numerous site investigations and studies as described above. The following describes the overburden and bedrock, geologic structure, and hydrogeological conditions at the site. Discussions of geotechnical design criteria and engineering design considerations are included in Section 10.3 of this feasibility report.

6.3.4.1. Overburden Materials

The overburden on the upper areas of the abutments, near the top of the slopes, consists primarily of glacial deposits (e.g. till) and colluvium, and talus (Drawing 01-01GT003). Overburden thickness in the dam site area is generally less than 50 ft. but may reach 70 ft. or more locally as indicated on bedrock contour map (Drawing 01-01GT004). Above El. 1900 ft., overburden thickness averages 20 ft. but is locally up to 50 ft. (upstream of the dam) on the left abutment. On the right abutment, the overburden thickness typically ranges from about 20 to 40 ft. Below El. 1900 ft., where overburden consists primarily of colluvium and talus, overburden has an apparent thickness typically between 15 and 20 ft. Subsurface investigations indicate that the contact between the overburden and bedrock is relatively unweathered and distinct.

In the river channel, alluvium beneath the proposed dam site area is typically between 70 to 80 ft. thick, but it is up to 140 ft. thick within the two bedrock depressions located upstream of the dam (Drawing 01-01GT004 and Drawing 01-01GT007). Within the dam footprint, the river channel alluvium typically ranges from about 60 to 105 ft. thick. The alluvium is comprised primarily of well-graded coarse-grained gravels, sandy gravels, and gravelly sands with cobbles and boulders (Harza-Ebasco 1983). Boulders are visible on the gravel bars and banks of the river and generally range from one to three feet in diameter but some are as large as five feet in diameter. Near the south abutment, the alluvium transitions to a thick talus deposit of diorite boulders.

For discussion of the overburden materials in the Watana Relict Channel refer to Section 6.3.6.4.1.

6.3.4.2. Bedrock Geology

The dam site is primarily underlain by Tertiary volcanic intrusions that range in composition from diorite to granodiorite to quartz diorite (Drawing 01-01GT003 and Drawing 01-01GT006). The bedrock is medium to dark green gray, fine to medium grained, generally hard to very hard, strong to very strong, competent, and generally fresh. However, bedrock is typically slightly to moderately weathered at the top of rock and along discontinuities to depths of 50 to 80 ft. Below the surficial zone of weathering, the rock mass is typically closely to moderately closely fractured. In outcrop, joints are typically tight to open, although they are mostly tight at greater depths, rough to smooth in profile, planar, and some contain iron stains, carbonate deposits, or are slickensided. At depth, local weathering can occur in areas of highly fractured rock, and the fractured rock may also contain breccia and clay gouge (shear zones) and/or be hydrothermally altered.

Bedrock directly downstream of and at higher elevations above the left abutment the dam site consists of extrusive volcanics, mostly andesite porphyry, which varies locally to dacite or latite. The andesite is similar in chemical composition to the diorite, and is generally dark gray to black, slightly weathered, strong to very strong, competent and in places contains diorite xenoliths. The nature of the contact of the andesite with the diorite is poorly understood. However, where mapped along the left abutment downstream of the dam, or drilled through, the contact zone is generally weathered and fractured in a zone up to 15 ft. wide and can exhibit signs of fracturing and shearing as evidenced by slickensides. Such shear fracturing suggests a manifestation of igneous and volcanic emplacement. The rock within this contact zone may have low RQD and can locally have core loss. Despite the fracturing, the hydraulic conductivity along the contact is relatively low. Downstream of the dam site on the south bank, the andesite exhibits slight to moderate alteration. There is strong hematite staining and the phenocrysts show signs of alteration to chlorite and clay minerals. Detailed discussion of the andesite porphyry/diorite contact is presented in an Acres (l982a) report.

The diorite body has been intruded by mafic and felsic dikes that are generally a few feet wide, and exhibit contacts that are tight and competent. Felsic dikes are observed in outcrop as well as boreholes. The dikes are light gray, aphanitic to medium grained, fresh, hard, and strong to very strong.

Mafic dikes are less common than felsic dikes but were encountered in outcrop and in several boreholes. The mafic dikes typically consist of andesite and are less than 5 ft. wide. They are dark gray to green-gray, fine-grained, fresh, hard, and strong. Mafic dikes may be porphyritic, include xenoliths of the parent rock (diorite), and generally have tight contacts with the parent rock.

Upstream of the dam site, a 300 to 400 ft. wide northwest-southeast trending dike consisting of diorite-andesite porphyry is mapped on the north and south sides of the river. The dike is dark gray to green-gray, fine-grained with medium-grained feldspar phenocrysts. The rock is generally fresh, hard, and locally exhibits weak flow banding. Toward the west, the contact of the dike with the diorite pluton coincides with an approximately 10 ft. wide shear and alteration zone that is mapped as part of previously identified “geologic feature” GF1. The east contact appears to coincide with a gully, but the contact is mostly obscured by talus and the contact could not be traced over a significant distance.

In a number of boreholes, hydrothermally altered bedrock was penetrated. Hydrothermal solutions have caused the chemical breakdown of the feldspars and mafic minerals in the host rock leaving a lighter greenish-gray to tan to white appearance. These altered zones are rarely seen in outcrop because the bedrock has been eroded into gullies where alteration is moderate to severe. Where encountered in rock cores, the width of the altered zones in boreholes ranges up to 20 ft. but are typically less than five feet, which altered rock is often associated with close fracturing, fracture zones, or shear zones. The transition between fresh and altered rock is gradational over a few inches to a few feet. The degree of alteration encountered is highly variable, but in the areas of severe alteration, the rock can be weak to extremely weak and contain zones of rock completely altered to clay minerals over several inches.

6.3.4.3. Geologic Structure

Geologic mapping and core drilling at the dam site have identified three major classes of rock mass discontinuities as summarized in the Table 6.3-5. The most common and pervasive class are joints. Fracture zones, which are less common than joints, consist primarily of very closely to closely spaced joints over short zones of depth intervals. Least common are shear zones, which exhibit some evidence of relative displacement such as the presence of gouge, breccia, and/or slickensides. Shear zones are often relatively narrow can be identified within fracture zones and altered zones.

Fracture zones and shear zones are typically oriented parallel to the major joint sets. The most prominent and persistent of the fracture and shear zones have been termed “Geologic Features” (e.g. GF1, etc.) beginning with reports by Acres (1982a). Joints, fracture zones, and shear zones exhibit a wide range of weathering, alteration, and healing, as they may have been conduits for fluid migration. Detailed characteristics of each type of discontinuity are described in the following subsections.

Table 6.3-5. Discontinuity Types

Discontinuity Type	Distinguishing Characteristics	Width/ Aperture	Persistence	Example
Joint	Generally planar breaks and fractures; some with minor infilling and mineralization. Healed joints are also present.	Less than 0.01 inch to more than 1 inch in outcrop	Individual joints are typically continuous from several ft. to more than 50 ft. Joints generally occur as coplanar joint sets with varied spacing.	Joint Sets 1 and 2
Fracture Zone	Areas of very closely to closely spaced (less than 1 inch to 8 inches) jointed rock where no apparent relative movement has occurred.	Up to 20 ft.	Tens to thousands of feet	GF-1, GF-4B, GF-5
Shear Zone	Zone of rock along which there has been visible evidence of or measurable displacement. These zones are characterized by breccia, gouge, and/or slickensides and frequently associated within fracture zones or altered zones.	Few inches but less than 5 ft.	Tens to thousands of feet	

6.3.4.3.1. Joints

Two major and two minor joint sets have been identified at the dam site, and the orientations are summarized in Table 6.3-6. Joint set 1 (JS1), which is the most prominent set, trends the northwest-southeast (300°) and dips between 70° northeast to 80° southwest (Acres 1982a; Acres 1982b; MWH 2014). JS1 is found throughout the dam site and parallels the dominant geomorphic trend in the lower valley (i.e., gullies). JS2 trends northeast-southwest (040°) and dips between 70° northwest to 80° southeast, but downstream of the dam dips more prominently to the northwest. JS3 and JS4 are considered minor sets but can be locally well developed. JS3 is better developed in the northwest quadrant of the dam site area, and trends between north-northwest to north-south, with an average trend to 350°, with steep dips to the east and west. JS3 is generally considered to form numerous open joints on the cliff faces downstream of the dam and is associated with fracture and shear zones that parallel this orientation (Acres 1982b). JS4 includes shallow dipping discontinuities of variable orientations. Results from the site investigations show that dominant discontinuities and structural features at the dam site are oriented mostly transverse to the Susitna River.

Table 6.3-6. Summary of Joint Set Orientations

Joint Set	Strike		
	Strike (Azimuth)	Strike Average (Azimuth)	Dip
JS1	270° to 330°	300°	70° NE to 80° SW
JS2	025° to 060°	040°	70° NW to 80° SE
JS3	340° to 020°	350°	70° E to 80° W
JS4	Variable	Variable	Less than 35°

In outcrop, discontinuities of the JS1 and JS2 are typically close to moderately spaced (2 inches to 2 ft.), planar, and rough and persistence between 10 and 30 ft. although can be more than 30 ft. Minor joint sets and random joints have similar spacing although the spacing may be greater in some areas due to decreased frequency. The minor joints and random joints have persistence generally less than 10 ft. It was also observed that the persistence is indirectly related to spacing, with wider spacing associated with more persistent joints, and vice versa.

In outcrop joint surfaces are typically fresh to slightly weathered and clean, but can be discolored or have iron staining or carbonate filling. Steeper joints can be tight, but many are open and have been widened due to stress relief, freeze-thaw, and other erosive forces. Shallow to moderate dipping joints tend be have narrower aperture. The joint patterns create a blocky rock mass structure and in areas with a greater numbers of joint sets and oblique joints, blocks can have a tetrahedral or, less frequently, a rhombohedral shape. The combination of the joint patterns and slope faces produce blocks and wedges capable of sliding or toppling, and ultimately form talus at the base of the outcrops and within gullies.

At depth, joint orientations and character are similar to those in outcrop, but joints tend to be tight to very tight, planar, smooth to rough, and have less staining or infilling than observed in outcrop. However, iron and carbonate infilling are observed more frequently near surface where the bedrock is more fractured and susceptible to weathering and effects of groundwater movement. Some joints, particularly those located near fracture, shear, and/or altered zones exhibit slickensides.

For additional details of joint orientations, characteristics, and properties used in engineering design and stability analyses refer to Section 10.3.

6.3.4.3.2. Fracture Zones

Fracture zones consist of very closely to closely spaced (less than 1 inch to 8 inches) jointed rock where no apparent relative movement has occurred. Fracture zones are common to all rock types and are generally encountered in boreholes and less frequently observed in outcrop. In general, fracture zones consist of rock that is more fractured rock, represents a structural weakness compared to surrounding rock and are preferentially eroded. Over time, fracture zones are widened by stress relief and freeze-thaw action and other processes, which form gullies and topographic lows along the fracture zone. The geomorphic landscape of the dam site appears to be developed, particularly lower in the river valley, from the prominent geologic structure or fabric that are oriented in the northwest-southeast direction (paralleling JS1) and to lesser extent to north-south features (paralleling JS3). Because fracture zones are generally not observed in outcrop and it is difficult to assess the orientation of fracture zones from downhole logs since fracture zones contain a large number of fractures over a wide range of orientations. Thus, the best indicator of orientation of fracture zones is trend of topographic features and the presence of discrete narrow shear zones within the wider fracture zone, from which orientations can be more easily identified.

6.3.4.3.3. Shear Zones

A shear zone is a zone of rock along which there has been visible evidence of movement or measurable displacement and are characterized by the presence of clay gouge, breccia, and/or slickensides.

Two types of shears are found at the site. The first type, which is found only in the diorite, is a healed shear zone and healed breccia. This type of shear zone consists of a well indurated diorite breccia healed within a matrix of aphanitic to fine grained and andesite/diorite. The diorite fragments range from less than 5 percent to 90 percent of the zone and are generally subrounded. The matrix and rock fragments, which are observed in both outcrop and boreholes, are fresh and very hard to hard. The contacts, although irregular, are tight and unfractured. Based on the characterization of these shear zones, they are interpreted to be features that formed during emplacement.

In outcrops, healed shear zones and breccia range from less than one inch to about 18 inches wide. One-foot offsets along these features have been observed where they cross felsic dikes. Two general orientations were found for this type of shear: 305° and dipping 45° to 70° to the northeast, and 300° (120° if using strike azimuth) and dipping 65° to the southwest. Healed shear zones and breccias were found in many recent boreholes. In all cases, the zone was found to be competent with high rock quality designations (RQDs) and high core recoveries. The largest healed shear zone was up to 140 ft. wide (apparent width) in borehole DH-11 (Acres 1982a). Lacking borehole orientation data, no correlations could be made between the healed shears and breccias noted in the drill holes from the 1980s and surface exposures.

The second type of shear zone is common to all rock types and consists of brecciated rock with clay gouge. This type of shear zone is most frequently associated with fracture zones and altered rock that typically trend northwest-southeast (paralleling JS1), particularly within the dam footprint and areas immediately upstream and downstream. These shear zones typically consist of coarse to fine-grained rock fragments (breccia) weathered to tan-yellow, orange, brown and sometimes includes a narrow zone (few inches) of silt or clay gouge within the central portion. Both the breccia and gouge can be soft to medium stiff, and friable. These shear zones vary from less than 0.1 inch up to 10 ft. wide (apparent width; Acres 1982a), but are generally less than 1 to 2 ft. wide. An example of a typical shear zone in outcrop is shown on Figure 6.3-18 and Figure 6.3-19. Carbonate and chlorite mineralization are commonly associated with this type of shear zones, and some are partially to completely filled and cemented with carbonate. Slickensides are often found in most shear zones, but not all, and can occur on both the carbonate and chlorite surfaces. When found in association with these fracture or alteration zones, shear zones have been referred to as shear/fracture and shear/alteration zones.

Figure 6.3-18. Shear Zone in Outcrop at GF1.

Figure 6.3-19. Close-up of 3 to 4 ft. Wide Shear Zone at GF1

Given the relatively narrow width of most shear zones with respect to the dimensions of the dam foundation, these features are not anticipated to be sources of major structural weaknesses in a foundation consisting of otherwise relatively fresh and sound bedrock. However, shear zones are expected to require local treatment, to remove soft or deteriorated materials to limited depth below the foundation level, and be replaced with dental concrete.

6.3.4.3.4. Structural Features

During the 1980s site investigations, geologic interpretations were developed that included characterization of the geologic conditions and the preparation of a geologic map of the dam site area (Acres 1982a, 1982b). Therein, a geologic framework was presented that identified several structural features that largely coincided with geomorphic expressions (e.g., gullies) in the abutment landscape, which were further defined by geologic mapping observations, drilling and in situ testing evidence of fracture, shear, and alteration zones, and lower bedrock velocities from seismic refraction data. The so-called “geologic features” identified by Acres (1982a, 1982b), were interpreted, and the postulated persistence of these features were depicted in the geologic maps produced at that time. Eight geologic features (designated GF1 through GF8) were delineated, which included fracture or shear zones with widths greater than 10 ft. and wide zones of alteration with associated fracture and shear zones (Acres 1982b; Figure 5.2).

Geologic features GF4A/GF4B and GF5 are projected to be encountered in the foundation of the proposed dam. It is these structural features in particular that were the focus of the 2012 and

2014 site investigation programs to reduce geologic uncertainties. These geologic features are expected to have significant influence on the design of the project, in particular the detailed siting and foundation design of the dam.

As part of the feasibility study, a new data set and tools were employed to investigate, define and evaluate the previously identified structural features. Light Detection and Ranging (LiDAR) surveying was performed in 2012 to develop bare-earth imagery and a detailed topographic map of the project area. The LiDAR imagery was also used to examine the dam site area landscape and to assess surficial geology and geomorphic features, and to identify potential lineaments or faults. Additionally downhole optical and acoustical televiewer logging was performed in the boreholes to obtain rock discontinuity orientations.

Based on a review of the earlier studies and the current geologic site investigations, the interpretation of the dam site geology has evolved, and updates and revisions of the interpretation are described herein. Evidence from seismic refraction surveys to support the extension or persistence of several “geologic features” over several thousands of feet, as depicted on the dam site geologic map (Acres 1982b) and extending from one abutment to the other is speculative or absent. Geomorphic evaluation using LiDAR elevation data; geologic mapping; drilling and in situ testing; and a careful review of the original geophysical testing supports the updated geologic interpretations as shown on Drawing 01-01GT006.

Other structural features, located upstream or downstream of the dam site that are not expected to directly impact the general arrangement or dam and other project structures, were also reviewed at a reconnaissance level for completeness and are discussed separately.

6.3.4.3.4.1. Structural Features in Dam Site Area

As alluded to earlier, a review of the existing data on the dam site geology was made and site investigations were performed that included lineament analysis of the dam site area using the newly acquired digital elevation data and abutment geologic mapping of and the drilling across the largely northwest-southeast trending structural features previously identified. The following is a discussion of the observations and reinterpretations made based on the efforts under this study.

Geologic Feature GF4

The 1980s studies interpreted GF4 to consist of two fracture/shear zones that are continuous across the current dam foundation and therefore, might also appear in the diversion tunnel and spillway excavations proposed at that time. The descriptions and interpretations from the 1980s indicate that on the south bank GF4 consists of two fracture zones with some minor shear zones

– each inferred to be less than 10 ft. wide – that extend upslope from the shoreline through a northwest-southeast trending gully to about El. 1950 ft., where it appears to terminate at a relict crescent-shaped rounded scarp-like feature between El. 1950 ft. to El. 2250 ft. Overall these two fracture zones with evidence of shearing (e.g. gouge) were postulated to extend across the dam site over a distance of up to 3,500 ft. According to Acres (1982b), the fracture zones contain moderately weathered rock that may be altered and is characterized by very closely to closely spaced joints from JS1, JS2, and JS3 and are heavily coated with carbonate and iron oxide staining.

In contrast, the mapping performed in 2014 indicates that the continuity and persistence of GF4A and GF4B (named by Acres 1982) cannot be reliably traced from the south bank to the north bank. To do so, would require the two fracture zones to transect a prominent 30-ft-high outcrop along the south river bank, which consists of sound, massive to blocky diorite. Thus, GF4A and GF4B are not persistent over the length previously shown and are reinterpreted as two features on either side of the river as shown on Drawing 01-01GT006.

Geologic mapping and drilling performed to intersect these structural features at depth in 2012 to 2014 have helped revise the previous interpretations of GF4 on the north bank. GF4B is described as multiple discrete fracture zones, splays or branches, orientated in the northwest-southeast direction, that intersect a north-south trending fracture zone. The fracture zones, which may contain narrow shear zones typically less than eight inches wide consisting of breccia and clay gouge, are correlated to several prominent gullies immediately upstream of the dam right abutment between the shoreline to about El. 1850 ft. that are as much as 40 to 50 ft. wide. Although the gullies appear wide at the surface, mapping and drilling suggest that the fracture zones are much narrower.

During 2012, drill hole DH12-3, was drilled inclined to the southwest to intersect the geologic structure below this group of gullies. Information from this drill hole indicates the rock alternates between zones of slightly to moderately fractured rock to very closely to closely fractured rock in the upper 300 ft. Some of the fracture zones contain some minor shear zones (less than 1 ft. wide) consisting of breccia and clay gouge. For example, there are three fracture zones some with gouge in the upper 300 ft. for the borehole. Between a depth of 76 and 80 ft., a 6-inch wide zone of completely weathered rock oriented east-west (278° to 288°) with vertical dip is associated with extremely close to closely spaced joints. At 130 ft. depth, another fracture zone included a 6-inch wide zone of plastic silt was encountered, but the orientation is not known. At a depth of 179 ft., an 8-inch wide zone of plastic clay was encountered within a fracture zone and oriented to the northwest-southeast (313°) and dipping 70° to the southwest. Below 300 ft., fracture zones in this borehole are generally less than about five to seven feet wide and occur less frequently in what is generally moderately fractured rock. Discontinuities within fracture zones are typically tight, surfaces are rough to smooth with iron oxide staining, white carbonate deposits, or chlorite, and some surfaces contain clay infilling with slickensides. The fracture zones appear to contain some minor shear zones, which are typically less than a few ft. wide.

In the 1980s studies the continuity or persistence of GF4B (formally GF4A and GF4B) had been tentatively correlated to lower seismic velocity zones and a change in bedrock slope on seismic profiles. However, re-examination of the geophysical profiles does not provide evidence sufficient to warrant this interpretation nor the extension of these fracture zones to the northwest as had been represented. The previous interpretation of geophysical survey line SL82-9 was that GF4A and GF4B were associated with a change in seismic velocity from 20,000 fps (ft. per second) to 16,500 fps. Both velocity values are high, and according to the criteria used at that time, are indicative of fresh to extremely fresh bedrock (Acres; 1982b). Therefore, it is not appropriate to consider such a minor contrast in the bedrock seismic velocity related to fracture zones to be of any major significance. If anything, such a contrast is more likely due to the presence of multiple narrower features of lesser prominence, slight changes in the rock material properties, or other variations.

Although fracture zones were not directly observed in outcrop, the drilling information and particularly observations from mapping support the interpretation that GF4B consists of multiple narrower fracture zones trending in the northwest-southeast to north-south directions. Mapping within the gullies suggests that the gullies formed by preferential erosion of narrower fracture zones (with or without minor shear zones) that were enhanced and widened by weathering processes. Continued removal of rock blocks and wedges by erosional processes such as stress relief along steep joints and freeze-thaw, has created the present geomorphic surface and filled the gully floors with boulder talus. For example, Figure 6.3-20 shows an approximately 5 to 7 ft. wide gully between outcrops of competent diorite. This width constrains the maximum width of the fracture zone to these dimensions.

Figure 6.3-20. Northwest Trending Gully of GF4B (width of fracture zone is constrained by the gully width)

Another example of gully formation on the right abutment is shown in Figure 6.3-21. The gully appears to have formed along a narrower zone of weaker geologic materials (e.g., fracture zone), but has been widened by erosion. On the left side of the photo (west) is an outcrop of competent rock with prominent joint set dipping 35° to 55° to the east (toward the gully), and on the right side of the photo (east) the outcrop has joints that dip steeply to the southwest (into the gully). The line of intersection of these joint sets trends to about 345° (nearly north-northwest to south-southeast), which parallels the trend of this gully. This observation supports the notion that the gullies were likely initiated by erosion of a relatively narrow fracture zones consisting of weaker rock. Projecting the major joints from each outcrop to the gully floor, constrains the maximum width of this fracture zone to about 10 ft. The gully has likely been widened by erosion of blocks from both outcrops and talus blocks are deposited in the gully floor.

Figure 6.3-21. North-northwest Trending Gully of GF4B

Although fracture zones are not readily observed at the ground surface, the conditions are better represented in the rock cores. Several fracture zones with breccia and gouge can be observed in the rock core from DH12-3, which is believed to cross several fractures zones comprising GF4B on the north abutment. For example, at a depth of 179 ft. a northwest-southeast trending fracture zone consisting of close to very closely fractured rock and eight-inch thick zone of clay gouge shown in Figure 6.3-22 was encountered. Although these fracture and shear zones are considered relatively minor features with respect to the dimensions of the dam, the project structures have been moved slightly downstream, to reduce the potential that this or similar structural features will impact the dam or require foundation treatment.

Figure 6.3-22. Rock Core from DH12-3 with Closely Fractured Rock and Shear Zone at Depth of about 179 ft. (red box)

Geologic Feature GF5

GF5 is located downstream of GF4A and GF4B and consists of multiple fracture zones with some minor shear zones that cross the dam footprint on the lower right abutment. The geologic structures comprising GF5 are similar to those of GF4B and trend northwest-southeast (310° to 320°). The structures are steeply dipping, and were anticipated to be encountered in the dam foundation, diversion tunnel, and spillway excavations. On the north bank of the river, GF5 is interpreted to fall within a 100-foot wide gully that extends from the shoreline to about El. 1700 ft., bound by the 75-ft-high rock face (Figure 6.3-23) immediately downstream. On the south abutment, GF5 was interpreted to extend to the SW to about El. 2100 ft. Overall, the fracture zones with evidence of shearing (e.g., breccia and gouge) are shown to extend across the dam site over a distance of up to 1,500 ft.

Figure 6.3-23. 75 ft. High Cliff on Right Abutment Forming the Downstream (Southwest) Boundary of GF5

Although there is no topographic expression of the fracture and shear zones at the surface on the north abutment above about El. 1700 ft., GF5 was correlated with several shear and fracture zones intersected in borehole DH-9 (Acres 1982). The joints and fractures in DH-9 are generally iron stained and carbonate-coated, and faint slickensides occur on some surfaces. The RQDs in DH-9 are lower, with an average of 57 percent. Hydraulic conductivities are generally between 10^{-1} cm/sec and 10^{-3} cm/sec, and decrease with depth. However, the orientation of the fracture zone in DH-9 is not known and therefore cannot be positively correlated with fracture zones of GF5.

Northwest of the spillway and dam proposed at the time, it was speculated (Acres 1982b) that GF5 is correlated to lower-bedrock velocity zones along several geophysical survey lines (SL82-1 and SL82-9). No low-velocity zones were encountered along SL80-2 that could imply continuation of this feature further. It is also worth noting that the low velocity zones observed in some profiles could also be due to north-south trending fracture zones that are more prevalent downstream of the dam in the northwest quadrant, localized weathered rock, changes in the rock material properties, undulating bedrock profile difference in overburden materials, or the presence of localized ice layers. In the absence of more reliable evidence, such as more inclined boreholes it is now considered speculative to assume GF5 extends more than 2,000 ft. to the northwest beyond the gully it has formed.

On the south bank, GF5 is correlated to a 10 ft. wide fracture zone at river level and a series of minor northwest trending shears between El. 1650 ft. and El. 1850 ft. upstream of the dam footprint (Acres 1982). In addition, further upslope, GF5 was correlated with a 15,000 fps bedrock velocity zone along SL80-3 and a bedrock depression found in borehole DH-25 and SL82-12. In this area, overburden thickens from 10 or 15 ft. to nearly 80 ft. However, upon recent re-examination of the topography and the geophysical data, the seismic velocities along SL80-3, which follow a relatively steep ridge, may instead be representative of a rock mass with open stress relief joints that are very common in steeper rock outcrops. In addition, the bedrock depression in DH-25 and SL82-12 may be associated with the fracture zones of GF4A and the landslide scarp located immediately upslope.

In 2012 and 2014, inclined drill holes DH12-4 and DH14-11 were drilled across this gully on the right abutment approximately normal to GF5. Based on a review of the geologic logs, downhole logging, and core photographs for DH12-4, several fracture and shear zones were observed in the upper 150 ft. At a depth of 74 to 79 ft., a shear zone consisting of closely fractured rock that is moderately to highly weathered that includes approximately 8 to 14 inches of light gray silty clay was observed. The downhole logging indicates this shear zone trends to the northwest-southeast (303°) and dips 86° to the southwest. Between depths of about 106 to 116 ft., the RQD ranges from 8 to 40 percent and contains a 6 to 12 inch wide shear zone at depth of about 113 ft. Within this zone, several prominent discontinuities in the rock core trend northwest and dip steeply to the northeast. Between depths of about 120 and 150 ft. the rock contains zones of closely fractured rock that is moderately to highly weathered, and some individual discontinuities are slickensided. Within this zone at a depth of about 137 ft. and again at about 148 ft., the joints are closely to extremely closely spaced over lengths of 8 inches to 2 ft. with some discontinuities exhibiting planar and slickensided surfaces with calcite, chlorite, and some clay infilling and coatings. In general, these discontinuities appear to trend in the northwest-southeast direction and have steep dips. Below 150 ft., the RQD is typically greater than 90 percent although a few runs had RQDs between 60 and 70 percent.

Data collected from drill hole DH14-11 indicate that the upper 65 ft. of the hole contains rock with moderate to closely spaced fracturing and localized zones of moderately to highly weathered rock. The discontinuities have heavy iron oxide staining, likely due to their proximity to the ground surface and the adjacent rock face. At a depth of 78 ft., a one-inch wide shear zone trending 303° and dipping 83° to the southwest was encountered and contains two-inches of altered rock on each side of the shearing plane and a fracture zone that extends to a depth of about 81 ft. Between depths of 87 to 103 ft., the rock is very closely to moderately closely fractured rock and includes an 8 to 12 inch zone of very closely fractured rock at about 90 ft. that is oriented nearly east-west (84° or 264°) that is nearly vertical. In addition, moderately to highly weathered rock at a depth of 101.5 to about 103 ft. includes a shear zone oriented west-northwest (about 284°) that is nearly vertical. Below a depth of 103 ft., the rock is slightly to moderately fractured with only localized fracture zones. A zone of close to very closely fractured rock was encountered between depths of 165 to 170 ft., which included a 1 to 2 inch shear zone at a depth of 165.6 ft. oriented north-south and dipping 77° to the west. Finally, a fracture zone consisting of closely to very closely fractured rock was encountered between depths of about 190 and 192 ft.

While subsurface and surface data relative to GF5 lack compelling demonstration for the presence of a significant, through-going, fault or shear zones, it has been depicted as the widest and most continuous feature in the dam foundation. However, based on the site investigations and a review of the previous studies, it appears that GF5 consists of several fracture zones ranging from about 5 to 10 ft. in width and some contain shear zones or gouge up to 14 inches wide. In addition, the persistence of GF5 to the northwest and southeast is only based on perceived “low” bedrock velocity zones and is therefore speculative at best. Therefore, in the current interpretation, the width of and presumed length of GF5 has been narrowed and reduced compared to representations from the 1980s studies. As with GF4A and GF4B, the fracture zones were not directly observed in outcrop, the drilling information and particularly observations from mapping support the interpretation that GF5 consists of multiple narrower fracture zones trending in the northwest-southeast directions with steep dips to the southwest and northeast. Mapping within the gullies suggests that the gullies formed by preferential erosion of narrower fracture zones that were enhanced and widened by weathering processes. Continued removal of rock blocks and wedges by erosional processes such as stress relief along steep joints and freeze-thaw, has created the present geomorphic surface and filled the gully floors with boulder-sized talus.

Because fracture zones in GF5 are readily observed at the ground surface, the conditions are best observed in the rock cores. In DH14-11 at a depth of 102 ft. a northwest-southeast trending fracture zone consisting of close to very closely fractured rock and approximately 20 inch wide shear zone (apparent width) of moderately to completely weathered and friable and brecciated rock as shown Figure 6.3-24. Although considered relatively minor features with respect to the dimensions of the dam, due to the location and trend of this and similar fracture zones and shear zones in GF4B, the project structures were moved slightly downstream, to reduce the potential impacts that this or similar structural features could have on the dam foundation.

Figure 6.3-24. Rock Core from DH14-11 with Closely Fractured Rock and Shear Zone at Depth of about 102 ft. (red box)

6.3.4.3.4.2. Additional Geologic Features

In addition to geologic features encountered within the dam footprint, six additional geologic features are located both upstream and downstream of the dam.

Geologic Feature GF1

Geologic Feature GF1 is located approximately 2,200 ft. upstream of the dam axis, and is visible on the north bank at the sharp bend in the river. The area is characterized predominantly by sound, jointed bedrock that includes steeply inclined northwest trending zones of closely fractured rock up to 15 to 20 ft. wide, 5 to 10 ft. wide zones of weak, friable altered rock, and shears that measure 1 inch to approximately 3 ft. in width (Figure 6.3-25). The 3 to 4 ft. wide shear zone exposed at river level is oriented 334° and dips 64° to the northeast. This particular structure is known as GF1E as mapped by Acres (1982b) is presumed to extend about 400 to 500 ft. to the northwest and intersect with another fracture/shear zone located within a steep sided gully.

The weaker zones have contributed to the erosion of steep gullies (Figure 6.3-26), which are separated by intact rock ridges. The gully (near OC 10 and OC 11 on Drawing 01-01GT002) is formed along the fracture and shear zone comprising the contact between the diorite to the left side of the photo (southwest) and andesite porphyry on the right side (northeast). The narrowest portion of the gully is between 5 and 10 ft. wide, which constrains the maximum width of the fracture and/or shear zone that forms this gully. The upstream part of GF1 also coincides with a steep, narrow gulley that is an approximately 10 ft. wide shear/alteration zone that forms the contact between the diorite and a large mafic dike. Above GF1, along its possible projection to the northwest, GF1 is blanketed by a thick layer of glacial drift, about 15 to 95 ft. thick. Beneath the glacial drift, unique to this location, a zone of highly weathered to decomposed diorite exists locally at the bedrock surface that is as much as 70 to 80 ft. thick. At depth, individual zones of closely fractured rock and alteration are as much as 15 ft. wide. These weaker and fractured zones have occasional slickensides and clay infilling, which may be related to local shearing, was observed. Healed breccia and microfractures are also common in the rock mass (Harza-Ebasco 1984).

In assessing the hydraulic characteristics of the highly weathered bedrock at elevations above GF1, the rock mass permeability was found to be very low and the groundwater levels in the rock were determined to be 10 to 20 ft. below the ground surface. The individual zones comprising GF1 are difficult to trace due to the steepness of the terrain and talus cover, and the thick glacial overburden deposits above El. 2000 ft.

In 1984, drilling was performed a short distance from the outcrops to the northwest along the projection of the GF1 in order to determine the persistence or continuity and the erosion potential of the northwest trending fracture and shear zones (Harza-Ebasco 1984). Based on the lack of any structural discontinuities other than fracture zones and relatively narrow shear zones, the low rock mass permeability, and high groundwater levels, it is concluded that there is no evidence of a major structural zone of weakness, that would be indicative of a distinct and continuous “fault” to the northwest. Neither is there a structure that would permit excessive seepage or internal erosion within the rock mass toward Tsusena Creek.

Figure 6.3-25. GF1 Located 2,200 ft. Upstream of the Dam Axis (view looking northwest)

Figure 6.3-26. Narrow Gully in Area of GF1

Geologic Feature GF2

GF2 is a northwest-southeast trending fracture zone with minor internal shear zones that is presumed to extend through prominent gullies on the north and south banks of the river. On the north bank, the fracture zone is located between outcrops that are oriented parallel to JS1 and about 70 to 100 ft. apart (Acres 1982a, 1982b). However, the fracture zone is not observed in outcrop on the north bank due to presence of blocky talus on the gully floor. The topography of the gully within which the geologic feature is located can be used to constrain the width of the geologic feature. On the south bank, GF2 is presumed to coincide with an incised gully that has side walls formed by close to very close spaced and open joints belonging to JS1. The topography indicates that the width of the narrowest part of the gully on the north and south river banks is about 20 to 30 ft. Presuming that the fracture zone has a similar character to the north, the narrower GF2 formed within a wider gully there suggests the width of the north gully has been enhanced due to erosion processes, similar to what was observed in other geologic features described above.

At higher elevations along the north bank, several geophysical survey lines correlated slower bedrock velocities with the extension of poorer quality and fractured rock of GF2. However, the survey lines do not clearly explicit anomalous velocities at these locations. Acres (1981) indicated apparent anomalies in SL81-15 might be due to topographic effects or slight changes in thickness of surficial materials. In addition, the geophysical surveys performed furthest to the northwest did not record any low velocity bedrock zones, a finding that suggests that GF2 is discontinuous to the northwest (Acres 1982b). Therefore, the extension of the fracture zone to the northwest beyond the surface expression of the gully is now considered speculative.

Geologic Feature GF3

GF3 is an area approximately 1,200 to 1,500 ft. wide on the north and south banks bound by GF2 and GF4A (south bank) and GF4B (north bank). Outcrops are well exposed on the south bank and are limited on the north side due to a wide blanket of talus covering the slopes below about El. 1650 ft. The fracture and shear zones in this area are predominantly parallel to Joint Set I, although geologic structure parallel to JS2 and JS3 have been measured (Acres 1982).

GF3 area is characterized by fracture and minor shear zones on the south bank that are generally less than 6 ft. wide. The most significant feature that was identified is a 20 ft. wide fracture zone within a deep gully, which is suggested to correlate with narrow gully on the north bank and is believed to parallel GF2 to the northwest (Acres 1982a). The gully is located more than 1,000 ft. upstream of the dam axis. Review of the topography and LiDAR data indicates that the outcrops on both walls of the gully constrain the fracture zone width to about 10 ft. The weaker fracture zone has likely been eroded, leaving a wider gully, a similar process that was observed in GF4B and GF1 described above.

Although the evidence of distinct fracture and minor shear zones is based on the gullies observed on the south abutment, there is no surface evidence for the continuation of these suspected features to the northwest and beneath the talus on the north bank. The talus has formed because of erosion of rock outcrops.

Based on the descriptions presented above, the fracture and shear zones that have been encountered in this area of the south bank are considered relatively minor and local features. As minor features in an otherwise competent rock mass, they would only locally influence the engineering design of the Project and if encountered during construction, they would likely receive localized ground treatment as needed. Therefore, it was misleading to characterize a 1,200 to 1,500 ft. wide zone of relatively minor features as a single geologic feature. Thus, it is now considered that GF3 is a non-existent feature and no longer applies. Instead, this area is now described as a zone of minor fracture zone and shears.

Geologic Feature GF6

Geologic feature GF6 is characterized by a north-south trending shear zones, fracture zones, and open joints; east-west trending open joints; and northwest trending shears. These features are exposed in deep gullies in the northeast-facing high, massive rock cliff on the south side of the river. As described by Acres (1982) in north-south gully features up to 2.5 ft. of gouge was observed in slope debris, and open joints dip to the east and may be several feet wide. East-west trending joints dip 70 to 80 degrees to the north (towards the river). The intersection of these joint sets has resulted in purported localized block slumping. These features were not inspected during the 2012 and 2014 investigations due to difficult access and because they are located 1,000 ft. or more downstream of the dam site.

Geologic Feature GF7

GF7 is characterized by numerous north to northwest trending, nearly vertical shear, fracture, and alteration zones that parallel JS1. North-south trending features, parallel to JS3 are also present. Initial mapping was performed in this area by the USACE (1978) and Acres (1980) and detailed mapping was performed by Acres in 1982 after this area was recognized as a zone where more prominent geologic structures were evident. These structural features are best exposed on the north bank of the Susitna River, as rock outcrops are limited on the south bank.

The northwest trending features typically trend 295° to 305° and have high angle dips ranging from southwest and northeast. These northwest trending features subparallel the trend of the Susitna River at this location. Within the diorite, alteration zones consisting of gouge and breccia up to 2 ft. wide is yellow-orange, soft, and friable. The rock surrounding these areas is generally fresh to slightly weathered, but the surrounding rock may have very closely spaced jointing. The extent of these features could not be traced accurately further downstream. In most areas, the shear zones were projected across outcrops, and where not exposed in the slope as they tend to form topographic lows or gullies. Slightly further upstream, the features are covered with talus, and their presence is inferred by lower seismic velocities.

The most prominent northwest trending features GF7J (Acres 1982) extends from the north bank to the shoreline along the south bank. On the north bank, GF7J lies in a deep, vegetated gully trending at 290°. Exposures in the gully show very closely spaced vertical fractures trending approximately 290° with thin zones of breccia and gouge. The andesite porphyry of the gully walls is slightly to moderately weathered. GF7J is projected south of the river to correlate with features exposed along the base of the high, massive rock cliff (associated with GF6) located about 1,000 ft. downstream of the toe of the dam. Based on the slope of the cliff, GF7J appears to dip about 75° to the northeast. GF7J has also been correlated with a shear zone between depths of 97.8 to 104.0 ft. in DH-1 in which the rock is slightly to moderately altered and includes shear zones less than 6 inches wide. The rock is moderately hard, but soft in shear zones. RQDs are generally less than 40 percent in DH-1 with permeabilities about 10^{-3} cm/sec. Drilling investigations of the northwest trending features by Harza-Ebasco (1984) indicated variable jointing, local shearing, alteration, and healed breccia, but did not encounter major structural features.

On the south bank, GF7J projects from the river bank and is correlated to an exposure in a steep-walled, 10 to 15 ft. wide gully at the andesite porphyry/diorite contact near El. 1750 ft., which cross-cuts both rock types. The rock within GF7J has a granular, nearly schistose, character typical of cataclastic rocks, although it has been healed and re-sheared. No exposures of GF7J have been found above the contact, but a projection of the exposure indicates that it may found in the dam foundation high on the left abutment.

Over more than a 600 ft. section of the south abutment downstream of the dam, the slope area is sparsely populated with rock outcrops, a break in the nearly continuous rock cliff and outcrop exposure that is seen from the dam left abutment upstream and in the bend downstream in the area of GF6. The slope is covered by talus and colluvium material. This area coincides with the projection of suspected northwest trending discontinuities that likely is subparallel to GF7, and may explain the lack of rock outcrops lower in the abutment on the south bank. No drilling investigations have been performed on the slope in this area and future investigations will be required to evaluate the conditions and any possible significance to the design. At this time, the general arrangement for the project has avoided placing any structures in this area.

Geologic Feature GF7Q (Acres 1982) is a north-south trending feature located about 2,800 ft. downstream from the dam and is most prominently exposed in a 40 ft. wide, deep talus-filled gully that coincides with the andesite porphyry/diorite contact. The rock is moderately close to closely fractured with local shears and alteration zones which trend parallel to JS1 (330°) and JS3 (0°). Slickensides on the gully wall indicate vertical displacement. The degree of rock fracturing varies widely in this area, and is influenced by structural control and near surface stress relief fracturing. Because of the lack of surface exposure, and the variability of the features, no major structural features could be identified in outcrop.

GF7Q is correlated to a prominent gully on the south bank. However, no surface exposures of the fracture and shear zones were observed in this gully, instead only talus filled gullies were encountered. However, the east face of the gully, oriented 294° and dipping 70° to the southwest, exhibited slickensides (Figure 6.3-27) plunging about 3° to 294°.

The presence of slickensides with different relative movements from one side of the river to the other suggests there may be multiple features with a relatively limited area or complex relative motions.

For a more detailed discussion of the geologic features and sub-features associated with GF7, refer to the Acres (1982b) and Harza-Ebasco (1984) reports.

Figure 6.3-27. Subhorizontal Slickensides along Outcrop Surface near GF7Q

Geologic Feature GF8

An approximately 400-ft wide northwest trending zone of altered rock had been previously interpreted on the south abutment downstream of the dam. The extent and trend of this alteration zone was largely inferred based on limited borehole data, and geophysical surveying performed by Acres in 1981 and 1982 due to the lack of bedrock outcrops, the area is overlain by glacial till.

From a single geophysical survey line, a lower velocity zone (12,000 fps) was noted that extends for about 1,100 ft. toward the east-southeast. Nearby, borehole BH-12 purportedly encountered nearly 200 ft. of altered rock. The core recovery was good, but the quality of rock was relatively poor. The altered rock included localized areas of moderate to severe alteration and shear zones less than 6 inches wide. Joints were generally closely spaced, healed, with some carbonate, and chlorite. However, in reviewing the alteration zone it is believed that there is insufficient evidence to support the delineation of a 400-ft. wide zone of altered rock. In reviewing the log for BH-12, the overlying 80-ft. thick andesite was largely unaltered except for an approximately 10 ft. wide band at depth associated with shear. Other features included ¼-inch thick clay gouge and fracturing and discrete alternation or shear alteration zones ranging in width from about one to four feet to a depth of about 290 ft. in diorite. Below this depth there are several zones of alteration or shear/alteration, in particular the slightly to moderately altered zones between depths of about 290 to 305 ft. and 345 to 386 ft. below the ground surface.

In most instances, the rock mass is only slightly altered, which has limited impact on the overall physical properties of the rock. Moreover, lacking evidence of shearing and alteration in the nearby boreholes BH-8, DH-12, DH-23, and DH-24 or in outcrops, the extension of the alteration zones of unknown orientation that was encountered at depth in BH-12 would be speculative. Thus, the wide band that had been part of earlier geologic interpretations has been omitted from the current interpretation of the site geology. Instead, only the limits of altered rock encountered in outcrop are shown on Drawing 01-01GT006.

Geology beneath the Susitna River

Because of east-west trending linear sections in the Susitna River valley near to and at the dam site, in earlier studies it had been conjectured that perhaps erosion of the river valley was structurally or fault-controlled. Gedney and Shapiro (1975) had identified an east-west trending lineament that roughly coincided with the Susitna River valley, but at the dam site, the lineament appeared to cross through the right abutment. Although drilling had been performed within the river for other objectives, sufficient data had not been obtained to understand the geologic conditions beneath the river.

During the 2014 site investigations, two inclined drill holes, DH14-9b and DH14-10, each just under 700 ft. long were drilled beneath the river, approximately 200 ft. apart from opposite banks. These boreholes provide about 90 percent overlay over the width of the river channel. In general, bedrock beneath the river channel is fresh to slightly weathered, strong to very strong diorite with occasional discrete zones of alteration and minor fracture and shear zones. The alteration zones were typically comprised of moderately altered, medium strong to strong diorite and were about five feet thick or less; however, some altered diorite zones were up to 14 ft. thick. Zones of closely to very closely fractured rock, generally less than five feet in width and sometimes less than two feet wide were encountered sporadically at depth. Minor shear zones with one to two inches of brecciated rock and clay gouge were encountered in DH14-9b at about 146 ft., 633 ft., and 660 ft. depth and in DH14-10 at depths of about 142 ft., 225 ft., and 507 ft. (Figure 6.3-28 and Figure 6.3-29), and included slickensides. These shear or shear/altered zones are not anticipated to be sources of major structural weaknesses in the otherwise sound bedrock foundation. The drilling encountered no large-scale shears zones or faulting beneath the river.

Figure 6.3-28. Narrow Shear Zone with Slickensides, Calcite Filling in DH14-10 at a Depth of 507 ft.

Figure 6.3-29. Close-up of Shear Zone with Slickensides in DH14-10 at Depth of 507 ft.

Fracture Zone Downstream of GF5 on North Bank

A narrow gully appears on the north bank approximately 220 ft. downstream of GF5 (Drawing 01-01GT006). This gully appears similar in character and orientation to those of GF4B and GF5, but is only 10 to 20 ft. wide on the gully floor (Figure 6.3-30). In 2014, borehole DH14-12 was drilled perpendicular to this gully to intersect the discontinuities and to characterize the geologic structure that may have contributed to this geomorphic feature.

Figure 6.3-30. Gully Downstream (west) Boundary of GF5 on the North Bank (view to southeast)

Data collected for borehole DH14-12 indicate that the upper 70 ft. of the hole contains rock with moderate to closely spacing and zones less than 3 ft. wide consisting of closely fractured and weathered rock. The discontinuities have heavy iron oxide staining due to their proximity to the ground surface and adjacent rock face. At a depth of 74.5 ft., a three-foot wide zone of closely fractured rock was encountered with a shear zone with 1 inch of gouge. This minor feature is oriented approximately east-west (100° to 280°) and dips near vertical. At a depth of about 107.5 ft., a five feet wide zone of moderately to highly weathered and altered rock was encountered, and between depths of about 110 ft. and 112 ft., the rock is brecciated and contains gouge. This interval is oriented approximately northwest-southeast (325°) and dips steeply to the northeast. Below a depth of 112 ft., the rock is lightly to moderately fractured with RQD greater than about 75 percent.

During mapping within this gully a shear zone was identified on the southwest wall of the gully and oriented approximately 290° and dipping about 70° to the southwest (Figure 6.3-31). The shear zone is approximately nine-inches wide and contains brecciated diorite and a two-inch wide central zone of clay gouge-breccia with angular sand size rock fragments. The brecciated rock is orange-brown and gouge is orange-yellow-tan. Eight inches on either side of the shear zone is moderately weathered and stained with iron oxide.

A second shear zone (or possibly a splay) inclined to the main shear zone is about 2 to 5 inches wide and is oriented 289° and dips 79° to the northeast. A third shear zone is 3 to 4 ft. west of the main shear zone and is oriented 315° and dips 78° to the southwest and is only about 1/2-inch wide and is rehealed with carbonate. It is suspected that that the gully is associated with the minor shear zones encountered in the borehole between 110 and 112 ft. depth, and to a lesser degree the nearly east-west trending shear zones.

Figure 6.3-31. Shear Zone near BS 36, Main Shear Zone on Right with Inclined Shear Zone Splay

South Bank Shear Zones between GF4A and GF5

Several narrow shear and alteration zones were observed along the south bank of the river upstream of the dam between GF4A and GF5 near observation points BS25 to BS29 (Drawing 01-01GT002 and Drawing 01-01GT006). These narrow features were identified at four locations over approximately a 75 ft. wide stretch of the river bank that predominantly consists of sound rock, an outcrop that is about 30 ft. high. Each zone is about 1 to 6 inches wide and consists of highly to intensely fractured, weathered and altered diorite. The central portion of each zone has yellow-orange-brown plastic clay gouge-breccia up to ½ inch wide. Although slickensides were not observed due to the weak and friable nature of the material, slickensides were observed on joints immediately adjacent to the shear zones. Some of the narrower zones are rehealed by carbonates. In addition, at two of the four locations the shear zones appear to have been cross-cut by felsic dikes at the shoreline (the dike was not observed at the other two locations). Although the dikes exhibit joints parallel to the shear/alteration zones, which trend northwest-southeast), the shear zones or carbonate did not extend through the dike as shown on Figure 6.3-32. This suggests that the dike intruded after the shear zone formed, and that no appreciable movement has occurred subsequent to dike emplacement.

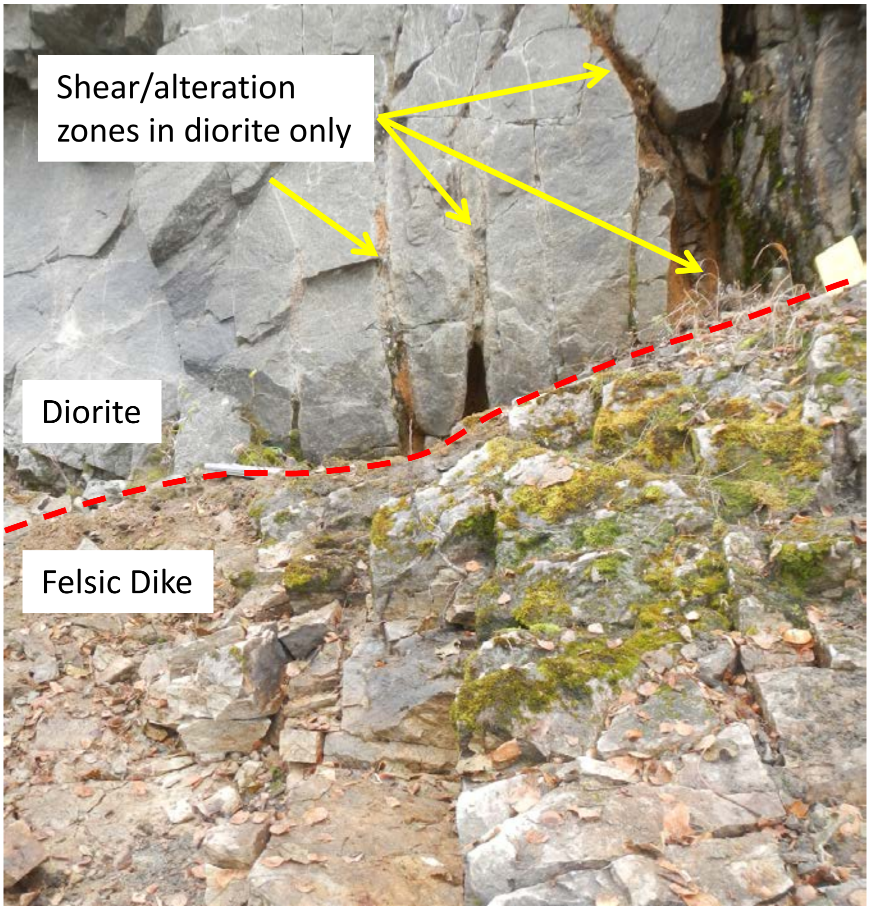


Figure 6.3-32. Shear/Alteration Zone at BS27 Cross-cut by Felsic Dike

Furthermore, one of the shear zones exhibits very thin healed joints that extend through the shear zone (Figure 6.3-33). This suggests that little to no movement has occurred since the joints were healed; otherwise the fragile joint structure within the shear/alteration zone would likely have been disturbed by subsequent shearing.

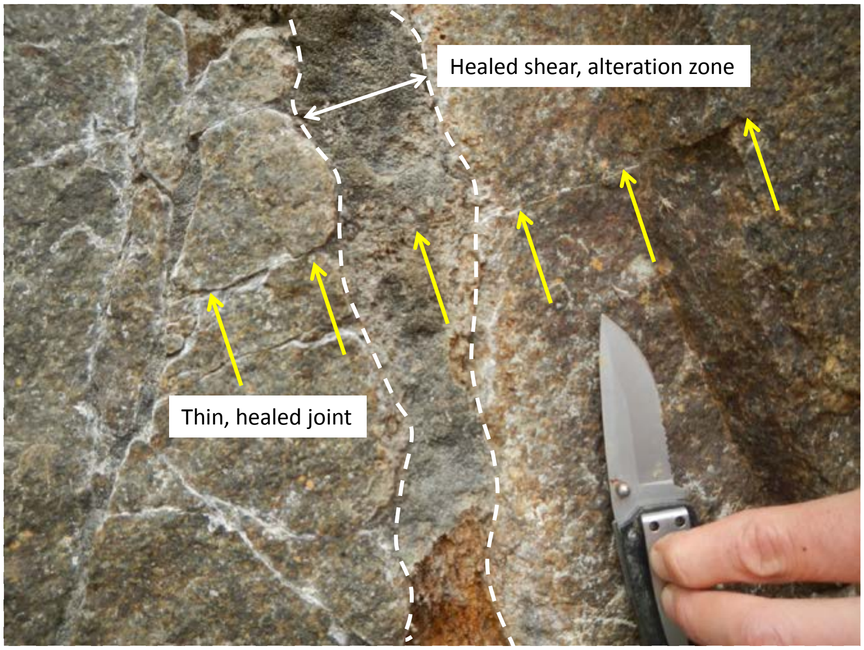


Figure 6.3-33. Continuous, Thin, Joint extending through a Healed Shear/Alteration Zone

6.3.4.4. Hydrogeology

6.3.4.4.1. Groundwater Units

The groundwater regime at the dam site is largely dominated by groundwater movement along fractures and joints in the rock mass (i.e. secondary porosity), the continuity of open fractures, and the gradients within the dam site proper. In general, the water table follows the shape of the surface topography. The groundwater conditions at the dam site are complicated by the presence of permafrost, on the left abutment and lower right abutment. Ice can be seen in numerous locations on both abutments in the winter, particularly on the steep slopes and gullies of the left (south) abutment.

Several piezometers were rehabilitated and re-established during the recent site studies, and instrumentation was installed in new boreholes to enable future monitoring of groundwater levels at the dam site. The groundwater table on the right abutment is generally from 30 to 150 ft. below the ground surface except in areas with steep terrain, where it is 5 to 80 ft. deep. Below

El. 1750 ft. near the dam axis, the groundwater table appears to be about 140 to 150 ft. below the ground surface on the right abutment.

On the left abutment, the groundwater conditions are influenced by the presence of permafrost. A relatively shallow aquifer within 10 ft. of the ground surface during the summer months appears to represent a “thawed” perched groundwater layer. In deeper piezometers, the groundwater level is 170 to 180 ft. below the ground surface. One exception is borehole BH-12, where artesian conditions were encountered at a depth of about 200 ft., and the hole produced about 2 to 3 gallons per minute.

6.3.4.4.2. Hydraulic Conductivity

The hydraulic conductivity of the rock mass does not vary significantly within the dam site area. Fresh, sound bedrock is generally characterized as low to very low permeability, less than 15 lugeons (2×10^{-4} cm/s). Areas of high hydraulic conductivity (e.g., 30 to 50 lugeons) are generally associated with fracture and shear zones. The hydraulic conductivity was also found to decrease with depth as fewer and tighter joints conduct less flow.

Due to the presence of frozen ground and ice-filled discontinuities, the low to very low rock mass permeability on the left abutment may be misleading, as the hydraulic conductivity may be influenced by ice restricting flow through joints. Therefore, tests in areas where ice filled joints were encountered are considered to represent a lower bound of hydraulic conductivity and would likely be greater if ice were not present. It should be assumed that the left abutment and other areas where ice and permafrost are encountered will need to be thawed prior to constructing the grout curtain.

6.3.4.4.3. Permafrost Conditions

Permafrost, frozen soil, and potentially ice-filled rock discontinuities are believed to be present at the dam site and in the project area. Permafrost is evident by periglacial or geomorphic features, observations of frozen soil exposed in landslide scarps, ice fillings observed in discontinuities in recovered rock cores, and ground temperature readings in boreholes. Frozen ground is believed to exist sporadically in the right abutment, based on ground temperature readings in two boreholes lower on the slope. In BH-6 (ground surface at El. 1607 ft.), just downstream from the dam axis, frozen conditions were encountered from about 60 ft. to as much as 160 ft. below the ground surface. In DH12-6 (ground surface at El. 1530 ft.), downstream of the dam axis and downstream diversion portal, frozen ground was detected from about 5 ft. to more than 40 ft. below the ground surface. In addition, in a few boreholes downstream of the powerhouse access tunnel portal, small, ice-rich samples were encountered in boreholes DH84-3 (ground surface at El. 1503 ft.), DH84-6 (ground surface at El. 1521 ft.) and DH84-8 (ground surface at El. 1677 ft.). Elsewhere on the right abutment, higher on the valley slope, no ice or permafrost were encountered.

On the left abutment, on the north-facing slopes and in general below approximately El. 2100 ft. (or possibly higher), ground temperature measurements indicate that permafrost exists to depths of 200 to 230 ft. below the ground surface (e.g., DH12-1 and DH12-6). The permafrost is believed to extend nearly continuously down to at least El. 1640 ft. (or lower) based on ground temperature monitoring data in the boreholes. The active permafrost layer, the layer subject to seasonal thawing, appears to be generally in the range of 10 ft. thick, but may extend deeper locally. The characteristics of the permafrost indicate that the site is underlain by a “warm” permafrost (within 2°F of freezing), and for the purposes of the feasibility design analysis, a temperature of 30°F is a reasonable assumption.

6.3.5. Dam Site Area Fault Rupture Evaluation

6.3.5.1. General

Permanent ground deformation from surface fault rupture can occur as primary, secondary, or sympathetic (triggered) rupture. Primary rupture is ground displacement associated with the main trace of a seismogenic fault. Secondary rupture is ground displacement from a fault that is structurally connected to the seismogenic fault, but is not the main seismogenic source. Sympathetic rupture is ground displacement from neither the main seismogenic source nor a secondary fault, but occurs principally from the effects of co-seismic strong ground shaking.

Potential sources of surface fault rupture hazard that were considered and characterized to the extent possible at the proposed Watana dam site consist of: 1) crustal seismic source faults with surface expression which transect the dam foundation directly or extend nearby, 2) buried or “blind” crustal seismic source faults with no direct surface expression, or 3) features, proximal to the dam site, not active in the contemporary stress regime that could be potentially reactivated through mechanisms of reservoir triggered seismicity. Each of these potential sources of surface fault rupture hazard was evaluated based on differing aspects and combinations of the existing geological, geophysical, and seismological data. Evaluation of crustal scale seismic source faults, either those with surface expression or “blind” structures, which are the source of primary or secondary fault rupture hazards underscores the importance of regional data because the source dimensions of these structures requires features with scales on the order of tens of kilometers. Evaluation of potential fault reactivation emphasizes knowledge of the existence, extent, and orientation of potential faults in the immediate site vicinity because of the potential significance to the dam. One common element for evaluation of each source of potential fault rupture hazard is the existence and characteristics of faults within the dam foundation. In an absence of known seismogenic faults at the dam site, the evaluation of fault rupture hazard focuses on the possibility of displacement along existing planes of weakness in the bedrock.

6.3.5.2. Methodology

The approach for evaluating surface rupture hazard at the dam site relies on four principal lines of independent data and analyses:

1. Assessment of the contemporary tectonic framework (stress field) of the site region as an indication of the potential for reactivation of site geologic features;
2. Geomorphic evaluation of Quaternary and post-glacial faulting (i.e., lineament mapping and analyses) to assess whether potential seismogenic faults are present near the site vicinity;
3. Field geologic transects to assess styles and patterns of structural deformation near the site; and,
4. Assessment of results of site-specific investigations of geologic structure in the dam foundation.

Collectively, these four lines of independent and relatively indirect evidence are integrated to develop the evaluation of (or supporting argument for no) fault rupture hazard at the dam site. This approach is in accordance with accepted methods and practices currently used for similar evaluations on projects involving major dam projects or critical facilities that pose potential hazard to the public and environment.

The evaluation collectively considers regional tectonic history, sub-regional deformation patterns observed in Mesozoic and Cenozoic rocks around the site, emplacement of intrusions and volcanics at the dam site, crustal stress orientations from earthquake focal mechanisms, known active faulting, plate motions, and GPS data, geomorphic landform evaluations, and current understanding of geologic features at the dam site. The surface fault rupture evaluation assesses the weight of evidence in relation to three topical areas:

- The regional and subregional evidence of Quaternary faulting;
- The presence or absence of faults and large-scale shear features at the dam site proper; and,
- The qualitative potential for reactivation of geologic structures at the dam site within the current tectonic framework.

Regional and sub-regional evidence of Quaternary faulting through geomorphic evaluation of post-glacial faulting is the strongest argument to address late Quaternary faulting at the dam site. The evaluation of post-glacial faulting consisted of carefully inspecting and analyzing the detailed LiDAR elevation data in the dam site area (and vicinity) to identify evidence of tectonic geomorphology suggestive of faulting. In addition, field investigations were conducted to verify the results of desktop based LiDAR lineament mapping (refer to the Crustal Seismic Source Evaluation which will be completed in 2015).

Certain methods used elsewhere to evaluate the paleoseismic characteristics of potentially active faults (such as trenching and dating of materials overlying fault traces) and help establish slip rates were not applicable in this terrain. This is largely due to the recent glacial history of the region and absence of materials that would be able to provide meaningful data to constrain activity and slip rates.

Data on the potential existence and characteristics of faults and shear features in the dam foundation are discussed in earlier sections of this report, and are further evaluated in the framework of the regional seismic source evaluations and sub-regional mapping near the dam site.

To evaluate the contemporary tectonic framework of the dam site, the updated information from the Susitna-Watana Seismic Network and the AEC regional network, as well as published literature, have been reviewed (AEC 2014). This includes data on crustal stress orientations from earthquake focal mechanisms, known active faulting, plate motions and GPS data, geomorphic landform evaluations, and current understanding of geologic features at the dam site.

6.3.5.3. Regional Evidence

The evaluation of potential crustal seismic sources has not identified any specific features with evidence of late Quaternary faulting within at least 25 mi of the Watana dam site. Within this region, faults depicted on existing geologic maps were evaluated through field and imagery analyses for evidence of late Quaternary faulting, and multiple types of imagery were reviewed to define lineaments, which were then evaluated through field investigation for evidence of potential Quaternary faulting (Fugro 2013, 2014). The area along the Susitna River, and extending at least 3 mi north and south in proximity to the dam site and deeper portions of the proposed reservoir, was also imaged with high-resolution LiDAR and aerial photography. This data improved resolution and potential detection capability to reveal the geomorphic expression and thus, the existence of potential late Quaternary faults. These efforts indicate that at least over the past 12,000 to 15,000 years – the time since deglaciation of much of the area – there is no evidence for major surface-rupturing earthquakes from crustal scale seismic sources within the dam site region (25 mi radius).

Over longer periods, the crustal seismic source evaluation also indicates an absence of significant zones of uplift or vertical deformation localized along specific surface or blind fault structures. Recurrent large earthquakes on blind faults, e.g. M ~6.5 or larger, with repeated dip slip motion over many events, eventually result in recognizable geomorphic features and topographic uplift which persists in the landscape proximal to these features. Thus, even for features with uplift rates as low as 0.1 mm/yr., a fault slip rate associated with large earthquake recurrence approaching 10,000 years, would result in relative uplift of about 3,300 ft. (1 km) over a period of 10 million years. For comparison, the topographic relief along the northwestern side of Mount Watana to the Fog Lakes area, taken as a proxy for maximum uplift in that area, is about 1,650 ft. (~500 m). Maximum topographic relief along even short, relatively linear sections of hills surrounding the Fog Lakes basin near the Watana dam site is primarily less than about 1,000 ft. (~300 m). For example, the Susitna Glacier fault, which was a “blind” initiating fault plane of the 2002 Denali M7.9 earthquake, ruptured the ground surface near the base of south-facing mountains that have about 1,500 ft. of relief. This illustrated the premise that blind or previously undetected Quaternary faults produce noticeable long-term topographic uplift near the “buried” fault tip even if the ground expression of surface rupture is not recognized. No such high-relief topography is present either at the dam site or in the site vicinity that would be a basis on which to postulate the presence of a nearby blind fault that might transect the site footprint.

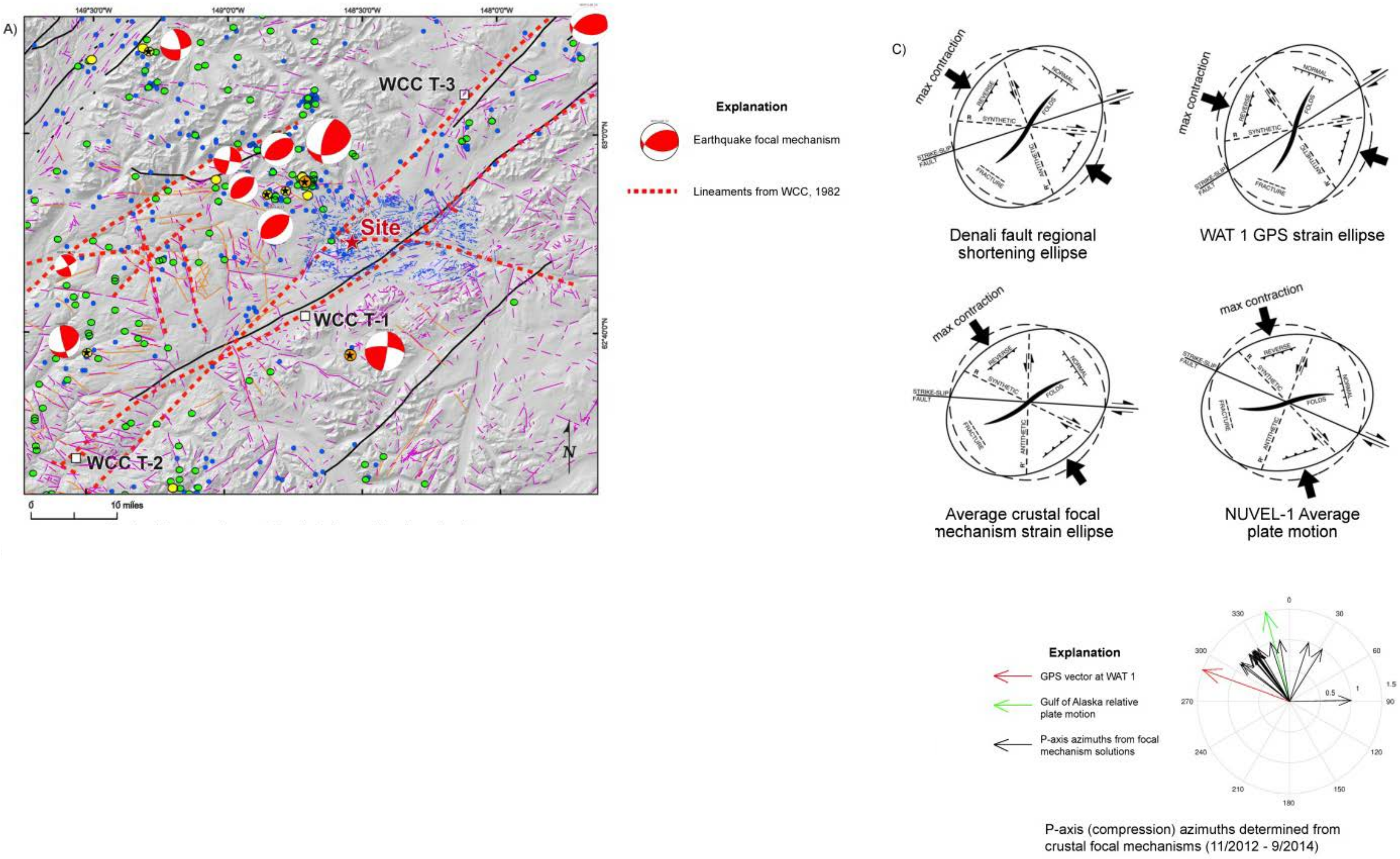
The contemporary stress regime, as defined by current plate tectonic models, GPS observations, earthquake focal mechanisms, and Quaternary faulting indicates that the Watana dam site area is subject to northwest-southeast oriented sub-horizontal compressive stress associated with the long-term ongoing subduction of the Pacific Plate in south central Alaska. Crustal deformation associated with the plate interactions has been accommodated primarily along the Denali fault, as right-lateral motion, at a relatively constant rate over the past 10 million years (Freymuller et al. 2008). Between the Denali fault and the Castle Mountain fault, geologic evidence suggests that the intervening Talkeetna Block – a region including the Watana dam site between the Copper River Basin to the east and the Susitna Basin to the west – has been relatively stable. This is consistent with the sub-regional mapping described above that indicates only gentle structural deformation (folding) and a relative paucity of penetrative faulting. Paleomagnetic data from volcanic rocks with ages of 30 to 50 million years indicates an absence of significant internal rotation or deformation within the Talkeetna Block (Figure 6.3-1). Likewise, the extent and distribution of these Tertiary volcanic rocks across the landscape of the Talkeetna Block argues against the existence of large-scale vertical or lateral fault displacements within the area.

Within the contemporary stress regime of the Talkeetna Block, the primary modes of tectonic deformation appear to involve right-lateral strike slip structures with east-northeast strikes (sub-parallel to the closest portion of the Denali and Castle Mountain faults), and with dip slip or compressional shortening along structures with northeast strikes or elongations (roughly perpendicular to the regional direction of crustal shortening), Figure 6.3-34. Structures with these orientations would be oriented roughly parallel to the overall structural grain of the pre-existing tectonic terrains and rock units within the Talkeetna Block. Secondary modes of tectonic deformation might involve left-lateral strike-slip motions along north to north-northwest striking faults, or potentially lessor amounts of extensional deformation along structures with northwest strikes. Because evidence suggests the dam site region is dominated by compression (Figure 6.3-34), extensional features are expected to be relatively less common and would primarily be expected as second or third order local structures, found locally in association with structural complexities of the primary east-northeast or northeast striking structures, instead of northwest-southeast trending structures that dominate the dam site (Drawing 01-01GT006).

6.3.5.4. Sub-Regional Geologic Transects

For evaluation of primary bedrock crustal structure, two sub-regional transects, one oriented roughly east-west along the Susitna River, and a second oriented roughly northeast-southwest along Watana Creek, provide the most complete bedrock exposures near the Watana dam site. These transects demonstrate that the Watana dam site lies within a relatively coherent structural block of folded Kahiltna Basin rocks which have been extensively intruded by mid to early Cenozoic igneous units. Data from these transects, and evaluation of existing geologic mapping, does not define any apparent crustal scale faults within at least 3 mi of the Watana dam site.

The most significant crustal fault structure in the area is the northeast-striking fault-bounded basin along Watana Creek that accommodated Tertiary sedimentation. Structural and stratigraphic data suggests that this basin most likely formed tectonically as an extensional graben in a right step-over between two strands of the Talkeetna fault, which was active at the time as a right lateral strike slip fault (essentially, a syntectonic depocenter). The dips, apparent section thickness, and extent of the Watana Creek basin sediments suggest vertical displacements of at least a few hundred meters, which would imply possible lateral offsets of at least a few kilometers. The Watana Creek basin contains non-marine sediments and undated volcanic flows that are tentatively correlated by Csejtey et al. (1978) to the Paleocene Chickaloon Formation of the Matanuska Valley. There appears to be a lack of sedimentary detritus from the surrounding more than 50 million year old dioritic and granitic sediments exposed in the surrounding the area, which in aggregate suggest a relatively older age for this period of strike slip faulting associated with the Talkeetna fault. The mid to early Cenozoic age of faulting implied by this data are consistent with existing mapping, which shows that the Talkeetna fault does not appear to offset or significantly displace plutonic rocks distally to the southwest of the Watana dam site (e.g., WCC 1982; Wilson et al. 2009). It is also consistent with new mapping in the Talkeetna Mountains Quadrangle that shows an absence of continuity for the Talkeetna fault south and east of the Susitna River (Twelker et al. 2014).



Denali fault regional shortening ellipse

WAT 1 GPS strain ellipse

Average crustal focal mechanism strain ellipse

NUVEL-1 Average plate motion

P-axis (compression) azimuths determined from crustal focal mechanisms (11/2012 - 9/2014)

Figure 6.3-34. Crustal Stress Orientations and Strain Ellipses (Fugro 2014)

Published regional mapping does not depict any other faults that would intersect the sub-regional transects or within at least 3 mi of the Watana dam site (Csejty et al. 1978; Wilson et al. 2009). Some earlier studies suggested the possibility of structural control of the east – west trending sections of the Susitna River near the Watana dam site (e.g. Gedney and Shapiro 1975; and Watana lineament of WCC 1982) based on regional-scale lineament evaluations. However, the recent field mapping evaluations have not revealed evidence for such structures and dam site drilling investigations in 2014, which included two inclined boreholes drilled from opposite banks of the river (DH14-9b and DH14-10) beneath the river channel, through bedrock, encountered no large-scale shears or fault beneath the river nor east-west oriented features.

Previous mapping conducted for Watana dam site has depicted or inferred several nearby potential faults of crustal scale (WCC 1982; Acres 1982b) as shown on Figure 6.3-6 and Figure 6.3-7. These faults are depicted with maximum map lengths of about 0.5 to 3 mi and are primarily inferred extensions of shear features found in river valley wall exposures upstream and downstream of the Watana dam site, and extended kilometers northwest to apparently similar features in the nearest bedrock exposures along Susitna River tributaries and Tsusena Creek. Bedrock exposures in the intervening areas are covered by Quaternary deposits, and geomorphic evaluations based on the detailed LiDAR data and ground reconnaissance do not disclose evidence of the fault continuity or offset of the Quaternary units. This fault is approximately 0.5 mi upstream of the Watana dam site and correlates to GF1.

An additional north-northeast trending fault is shown by Acres (1982b) upstream of the dam site near the mouth of Deadman Creek (Figure 6.3-6 and Figure 6.3-7); however, no detailed description of the fault was provided. No exposure of this “fault”, or of structures with similar orientations in the Kahiltna Basin rocks near the dam site were observed during mapping for the sub regional transects along the Susitna River in 2014. Moreover, there is no expression in the LiDAR data set of this fault along possible extensions to the northeast, and no indications of this structure in the Susitna River canyon exposures to the southwest or at the dam site. As depicted by Acres (1982), much of the trace of this fault lies beneath the Susitna River channel or beneath Quaternary glacial deposits. Near the confluence of Deadman Creek and the Susitna River, the mapped location of this “fault” was inferred from widely spaced outcrops at river level observed during 2014 mapping. However, additional outcrops of Kahiltna Basin rocks observed from aerial traverses and evident in the LiDAR data set to the north and east of the confluence suggest the “fault” is more likely the intrusive contact zone between the Tertiary intrusive rocks and the Cretaceous Kahiltna Basin rocks, with an irregular, not planar geometry.

Mapping in 2014 identified two additional minor faults in bank exposures of the Cretaceous rocks along the north bank of the Susitna River at approximately 3.5 mi upstream of Deadman Creek. Neither fault can be traced beyond the bank exposures, and no indication of these faults is evident along strike in the detailed LiDAR data set. The two faults are located about 165 ft. apart from each other and have strike and dip of 303°, 42° S and 300°, 32° S; thus, the faults trend northwest-southeast similar to the structural fabric observed (e.g., geologic features) at the dam site. Bed separation measured on the shallow dipping fault plane was 4 inches on both faults. Net slip estimated based on fault plane slickensides and a dipping bed offset by the fault indicates less than 3 ft. of net slip; hence these are considered minor faults. Based on the sub-regional transects, these faults appear to represent a distinctly different style and orientation of faulting compared to that expressed by the geologic features observed at the Watana dam site. Overall, the Cretaceous rocks appear to be a structurally coherent block, not disrupted by major faults and there is no expression of these faults in the overlying Quaternary deposits.

6.3.5.5. Dam Foundation Geologic Features

Based on recent site mapping and re-interpretation of previous mapping, the principal geologic features that underlie the dam footprint are:

- Geologic Feature GF4
- Geologic Feature GF5
- Other similar but unnamed geologic features:
    - An unnamed structure delineated as underlying part of the dam foot print on the north bank of the Susitna River, approximately 220 ft. downstream from GF5.
    - Another unnamed feature mapped 580 ft. downstream of GF5 on the north bank of the Susitna River.

Each of these features, described in detail elsewhere in this report, was evaluated for their significance as potential fault rupture hazards.

6.3.5.6. Summary of Dam Foundation Fault Rupture Evaluation

In the evaluation of fault rupture hazards in the dam foundation, the approach used involved separate lines of enquiry that took into consideration various independent types of evidence. The evaluation assessed the weight of evidence in relation to: a) the regional and subregional evidence of Quaternary faulting, b) the presence of significant faulting or shear zones at the dam site, and c) the qualitative potential for reactivation of geologic structures at the site within the current tectonic framework.

The evaluation found that one of the more compelling findings is the absence of crustal scale surface faults or apparent “blind” structures within several kilometers of the dam site. From detailed evaluations of new imagery data, evaluations of local and regional scale mapping, and field investigations, no evidence has yet been revealed of potential Quaternary faulting within at least 15 mi of the Watana dam site. Thus, this information strongly suggests that potential sources of primary or secondary, surface fault rupture at the dam site are absent. Further, geomorphic evaluations based on the detailed LiDAR data within about 3 mi of the site has not identified any expression or continuity of potential faults or specific geologic features extending from the site area that would be indicative of deformation of Quaternary deposits. Given the absence of potentially active crustal scale seismic sources in the immediate site vicinity, the potential existence of small and minor structural features in the dam foundation bedrock does not indicate an elevated potential for a fault rupture hazard.

From sub-regional transects and evaluation of the existing mapping within about 3 mi of the dam site suggest that the Watana dam site lies within a relatively coherent block of relatively gently folded Kahiltna Basin rocks that have been cross cut and locally disrupted by early Tertiary igneous and volcanic rocks. The intrusive process likely resulted in numerous alteration zones, fractures, and shears, but does not appear to be associated with nearby fault structures of significant crustal extent. The few short faults near the dam site depicted by Acres (1982b) are mostly likely similar features, and not post-intrusive, crustal scale faults. The closest major Tertiary structure appears to be the fault-bounded depositional basin along Watana Creek, approximately 8.5 mi upstream of the Watana dam site.

The orientation of discontinuities and narrow shear features mapped at the site chiefly have northwest strikes and steep, vertical to near-vertical dips (USACE 1979; Acres 1982; Harza-Ebasco 1984; this study). Based on review of the 2012 and 2014 drill hole logs, the bedrock encountered is pervasively fractured, with jointing prevalent in each and every boring. The joints are high-angle, and are reported as 70° dip or greater. Thin shear zones, generally less than one-foot wide are occasionally present in the rocks encountered beneath the dam footprint but with a much lesser frequency than joints. Elsewhere in the site area, shear zones are generally less than 2 ft. wide. Based on geologic mapping and oriented discontinuities in rock core in recent drill holes it appears that thin shear zones present are high-angle features of about 80° dip. This is relatively consistent with the near vertical shears exposed in outcrop.

Regarding specific features that may lie within the dam footprint, existing data show a dominant structural fabric of northwest strikes and high-angle dips. Site mapping and overlapping drill holes beneath the Susitna River appear to exclude structures with orientations parallel to the river channel at the site. Those joints and shear zones that do cross the dam footprint appear to be relatively discontinuous along strike and are challenging to map and correlate from outcrop to outcrop. The shear zones and fracture zones appear to be spatially associated with erosional gullies that have been enhanced in size at the ground surface due to weathering, stress relief, freeze-thaw, and/or block movement. Thus, the subset of geologic features that are depicted to transect the dam footprint appear to be relatively minor structures, with potentially limited bedrock continuity or persistence, and appear to have dominant orientations that are least favorable to reactivation in the contemporary stress regime.

The following is a summary of the principal findings and lines of evidence in relation to potential surface fault rupture:

1. The contemporary stress regime, as defined by current plate tectonic models, GPS observations, earthquake focal mechanisms and Quaternary faulting, indicates that the Watana dam site area is subject to northwest-southeast oriented sub-horizontal compressive stress associated with the long-term ongoing subduction of the Pacific Plate in south central Alaska. Crustal deformation associated with the plate interactions has been accommodated primarily along the Denali fault, as right-lateral motion, at a relatively constant rate over the past 10 million years. Between the Denali fault and the Castle Mountain fault, geologic evidence suggests that the intervening Talkeetna Block, a region including the Watana dam site, has been relatively stable.

2. Paleomagnetic data from volcanic rocks with ages of 30 to 50 million years indicates an absence of significant internal rotation or deformation within the Talkeetna Block. Similarly, the extent and distribution of Tertiary volcanic rocks across the Talkeetna Block argues against the existence of large-scale vertical or lateral fault displacements within the area.

3. Within the current stress regime of the Talkeetna Block, the primary modes of tectonic deformation appear to involve right-lateral strike slip structures with east-northeast strikes, and with dip slip or compressional shortening along structures with northeast strikes or elongations (roughly perpendicular to the regional direction of crustal shortening). Structures with these orientations would be oriented roughly parallel to the overall structural grain of the pre-existing tectonic terrains and rock units within the Talkeetna Block. Secondary modes of tectonic deformation might involve left-lateral strike-slip motions along north to north-northwest striking faults, or potentially smaller amounts of extensional deformation along structures with northwest strikes. Because regional evidence suggests the dam site region is dominated by compression, extensional features are expected to be relatively less common and would primarily be expected as second or third order local structures found locally in association with structural complexities of the primary east-northeast or northeast striking structures.

4. Detailed evaluations of new imagery data, evaluations of local and regional scale mapping, and field investigations have not identified any evidence of potential Quaternary faulting within at least 15 mi of the Watana dam site. These data strongly suggest that potential sources of primary or secondary, surface fault rupture at the dam site are absent.

5. Evaluation of existing mapping within the dam site area, and data from sub-regional transects along the Susitna River do not support the existence of major crustal faults near the dam site. Mapped shear zones within this area appear to be primarily associated with the mid-early Tertiary intrusive rocks, similar to those at the site.

6. Geomorphic evaluations based on the detailed LiDAR data within the dam site area have not identified any expression or continuity of potential faults or specific geologic features extending from the site area that would be indicative of deformation of Quaternary deposits. This indicates that although shear features may be present in the foundation, there is evidence to support lack of surface displacement along these features in the last 12,000 to 15,000 years.

7. Recurrent large earthquakes on blind faults, e.g. M ~6.5 or larger, with repeated dip-slip motion over many events, produce and eventually result in recognizable geomorphic features and topographic uplift which persists in the landscape. No such high-relief topography is present at the dam site, which would be a basis on which to postulate the presence of a nearby blind fault or seismic source in the site vicinity.

8. Bedrock beneath the proposed dam, powerhouse, spillway and appurtenance structures consists of fresh to slightly weathered, blocky, strong to very strong diorite that is locally altered and fractured and includes minor shears and shear zones. Fracture zones, shear zones, and alteration zones tend to trend in a northwest-southeast direction. On the south abutment just upstream of the proposed dam, several narrow northwest trending shear zones are cross-cut by a felsic dike and at least one healed fracture cuts across the shear zones. Together with the observations of healed shear and alteration zone, these observations suggest that many of the fracture and shear zones are likely associated with mid-early Tertiary intrusive processes and are not related to geologically recent seismotectonic processes.

9. Inclined drilling beneath the Susitna River, encountered generally fresh to slightly weathered, strong diorite. Although some widely spaced, narrow fracture zones

and minor shear zones were intersected in the drill holes, no significant geologic structure was revealed beneath the river. This supports the interpretation that the river at the dam site is not controlled by a major through-going fault or shear zone.

10. Investigations were made of previously identified "geologic features", shear and/or fracture zones greater than 5 ft. in width, several of which cross beneath the dam site. It is now considered that the prominence of these features, particularly those that would be encountered in the dam and spillway foundations, has been over-represented in geologic characterization conducted in previous studies. Further, the subset of geologic features that are depicted to transect the dam footprint appear to be relatively minor structures, with potentially limited bedrock continuity or persistence, and appear to have dominant orientations that are least favorable to reactivation in the contemporary stress regime.

In conclusion, therefore, it is considered that the potential for any reactivation of the geologic features that might transect the dam footprint must be considered extremely low given the following:

- The apparent lack of continuity and small scale of structural geologic features at the site (shear zones) upon which surface fault rupture could conceivably take place;
- The dominant northwest-southeast trend is unfavorably oriented with respect to the contemporary tectonic stress regime, as the primary mode of tectonic deformation appear to involve right-lateral strike slip structures with east-northeast strikes;
- The absence of any nearby crustal scale fault structures and any neotectonic or paleoseismic evidence of Quaternary faulting; and,
- The absence of Quaternary faults mapped with about 15 mi of the dam site.

6.3.6. Reservoir Geology

6.3.6.1. Geomorphology

The dam site and reservoir areas lie within the Upper Susitna River basin in the Talkeetna Mountains and the proposed reservoir extends approximately 42 mi to the east of the dam site. The river basin consists of a high, broad plan of low relief. Through this basin, the Susitna River has incised an approximately 800-ft-deep, east-west trending gorge at the dam site. The glacial upland and higher valley walls of the Susitna River and tributaries were likely widened and leveled by repeated cycles of glacial action while the deeper and rugged canyons at lower elevations were carved by down cutting from glacial melt water or subglacial rivers.

6.3.6.2. Overburden

Overburden deposits mask much of the bedrock in the area, especially in the lower and uppermost reaches of the reservoir. The soil stratigraphy is complex, generally consisting of variable thicknesses of late-Quaternary glacial till, lacustrine, colluvium, outwash and alluvium overlying igneous and metamorphic bedrock. Bedrock is exposed along much of the main channel confining deep deposits of coarse alluvium.

Generally, the lower section of the Watana Reservoir and adjacent slopes are covered by a veneer of glacial till and lacustrine deposits. Two main types of till have been identified in this area: ablation and basal tills. The basal till is predominately overconsolidated, with a fine grain matrix (more silt and clay) and low permeability. The ablation till has fewer fines and a somewhat higher permeability. Lacustrine deposits consist primarily of poorly graded fine-grained sands and silts, with lesser amounts of gravel and clay, and exhibit a crude stratification.

On the south side of the Susitna River, the Fog Lakes area is characteristic of a fluted ground moraine surface. Upstream in the Watana Creek area, glaciolacustrine material forms a broad, flat plain that mantles the underlying glacial till and the partially lithified Tertiary sediments. Significant glacial features such as kames and eskers have been observed on the upland slopes adjacent to the river valley.

6.3.6.3. Geologic Units

The oldest bedrock unit proximal to the dam site is comprised of Cretaceous shales, argillite, and greywacke of the Kahiltna assemblage (Csejtey et al. 1978). The Cretaceous sediments are regionally intruded by small bodies of Paleocene granite units with interfingering migmatite and pelitic schists, and granodiorites with minor diorite (Csejtey et al. 1978).

The intrusive rocks in and around the dam site are part of a large suite of largely granitic and granodioritic rocks that intruded between 53 to 64 Ma. The youngest bedrock units in the site vicinity are Paleocene to Miocene volcanic rocks and related shallow intrusives that may be related to the Paleocene plutons (Woodward Clyde 1980). Basalt flows outcropping in Deadman Creek, to the east of the dam site, are approximately 48 Ma (Schmidt et al. 2002).

For additional information regarding geology of the reservoir, refer to Section 6.3.1.2.3.

6.3.6.4. Buried Valleys (Relict Channels)

The existence of buried valleys or relict channels near the dam site beneath the glacial and interglacial unconsolidated sediments was first identified by the USACE (1979). The exploration programs undertaken during the 1980s were performed to improve definition of the limits of the materials that have infilled the Watana and Fog Lakes relict channels to the north and south of the dam site, respectively.

6.3.6.4.1. Watana Relict Channel

The Watana Relict Channel is located on the north bank of the Susitna River, just downstream of Deadman Creek, and meanders beneath the thick sequence of glacial and fluvial deposits blanketing the area to Tsusena Creek (Drawing 01-01GT003). The minimum distance between the proposed reservoir and Tsusena Creek is approximately 7,000 ft., or about 8,000 ft. along the thalweg of the relict channel. The Watana relict channel extends about 9,000 ft. from the Susitna River near Deadman Creek to about 3,600 ft. upstream of the dam site and empties into Tsusena Creek (Drawing 01-01GT005). The maximum thickness of overburden in the thalweg is approximately 450 ft. or approximately 300 ft. below the normal maximum operating level, at approximately El. 1750 ft. However, there is a depression that extends to depths below about El. 1700 ft. nearby, and the overburden is about 500 ft. thick. Overall, the course of the channel is irregular but trends from the southeast to the northwest. Several low depressions in the bedrock surface, downstream of Deadman Creek, coalesce and form the deep bedrock valley.

The stratigraphy in the channel has been differentiated into a number of glacial and fluvial stratigraphic units designated Unit A through Unit K. Detailed discussions of the Watana Relict Channel stratigraphic units are presented in the Acres (1982a) report, Acres (1982b) report, and the Harza-Ebasco (1983) report.

6.3.6.4.2. Fog Lakes Relict Channel

Subsequent to the findings of a the Watana relict channel on the right abutment, investigations were undertaken to determine if there were any other relict channels in the reservoir area. This work was initially undertaken when the proposed maximum reservoir operating level was considerably higher, El. 2185 ft.

In 1981, seismic refraction surveys indicated a bedrock low on the south side of the river in the Fog Lakes area, between the dam site and the higher ground approximately five miles to the southeast. Seismic refraction surveys in this area indicated a series of ridges and valleys that trend roughly northeast-southwest, between River Mile 186 and 195. In this area, the bedrock surface is as much as 350 ft. below ground surface, El. 1900 ft., or 150 ft. below normal maximum operating level of the current reservoir. However, there is bedrock separating the relict channel and the reservoir, so this relict channel does not appear to present a problem with respect to seepage or stability. The channel is filled with unconsolidated glacial deposits to the present day surface.

Detailed discussions of the Fog Lakes Relict Channel stratigraphic units are presented by Acres (1982a, 1982b).

6.3.6.5. Landslides and Slope Stability

Near the dam site, landslide scarps are noted on the north and south banks of the river. One circular shaped scarp was identified above El. 2100 ft. and upstream of the left abutment in what appears to be confined within glacial deposits, although may extend into the upper part of bedrock. This feature appears to be ancient and inactive, but a smaller, secondary scarp may be considered active as the LiDAR shows some possible surface erosion (Drawing 01-01GT003). On the north bank and about 600 ft. upstream of the dam, an approximately 300 ft. long scarp parallels the slope between EL. 1650 ft. and El. 1700 ft. The scarp is characterized by open joints oriented parallel to the slope and exhibit downslope movement. Downstream of the dam in the area of GF7, several scarps on the north bank parallel the slope and define a 200 ft. wide slide block that is considered active.

Although highly unlikely, breaching of the reservoir rim must be evaluated where the bedrock surface is below the proposed reservoir elevation. As mentioned earlier the Watana Relict Channel is identified just upstream of the dam site. Although previous studies have not completely eliminated the possibility for a slide to occur within the Watana Relict Channel, field investigations and studies indicate that the likelihood of such a catastrophic event is remote due to the low gradient, density of soil deposits, the low permeability of the upper stratigraphic units, and the discontinuous nature of the more permeable sorted sand and silt lenses that were encountered. Because of the bedrock elevation and other conditions at the Fog Lakes Relict Channel, it is considered even less critical than the Watana Relict Channel although geotechnical investigations before final design will be required. Relict Channel treatment is discussed in Section 10.28.

Numerous active and inactive landslides have been identified on the slopes in the proposed Watana Reservoir area, especially in sediments comprising basal till (MWH 2013). The Watana Creek area appears to be the most active area in terms of slope instability. In this area, instability of slopes occurs in lacustrine deposits that overlie basal till that are interpreted to be frozen. Slope movement appears to be the result of the thawing of ice-rich permafrost in the basal till. As the basal till thaws and fails, the overlying lacustrine deposits are undermined and the slide debris is comprised of both materials. The head scarps from these failures are typified by near-vertical slopes in the capping lacustrine deposits and significantly lower-angled slopes in the basal till. The most active slide areas typically have wet surface soils indicating the thawing of excess ice in the basal till.

Preliminary assessments of the slope conditions in the proposed reservoir area indicate that bi-modal and debris flows are present, particularly in the lower reservoir area. Slope instability is associated with progressive actions from thawing permafrost within slopes and the bi-modal and debris flows are the primary modes of slope erosion and failure of both active and historical slope development and movement. These movements are generally shallow as they occur within the active layer of the soil profile, and move with a slow to moderate rate of movement.

Following impoundment of the reservoir, slope movement due to the reservoir or reservoir operation is expected to be confined to near shore areas. No geomorphic evidence was found within the reservoir area of a large scale, rapid movement landslide that would have the potential to create a large impulse wave within the reservoir. Additionally, no evidence was found that would indicate that large-scale landslides or slope failures, either alone or in aggregate, that will cause a significant environmental impact due to the reservoir or reservoir operation.

6.3.6.6. Permafrost

Permafrost distribution in the greater Susitna-Watana region has been characterized as “discontinuous” (50 to 90 percent) except along the immediate river corridor itself, which is characterized as “sporadic” (0 to 10 percent) (Jorgenson et al. 2008). Permafrost is evidenced by ground ice, patterned ground such as stone nets, and slumping. Based on the subsurface investigations, most of which are within two miles of the proposed dam site, permafrost is generally continuous beneath north-facing slopes. The frozen ground is typically encountered within 10 ft. of the surface and extends to depths up to approximately 230 ft. Ground temperatures typically range from 30°F to 38°F. Permafrost has typically been absent directly under the river channel and south-facing slopes under the right abutment, although sporadic permafrost was encountered in a few boreholes downstream of the dam. Gentle south-facing slopes in upland areas above the canyon on the right abutment have been investigated with numerous boreholes in the wider vicinity of the dam and typically encountered unfrozen ground, although sporadic permafrost was present in localized zones (Acres 1983). This evidence suggests that the presence of permafrost is sensitive to sun angle.