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- [Main report]
- Figures
- Appendix A. Strip maps and photographic documentation of lineament data presented in FCL (2013)
- Appendix B. Strip maps and photographic documentation of lineament data for lineaments mapped by Reger et al. (1990)
- Appendix C. Final luminescence age report / prepared by Utah State University Luminescence Laboratory.

All parts of Section 16.6 (the main report and all attachments are in separate electronic files due to large file sizes.

ATTACHMENT 5: CRUSTAL SEISMIC SOURCE EVALUATION

Report
14-33-REP
v0.0

Susitna-Watana Hydroelectric Project
Crustal Seismic Source Evaluation

AEA11-022

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Explanation of Abbreviations

AEA	Alaska Energy Authority
AEC	Alaska Earthquake Center
DEM	Digital elevation model
FCL	Fugro Consultants, Inc.
FERC	Federal Energy Regulatory Commission
ft	feet
GIS	Geographic information system
GPS	Global positioning system
INSAR	Interferometric synthetic aperture radar
ka	kiloannus (thousand years)
km	kilometer
LGM	last glacial maximum
LiDAR	Light detection and ranging
m	meter
mi	mile
Ma	megaannus (million years)
MatSu	Matanuska-Susitna Borough
MWH	MWH Americas, Inc.
NFFTB	Northern Foothills Fold and Thrust Belt
OSL	Optically Stimulated Luminescence
PSHA	Probabilistic seismic hazard analysis
RCC	Roller-compacted concrete
RTS	Reservoir-triggered seismicity
SI	International System of Units
TM	Technical memorandum
USGS	United States Geological Survey
WCC	Woodward Clyde Consultants

Explanation of Units

Measurements in this report were made using the International System of Units (SI), and converted to English system for reference. For the conversions, the measurements reported in the English system were rounded off for simplification purposes. Both sets of numbers are presented for the reader, except in cases of very small numbers that are shown only using SI (i.e. metric).

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EXECUTIVE SUMMARY

The proposed Watana Dam is a hydroelectric power development project planned for the upper Susitna River under the auspices of the Alaska Energy Authority (AEA) and the regulatory authority of the Federal Energy Regulatory Commission (FERC). Under subcontract to MWH Americas (MWH), Fugro Consultants, Inc. (FCL) is investigating and evaluating the seismic hazards in support of engineering feasibility, and the licensing effort for the Susitna-Watana Hydroelectric Project. This report presents part of the continued seismic evaluations associated with the proposed dam, specifically a field investigation of lineaments. The purpose of the lineament mapping and evaluation is two-fold: (1) to identify potential crustal seismic sources that could appreciably contribute to the seismic hazard at the proposed hydroelectric project and affect dam design; and (2) to identify faults and assess their potential for surface fault rupture in the proposed dam site area.

In 2011, FCL prepared a preliminary seismic hazard source model and probabilistic ground motion assessment based on desktop review of prior studies and recent literature (FCL 2012). Subsequent to the preliminary seismic hazard ground motions assessment, FCL completed lineament mapping based on interpretation of recently acquired, detailed, topographic data (i.e., INSAR- and LiDAR-derived DEM data). The mapped lineaments were assembled into lineament groups, and evaluated in the office using semi-qualitative criteria to reject or select lineament groups for further investigation during the summer field season of 2013 (i.e., FCL 2013; 13-08-TM, formerly TM-8). In total, 22 lineament groups and three broader lineament areas were advanced to the field investigation phase that took place in summer of 2013 and 2014.

A primary objective of the lineament field investigation was to document and interpret available field evidence for the presence or absence of potential crustal seismogenic sources (faults) along features identified through lineament mapping, and evaluate the features' significance with respect to Quaternary faulting and their potential as seismic sources of significance to the Susitna-Watana Hydroelectric Project seismic hazard evaluations.

The lineaments inspected were assessed based on geomorphological characteristics observed in the field and field geologic relationships around the lineaments. As guidelines for the field teams conducting the evaluation of individual lineament groups, a series of questions were developed as an aid to focus observations made during the field investigation. To evaluate the field data, a set of questions and criteria similar to those used by FCL (2013) for evaluation of the desktop findings were developed. The principal objective of these criteria is to guide judgments and consistency regarding the lineaments' origins in order to evaluate their potential association with Quaternary faulting and potential crustal seismogenic sources.

Synthesis of previous studies and research of Alaskan glacial chronologies coupled with field observations on the type and distribution of glacial constructional and erosion landforms suggests that there are three broad age categories within which the landscape may be viewed. These are, from youngest to oldest: late Holocene, mid- to early Holocene, and post-late Wisconsin period of the late Pleistocene. It was judged that the preponderance of surficial geologic deposits are post-glacial (~12,000 – 15,000 yrs), and thus are the limiting age for detecting Quaternary deformation. Samples for OSL dating of this last stage of deglaciation were collected from the field in 2014 about 4 km northeast of the Watana Dam site. The results of the age dating document deglaciation before 15 ka +- 2 ka.

All lineament groups targeted for field investigation received a low-altitude aerial observation, and ground inspection was completed at selected locations where features of interest were identified. Based on the work to-date and access restrictions, the lineament groups are placed into three categories.

- Category I. Lineament groups in category I were not advanced for field observations, but where convenient, brief fly-overs in 2013 visually confirmed their placement in category I, with no further field investigation suggested. In general, most lineament groups not considered for further evaluation were generally isolated, short features at distances greater than 30 km from the dam site, or other features for which the lineament mapping provided little geologic or geomorphic evidence as potential Quaternary faults (FCL 2013).

- Category II. Lineaments in this category are judged to be: 1) dominantly erosional in origin, 2) related to rock bedding or jointing, or 3) to a lesser extent, a result of constructional geomorphic processes. This category is subdivided in to categories IIa and IIb. Category IIa lineament groups are those which are not evidently associated with bedrock faults. Category IIb are lineament groups that do appear to be associated with bedrock faults (Category IIb). For both categories no further field investigation is suggested.

- Category III. Lineament groups in this category have justifiable basis for consideration or inclusion as crustal seismic sources in an updated seismic source model: lineament group 27 (Sonona Creek fault) and the Castle Mountain fault extension are the two lineaments in this category. No further field investigation is suggested because of their distance from the site.

The results of our field investigations did not identify any specific features with evidence of late Quaternary faulting within at least 40 km (~25 mi) of the Watana dam site. For most of this area, the time and detection limits of the imagery and field investigations imply post-glacial time limits of about 15,000 years, and detection of surface offsets of more than about 1 m extending over several kilometers. For the area near Watana dam site, where detailed LiDAR data was the basis for this evaluation, potential detection limits of surface fault displacements are much lower – on the order of about one and a half feet over several hundreds of feet (a half meter over several hundred meters).

With respect to potential for surface fault rupture at the dam site, the approach for this study relies on four principal lines of independent data and analyses: 1) 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; 2) field geologic map transects to assess styles and patterns of structural deformation near the site; 3) assessment of results of site-specific investigations of geologic structure in the dam foundation; and 4) assessment of the contemporary tectonic framework (stress field) of the site region as an indication of the potential for reactivation of site geologic features.

Investigations to date regarding the presence of faults at the dam site indicate: 1) northwest-oriented joints (270° to 330° strike, 300° average strike, near vertical), fractures, and narrow, apparently discontinuous shears in the dam foundation; 2) a lack of evidence to support the presence of substantial, or “major”, faults or through-going shears in the foundation; 3) evidence of north-south or east-west orientations is rare to absent, and borings that cross beneath the Susitna River from opposing sides demonstrate an absence of major east-west oriented structures beneath the Susitna River; 4) Geologic Feature 1 (GF1), 0.5 mi (0.8 km) upstream of the dam site, is the most significant shear zone feature in the dam site area, and similar to other geologic features at the site, may have less structural continuity than inferred from some previous studies; and 5) geomorphic expression of the dam site area geologic features is absent along projections of these features beyond the steep canyon slopes near the Susitna River, consistent with a lack of Quaternary displacement.

Synthesis of regional geology and seismology, sub regional mapping transects, and site data all indicate that major faults, typical of active crustal seismic sources capable of primary surface rupture associated with major earthquakes in the contemporary tectonic environment, are absent from the Watana dam site area. The evaluation of potential crustal seismic sources has not identified any specific features with evidence of late Quaternary faulting within at least 25 miles (40 km) of the Watana dam site. This is consistent with the observations that the reservoir area is structurally coherent with lack of pervasive penetrative deformation. This conclusion is also consistent with previous fault studies completed in the dam site area.

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 subhorizontal compressive stress associated with the long-term ongoing subduction of the oceanic plate beneath south central Alaska.

The contemporary stress regime of the Talkeetna Block is illustrated by the recent seismicity recorded by the Watana Seismic Network. These earthquakes illustrate that the primary modes of tectonic deformation appear to involve right-lateral strike slip structures with east-northeast strikes (subparallel 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).

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 of geologic features is unfavorably oriented with respect to the contemporary tectonic stress regime, as the primary mode of tectonic deformation appears 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 geomorphic expression and therefore Quaternary faults mapped within about 25 mi (40 km) of the dam site.

Despite the apparent absence of geologic evidence for late Quaternary faulting in the broader region, updates to the seismic source model (FCL 2012) may consider inclusion of portions of some new sources. Such an updated source model would consider the findings and limitations from this evaluation, seismicity recorded since 2012, and other data, although some seismic sources may be constrained to very low slip rates as defined by this crustal seismic study.

1. INTRODUCTION

The proposed Watana Dam is a hydroelectric power development project planned for the upper Susitna River under the auspices of the Alaska Energy Authority (AEA) and the regulatory authority (among others) of the Federal Energy Regulatory Commission (FERC). The proposed dam would be constructed near about River Mile 187 on the Susitna River, north of the Talkeetna Mountains near the Fog Lakes area. Current concepts envision a roller-compacted concrete (RCC) dam approximately 705 feet high, with an installed turbine capacity of 459 MW, impounding a reservoir with a maximum water surface elevation at about 2,050 feet. At this elevation, the dam would impound a reservoir of approximately 5,170,000 acre-feet.

MWH Americas (MWH) is the prime contractor providing engineering and geotechnical services to AEA for the project development and submittal of licensing documents to the FERC. Under subcontract to MWH, Fugro Consultants, Inc. (FCL) is investigating and evaluating the seismic hazard aspects in support of engineering feasibility and the licensing effort for the Susitna-Watana Hydroelectric Project.

This report presents part of the continued seismic evaluations associated with the proposed dam, specifically lineament field investigation and evaluation of potential surface fault rupture at the dam site. The purpose is two-fold: (1) to identify potential crustal seismic sources that could appreciably contribute to the seismic hazard at the proposed hydroelectric project and affect dam design; and (2) to identify faults and assess their potential for surface fault rupture at the proposed dam site area.

1.1 Background

In 2011, FCL prepared a preliminary seismic hazard source model and ground motion assessment based on a desktop review of prior studies and recent literature (FCL 2012). The ground motion analysis identified the subducting Pacific Plate slab as the dominant driver of seismic hazard to the site. However, studies of crustal faulting in the general Talkeetna Mountains region – located between the Denali and Castle Mountain faults – had not been performed since the early site investigations three decades prior. Therefore, as part of the project study, and subsequent to the preliminary seismic hazard ground motions assessment, FCL interpreted recently-acquired, detailed, topographic data (i.e., INSAR and LiDAR) to examine the regional landscape for evidence of potential faults, lineaments, or geomorphic landforms suggestive of Quaternary faulting. Such features could, if warranted, be considered as a crustal seismic source.

The initial desktop lineament mapping data, analysis, and selection of lineament groups for field investigation is documented in 13-08-TM (i.e., FCL 2013, formerly TM-8). Succinctly, the mapped lineaments were assembled into lineament groups (Figure 1-1), and analyzed in the office using semi-qualitative criteria to select lineament groups for further investigation during the summer field season. This analysis included lineaments identified by WCC (1980, 1982) for the two-dam scheme at Devil's Canyon and Watana as originally envisioned in the 1970s and 1980s. In total, 22 lineament groups and three broader lineament areas were advanced to field investigation phase in the summers of 2013 and 2014. A primary focus of field evaluations for the 2014 investigations was the evaluation of potential surface fault rupture at the proposed Watana dam site, and included field geologic mapping, review of rock core samples, and inspection of a selected dam site geologic features.

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 sub-regional 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.

This document describes the results of the lineament field investigation for the evaluation of crustal seismic sources and also the results of the potential surface fault rupture at the dam site based on the lineament evaluation as well as site data and analyses.

1.2 Scope of Work

The scope of work for this FCL investigation is defined under MWH Task Orders T10502190-99468-OM dated March 11, 2013, T10502190-99894-OM dated July 1, 2013, and T10502190-101829-OM dated July 1, 2014. In general, the focus of the studies is continuation of the crustal seismic evaluations. Specific technical activities within the scope of work include: development of field plans and logistics, health and safety plan update, field geologic mapping, seismometer station site characterization through collection of Vs30 measurements, field investigation of lineaments, assessment of the lineament feature origin, and analysis of potential crustal earthquake sources of project significance and preliminary evaluation of surface fault rupture hazard. Other activities specified in the task order include review of earthquake monitoring data, interim probabilistic seismic hazard assessment (PSHA) sensitivity analyses, and work planning studies in support of project licensing. Findings related to most of these activities are reported separately and are not described in this report.

1.3 Report Structure

This report is organized into seven sections. Section 1, the Introduction, describes the background, purpose, and scope for the crustal seismic source evaluation and surface fault rupture evaluation. Section 2 provides an overview of the approach, including data used and analytical criteria for evaluation of lineaments, field geologic investigation and mapping, and surface fault rupture evaluation approach. Section 3 presents a framework for evaluating the field data, including regional seismotectonic setting and geologic history, discussion of surface-modifying geomorphic processes, Quaternary geologic and chronologic model, and a framework for assessing limitations to ground feature detectability. A detailed description of observations and interpretations (desk and field) for the lineament groups, including discussion of the Talkeetna fault, the Susitna feature and the Watana lineament, is provided in Section 4. Section 5 presents the sub-regional and site data followed by an analysis of principal stress orientations with respect to orientations (strike) of features in the dam site and broader region. Section 6 presents the summary of findings for the crustal seismic source and surface fault rupture evaluations. Section 7 provides the references cited in this document. Finally, detailed lineament strip map figures are included as Appendices A and B. Appendix C contains the final report from the age dating analysis performed by Utah State University luminescence laboratory.

2. APPROACH

The approach to the lineament evaluation, in general, consisted of desktop digital terrain mapping and analysis (i.e., FCL 2013) complemented by field investigation and mapping in the summer of 2013 and 2014 (this report). The approach for evaluation of the potential for surface fault rupture at the dam site consisted of synthesizing the lineament evaluation results with additional field geologic mapping and data collected in the dam site area.

2.1 Lineament Evaluation

The desktop lineament mapping and analysis report (TM-8; FCL 2013) describes the approach for mapping of individual lineaments across the Project area, that is, within a 100 km (~62 miles) radius from the dam site. For that effort, criteria were established to provide a basis for delineating lineament groups (that is, aggregates of individual lineaments) that appear to have sufficiently extensive lateral continuity and geomorphic expression consistent with an origin by tectonic processes (FCL 2013). Additional criteria were developed to exclude lineament groups that were created by erosional or depositional processes (i.e. non-tectonic lineaments), lineament groups that are chiefly related to lithologic controls (i.e., differential erosion), lineament groups that did not meet length and distance criteria, and lineaments that did not show consistent senses of displacement along strike. For completeness, the criteria used to identify and analyze lineament groups are reviewed below in Section 2.4.1. In total, 22 lineament groups and three broader lineament areas were advanced to further field investigation and evaluation (FCL 2013).

The lineament evaluation field teams consisted of two, two-person groups and involved visual inspection of landscape and geomorphic features within lineament groups via low-altitude helicopter fly-overs and ground data collection in selected locations where access was permitted. The mapped lineament groups were visually inspected in the field to identify positive evidence for (or against) tectonic deformation of the Quaternary deposits (as present in the field) that may overlie, or project toward, the lineaments. The ground-based geologic data collection included walking of parts of mapped lineaments, photo documentation, exposure and logging of shallow soil pits, local mapping, collection of relevant structural measurements (strike, dip), and comparison of existing geologic mapping to field exposures and findings.

Each field team used a ruggedized field laptop computer (Toughbook) with real time GPS tracking and GIS capabilities. The geologic database compiled by FCL (2013) for the seismic studies was loaded onto each Toughbook with LiDAR and INSAR (Interferometric Synthetic Aperture Radar) digital elevation and derivative surface models. This approach allowed for: (1) accurately locating position with respect to lineament features in the field in real time, and (2) real-time analyses of the existing geologic mapping and landscape models to the features observed in the field.

The helicopter inspection was conducted chiefly with R-44 type aircraft. Other rotary wing aircraft were used to a lesser extent during the aerial inspection. Each ruggedized field laptop was carried in the helicopter with the GPS enabled to record a "track" for each team's course, position, and pattern for each flight (Figures 2-1A and 2-1B). Minor satellite signal loss occurred during parts of the field investigation, but was supplemented with redundant auxiliary tracks collected by hand-held GPS units. Hand-held GPS units were primarily used to collect way points at selected locations of the ground investigation. The field tracks document the extent and location of low-altitude inspections, and way points document ground locations relevant to the geologic data collection.

Photographs were taken during the low-altitude flyovers and while on the ground, and serve to document the field observations. The photographs were collected with a digital camera whose internal clock was synchronized with the hand-held GPS clock. This allowed geo-referencing of the photographs to the location where the photo was collected, and ensured collected photos were assigned to the correct place, feature, or lineament group. In some instances, inclement weather (rain, clouds) hindered quality of photo documentation. In other instances, glare or distortion from aircraft windows is apparent in the photographs.

The lineament groups and larger areas are depicted in detail on a series of strip maps and plates on which relevant field- and office-generated geologic and geomorphic data are compiled and evaluated. Examples of this field data collection and synthesis effort are shown in Figures 2-2, 2-3, and 2-4. (The map data are presented in-full in Appendices A and B and each lineament group is described in Section 4.) The content of the strip maps and plates is customized for each lineament group and only the most the relevant field data and geologic map data are shown alongside the mapped lineaments with the most appropriate base imagery, given the local terrain and features of interest (e.g., Figure 2-2). Figure 2-3 demonstrates the annotated field photographs that are linked to the maps while Figure 2-4 provides an example of an explanation sheet that accompanies the maps.

2.2 Field Mapping

Existing regional geologic mapping has been established by Csejtey et al. (1978) and subsequently by Wilson et al. (2009) (Figure 2-5A and 2-5B). Many other maps exist that 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. Therefore, new sub-regional mapping (depicting both the dam site and the general vicinity within 5 to 10 miles) was completed to develop a better understanding of, and framework for, the geologic and structural relationships in the area at the dam site and surrounding areas, to help evaluate the potential impacts of local faulting on the dam and other critical structures.

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 geologic transects were completed to document styles, distributions, and extent of structural deformation sub-regionally and near the dam site. Sub-regional field transects were completed where outcrops were accessible in terms of helicopter landing sites, river water level conditions, and availability of outcrop exposures. The transects were completed chiefly along the Susitna River, Watana Creek, and to a much lesser extent, Tsusena Creek. The transect data were synthesized with regional mapping to characterize the significance of structural features such as terrane bounding faults and deformation of sedimentary strata. These observations, in turn, allow development of a conceptual tectonic model that provides a consistent framework that helps explain the presence or absence, as well as significance, of the structural geologic features at the dam site.

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. Mapping of the dam site geology and structure is presented in detail in MWH (2015).

2.3 Geospatial Data

The primary digital data sets utilized by FCL (2013) for the lineament mapping phase and during the field work consisted of several high-resolution topographic and aerial imagery datasets (Table 2-1). Of the available data, the INSAR and LiDAR (Figure 2-5) were the most valuable due to their high resolution and broad coverage of areas of interest. INSAR coverage is complete for the entire region of study interest within about 100 km of the Watana dam site as well as a broader region of south-central Alaska. LiDAR coverages are available for much more restricted areas, and near the Watana dam site is generally limited to a narrow corridor along the Susitna River (Figure 2-6). Both INSAR and LiDAR can penetrate through vegetation cover to map the ground surface beneath and can be used to create a "bare earth" digital elevation model (DEM) of the landscape.

In addition to the elevation data, two imagery datasets covered the study area: 1) ortho-imagery (0.3 m) collected as part of the Matanuska-Susitna Borough (MatSu) LiDAR collection project, and 2) regional Landsat scenes (30 m) (Table 2-1). The MatSu aerial imagery coverage has limited regional extent coincident with the extent of the MatSu LiDAR data (Figure 2-6). Both imagery datasets provide data in the visible spectrum. These imagery datasets were used to provide context and better understand landscape features displayed on the INSAR and LiDAR data and also navigate the terrain during the field work.

Table 2-1. Principal Data Sets Utilized During the Lineament Mapping

Data	Cell Size	Year	Source
INSAR elevation data (bare earth)	5 m (~16 ft)	2010	Data collected by Intermap (50%) and Fugro EarthData. Inc. (FEDI) (50%)*
MatSu LiDAR elevation data (bare earth)	1 m (~3 ft)	2011	Matanuska-Susitna Borough*†
LiDAR elevation data (bare earth)	1 m (~3 ft)	2014	TetraTech
MatSu aerial imagery	0.3 m (~1 ft)	2010	Matanuska-Susitna Borough*†
Landsat satellite imagery	30 m (~100 ft)	2010	NASA/USGS§

*Data downloaded from the Geographic Information Network of Alaska (GINA) at the University of Alaska
†For more information see: http://www.matsugov.us/it/2011-lidar-imagery-project
§ Downloaded from http://glovis.usgs.gov/

2.4 Desktop Approach for Lineament Evaluation

2.4.1 Criteria for Selection of Lineaments Requiring Further Analysis

FCL (2013) defined multiple acceptance criteria to serve as a basis for delineating potentially tectonically-relevant lineament groups (Table 2-2). In general, the lineament groups consisted of individual lineaments having consistently similar orientations that when aggregated together as a group, have a relatively appreciable length and which trend across terrain. Multiple criteria were established to serve as a relatively inclusive basis for delineating lineament groups within the study area. These criteria from FCL (2013) are described below (Table 2-2), and are presented in generally decreasing degree of confidence in lineament delineation as a potential crustal feature.

Table 2-2. Criteria for Delineating Lineament Groups

Criterion	Reasoning
Lineaments that are expressed in Quaternary deposits, that collectively aggregate to greater than about 10 km (~6 miles) in length.	Quaternary lineaments may strongly represent neotectonism.
Lineaments that appear to represent potential extensions or continuations of known Quaternary faults.	These lineaments may contribute to additional fault source length in ground motion calculations.
Lineaments with possible tectonic geomorphologic evidence that are spatially associated with previously mapped faults or lineaments.	Suggestive, but not conclusive, of neotectonism. Association with previously mapped faults or lineaments supports inference of structure.
Lineaments with possible tectonic geomorphologic evidence that are not spatially associated with previously mapped faults/lineaments.	Suggestive, but not conclusive, of neotectonism.
Lineaments that aggregate to greater than 10 km (~6 miles) in length.	Length criterion is based on an approximately minimal structural length for a seismogenic source capable of ground rupture.
Lineaments that are within 30 km (~18 miles) from the proposed site and reservoir, and are greater than 20 km (~12 miles) in aggregated length.	Seismogenic features within 30 km (~18 miles) of the site may contribute non-trivially to the ground motion calculations.

The lineament groups identified through the inclusion criteria were subsequently screened using semi-objective exclusionary criteria (Table 2-3). The semi-objective criteria included length and distance restrictions, and also geologic process restrictions. The screening process thus required an examination of the identified lineament groups to assess the possible genesis of the features. The screening step eliminated lineaments that show strong evidence of being non-tectonic in origin (e.g. erosional, depositional), or those that likely would not appreciably contribute to the seismic hazard at the proposed dam site.

Table 2-3. Desktop Evaluation Exclusion Criteria

Criterion	Reasoning
Lineament groups that are greater than 100 km (~62 miles) distance from the proposed dam site, excepting potential extensions of the Castle Mountain fault.	Lineaments over 100 km (~62 miles) distant would have very little contribution in hazard calculations. Potential extensions of the Castle Mountain fault may contribute to hazard calculations.
Lineament groups that are greater than 70 km (~43 miles) distance from the proposed site and less than 40 km (~25 miles) aggregate length and with no apparent association to previously mapped structures.	These lineament groups likely would not appreciably contribute to the hazard calculations, based on the Sonona Creek seismic source contribution in the preliminary PSHA (FCL 2012).
Lineament groups that are greater than 30 km (~18 miles) from the proposed dam site and less than 20 km (~12 miles) in length are excluded from further analysis, where the group cannot be linked to an adjacent group.	Based on the results of the preliminary PSHA (FCL 2012), it is likely that these lineament groups (if seismic sources) will not appreciably contribute to the hazard calculations.
Lineament groups whose individual features are dominantly erosional and/or depositional with no apparent association with previously mapped faults or lineaments.	Such lineaments are non-tectonic in origin and not considered further.
Lineament groups with inconsistent expression of kinematics along strike.	Inconsistent, contrasting, or discrepant lineament kinematics indicates low likelihood as a potential seismic source.

A second, more subjective, evaluation process (Table 2-4) was applied by FCL (2013) to the remaining lineament groups, based on desktop geological examination of the data compiled on the lineament group strip map. This process served to identify potentially significant lineament groups that would need additional data and evaluation as part of the field studies.

Table 2-4. Criteria for Desktop Geologic Evaluation of Lineament Group

Criterion	Reasoning
Lineaments within groups that appear to have expression in Quaternary units or Quaternary landforms proceed to further analysis.	Quaternary-age lineaments may strongly represent neotectonism, if not erosional or depositional in origin.
Lineament groups that transect or cut across different geologic units proceed to further analysis.	Lineaments that are traceable across different geologic units imply crustal structure exists, as opposed to lineament genesis from lithology, bedding, or jointing.
Lineaments within groups that may be tested for positive evidence of inactivity (e.g., overlain by Tertiary volcanic units) proceed to further analysis.	Determining inactivity via positive evidence will remove lineament group from further study.
Lineament groups that demonstrate relative consistency of geomorphic expression and anticipated structural kinematics along strike proceed to further analysis.	Consistent expression and structural style suggests a common genesis such as neotectonism because many other processes of formation change along the length of their occurrence.
Lineament groups that are explainable in the context of the tectonic model proceed to further analysis.	The tectonic model serves as a guide for anticipating orientation and sense of motion with respect to crustal stresses.

2.4.2 Criteria for Evaluation of Lineaments, Summer Field Investigations

The lineaments inspected in the field were assessed based on geomorphological characteristics observed in the field and geologic relationships around the lineaments. As guidelines for the field teams conducting the field investigation of individual lineament groups, a series of questions were developed prior to the field activities as an aid to focus observations and data collected during the field investigation. The intent was for the field teams to discuss and debate during the process of the lineament field evaluations as an ongoing field methodology to help ensure that field observations were sufficiently complete during the field time available. Table 2-5 lists these questions and the reasoning which supported the need for collecting the associated field data in order to assess each lineament in a relatively consistent fashion.

Table 2-5. Field Team Geologic Data Collection Guidance

Field Data	Reasoning/Comments
Is a previously mapped bedrock fault structure coincident with or near the lineament group?	Spatial proximity to or association with a previously mapped fault may support the lineament group having a tectonic origin.
Was field evidence of fault structure observed (either directly or indirectly)?	Direct evidence: exposure of shear zone or fault contacts observed. Indirect evidence: apparent rock type juxtapositions, alteration zones, color changes.
What does the trend of the lineament across the topography imply about the geometry of the potential structure?	Topographic expression provides a basis for defining the potential 3D geometry and potential style of faulting or constraints on potential non-tectonic origins.
What types of deposits or geomorphic surfaces is the lineament expressed in?	Quaternary glacial, lacustrine, alluvial, and colluvial deposits or bedrock units? Are the geomorphic surfaces constructional or erosional?
What is the oldest deposit in which the lineament occurs?	Age of deposit may constrain age of activity or limit of reasonable hypotheses of origin.
What is the youngest deposit in which the lineament occurs?	Age of deposit may constrain age of activity or limit of reasonable hypotheses of origin.
Do the mapped lineaments transect or cut across different geologic units or landforms?	Expression of lineament across multiple units or landforms may indicate continuity of geologic process.
What is the scale (magnitude) of expression of the lineaments along strike?	Expression that is proportionally consistent across different age portions of the landscape suggests continuity of process.
Is the lineament discordant with glacial ice flow directions?	Discordance with ice flow direction suggests origins other than ice flow.
Is there field evidence that linear strain markers (such as moraine or ridge crests, esker ridges, terrace risers or treads, lake shorelines, drumlins or other ice scour-generated striae) are cross-cut, deformed or displaced? If deformed, what is the amount?	Disruption of Quaternary strain markers may suggest a recent tectonic origin.
What does the morphology of the lineament imply about the kinematics of a potential fault? What are the apparent structural kinematics needed to produce the morphology of the lineament?	Kinematics need to be consistent along strike.

To evaluate the field data and guide development of documentation for the evaluation of each lineament group, a set of questions and criteria similar to those used by FCL in TM-8 (13-08-TM; FCL 2013) for evaluation of the desktop findings were developed (Table 2-6). In much the same way that the data collection guidelines shown in Table 2-5 were intended to enhance consistency and focus across the range of features visited in the field, the guidance which follows in Table 2-6 is intended to build those observations into a consistent set of discussions for documentation of the evaluation of each lineament group. The principal objective of these criteria is to guide judgments regarding the lineaments' origins in order to evaluate their potential association with Quaternary faulting and crustal seismogenic sources.

Table 2-6. Criteria for Evaluation of Field Data

Criterion	Reasoning
Does the lineament show evidence of geomorphic expression in Quaternary deposits or landforms? What is the character of expression?	Quaternary-age lineaments may strongly represent neotectonism, if not clearly of erosional or depositional in origin.
Does the lineament group transect or cut across different geologic units or landforms?	Lineaments that are traceable across different geologic units may indicate through-going crustal structure exists, as opposed to lineament genesis from local lithology, bedding, or jointing.
Does the lineament group demonstrate relative consistency of geomorphic expression and apparent structural kinematics along strike?	Expression that is proportionally consistent across different age portions of the landscape suggests continuity of process. Consistent expression and structural style suggests a common genesis such as neotectonism because many other processes of formation change along the length of their occurrence.
Are the lineaments' apparent origins dominantly erosional and/or depositional?	Such lineaments are likely non-tectonic in origin.
Are the individual lineaments or lineament groups associated with previously mapped faults?	Spatial proximity to or association with a previously mapped fault may support the lineament having a tectonic origin.

2.5 Surface Fault Rupture Evaluation Approach

Permanent ground deformation from surface fault rupture can occur as primary, secondary, or sympathetic (triggered) rupture. Primary rupture is ground displacement from 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. In an absence of known seismogenic faults at the site (largely based on the results of the crustal seismic source evaluation), the evaluation of potential fault rupture hazards focuses on the possibility of displacement along existing planes of weakness in the bedrock.

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

1. Geomorphic evaluation of Quaternary and post-glacial lineaments and faulting (i.e., lineament mapping and analyses) to assess whether potential seismogenic faults are present near the site vicinity;

2. Field geologic transects to assess styles and patterns of structural deformation near the site;

3. Assessment of results of site-specific investigations of geologic structure in the dam foundation, and

4. Assessment of the contemporary tectonic framework (stress field) of the site region as an indication of the potential for reactivation of site geologic features;

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.

Based on geomorphic evaluation of the post-glacial landscape, the observed lack of geomorphic indicators, lack of tectonic features, or lack of observed displacement in the recent glacial deposits is the strongest evidence against late Quaternary surface faulting in the dam site area. 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, as well as field investigations to verify the results of desktop based LiDAR lineament mapping (i.e., Fugro 2014). Derivative models from the elevation model were developed to provide additional layers of landscape analysis that contribute to evaluating potential tectonic-related deformation.

As discussed in Section 2.2, field geologic transects were completed to document styles, distributions, and extent of structural deformation sub-regionally and near the dam site. Results from the transects were used to develop a conceptual tectonic model that provides a consistent and defensible framework that helps explain the presence or absence, as well as significance, of the structural features at the dam site.

Results of site-specific surface and subsurface investigations at the dam site were reviewed to support the evaluation of fault rupture hazard. This consisted of review of selected rock core samples drilled in 2012, review of previous site geologic mapping, and review of new geologic mapping and rock core samples at the dam site undertaken in 2014.

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.

3. FIELD DATA EVALUATION FRAMEWORK

The field evaluations focused on two main topics: (1) evaluations of lineaments identified from desktop studies (FCL 2013) as potential crustal seismic sources, and (2) evaluation of potential surface fault rupture hazard associated with geologic structures in the dam foundation. The field evaluations were conducted over two seasons, with 2013 investigations emphasizing regional lineament evaluations, and 2014 investigations emphasizing evaluations of structures in proximity to the dam site. The 2013 field activities and lineament evaluations revealed three topics with broad impacts across several aspects of the lineament and fault rupture evaluations. These topics include: (1) insights gained from field investigation and evaluations on the scale and resolution of DEM data, (2) identification of the dominant geomorphic processes acting to modify the landscape, and (3) updated regional age estimates for late Quaternary landscapes and events in south-central Alaska. Interpretations and evaluations of most lineament groups and individual features within these lineament groups are linked to key principles or limitations posed by data or concepts associated with these three topics. The 2014 evaluations used these results to provide closer focus to the evaluations of lineaments and fault rupture hazards in the immediate dam site vicinity.

The Watana dam site 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 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 (Figure 3-1).

The following sections provide a background of tectonic setting and history of south-central Alaska that is relevant to the crustal block in which the Watana Dam will be located along with a short discussion of igneous and volcanic emplacement at the dam site. This followed by discussions of data evaluation issues associated with DEM data, geomorphic processes associated with lineament formation, and the late Quaternary glacial history of the region.

3.1 Seismotectonic Setting

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 (Figure 3-2).

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). 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 3-2.

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 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 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 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 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), although this is probably a lower bound of the long term slip rate.

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 3-3. The estimated ground shaking hazard associated with this seismic source is evaluated and discussed in FCL (2012).

To the north of the Denali fault 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 3-3). 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; Bemis et al. 2015).

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 3-4. 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).

3.2 Regional Tectonic Setting and History

The tectonic evolution of south-central Alaska is characterized by long-term plate convergence, with Mesozoic (i.e., Jurassic-Cretaceous) collision of the Wrangellia composite terrane to North America. The Wrangellia composite terrane itself is an accretion of the Peninsular terrane to the Wrangellia terrane. The Wrangellia terrane generally consists of late Paleozoic flood basalts and metavolcanic rocks; the Peninsular terrane consists of Mesozoic (Jurassic) arc volcanics, metasediments, and igneous plutons. The two terranes originated well south (~30° latitude) of their current position, and were sutured together in the Late Jurassic (Figure 3-5; Csejtey et al. 1978). The Wrangellia 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 (Figure 3-6). Between the converging Wrangellia composite terrane and North America was a marine basin (Kahiltna basin) that accumulated syn-collisional Jurassic-Cretaceous sedimentation shed from the southeast direction (Kalbas et al. 2007). The northeast-striking Talkeetna fault, located approximately 3.5 miles southeast of the Watana dam site, is the eastern boundary of the Wrangellia composite terrane, with the Jurassic-Cretaceous sedimentary rocks (i.e., Kahiltna Basin deposits) on the northwest of the fault and the Wrangellia composite terrane rocks to the southeast of the fault (Figure 3-5). 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 or pinches out 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 Talkeenta Mountains and forming a structural inversion; that is, 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 3-5, 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 early through the late Cretaceous as westward sediment transport on fluvial, shallow marine and submarine fan depositional environments (Figure 3-6). The Kahiltna assemblage is about 2 to 3 mi (~3 to 5 km) thick, and consists of turbidite sequences, chert, mudstone, sandstone, and graywackes that comprise eight distinct lithofacies (Kalbas et al. 2007). Thus, progression in the understanding of the relationships between the terranes, stratigraphic 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”.

Oblique subduction of an oceanic spreading center during Paleocene to early Eocene initiated magmatism and formation of short-lived northwest trending extensional (normal) faults (Trop and Ridgeway 2007; Figure 3-6). Included in these volcanics are the Cantwell and Jack River volcanic fields dated at 55 to 60 ma, and 50 to 56 ma, respectively (Figure 3-7). 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 also the Talkeetna fault (Figure 2.5A, Figure 3-5, bottom panel; also see Section 4.1.2).

Regional crustal rotation of southern Alaska took place sometime in the early to mid-Tertiary, with rotation on the order 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 (Figures 3-6 and 3-7).

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 the 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). As a consequence, 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.

3.3 Igneous and Volcanic Emplacement at the Dam Site

The regional magmatism described in the previous section directly formed 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 et al. 2009). The rocks present at the dam site range in mineralogic composition and texture, including diorite intrusions, andesite, felsic dikes and, to a lesser extent, mafic volcanic extrusive rocks (Acres 1982b). 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 intrusion bodies is relatively common (USACE 1979). Review of rock core drilled for the project (Golder, 2013; MWH 2015b) 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 and compositions. At some locations, diorite bodies 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 1982b). The intrusions likely occurred sometime between 50 to 60 Ma (Figure 3-7, Figure 3-8, Figure 3-9), the field observations and relationships confirm multiple ages (or, episodes) of volcanism, intrusion, or flows for which the specific chronology has yet to be defined. Mapping by Csejtey et al. (1978) suggests that the dam site rocks could be on 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 for future absolute dating purposes to establish site chronology to help assess timing of last movements based on cross cutting relationships of plutons and dikes.

Processes for pluton emplacement in the crust are diverse and many plutons studied around the world have different evidence of style of emplacement, from buoyancy driven vertical ascent to incremental emplacement through individual dikes or sheets. The aspect relevant to this study is whether the geologic features observed in the igneous rocks at the dam site are a function of magma emplacement, or whether they are of post-emplacement tectonic origin. The most intense ductile strain occurs in plutonic rocks adjacent to country rock, and in these locations, rapid changes in igneous rock type are common, including the presence of mafic rocks (Pe-Piper et al. 2002). Pe-Piper et al.'s (2002) study of diorite and quartz diorite plutons argues for the emplacement of plutonic rocks to have been achieved by progressive creation of space by lateral translation in a sub-vertical shear zone. Other studies of igneous rock emplaced in convergent orogenic belt settings (akin to this study area) argue for contemporaneity in deformation and granite ascent through the crust (Solar et al. 1998). In contractional orogenic belts that have oblique-reverse tectonic regimes where the maximum principal finite elongation direction has steep to sub-vertical plunge, the igneous rocks generally do not develop C-S fabrics (Brown and Solar 1998), as is the case with observations of rocks at the dam site (MWH 2015a). This absence of C-S fabric is used by Brown and Solar (1998) as evidence for a model of emplacement of melt that flows up and along what is essentially the direction of minimum compressive stress, with build-up of melt pressure resulting in rock fracturing. Conceptually this model produces near-vertical sheets of intrusive rock (in contrast to horizontal sills) with primary fractures and joints that are oriented along a similar azimuth consistent with the sheets.

The above paragraph is not intended to provide a comprehensive review of competing models of igneous emplacement; clearly debatable topic. Rather, it acknowledges the possibility that the geologic features and fractures observed at the dam site may be derived from or during emplacement process and may not necessarily be completely reliant on plate tectonics. At the same time, while such possibility may exist, it does not preclude that geologic features and fractures observed at the dam site are of tectonic origin (or some combination therein).

3.4 Post-Field Data Evaluation of DEM Data

As noted in Section 2.3, two sets of topographic data were used for the desktop lineament mapping: INSAR and LiDAR (FCL 2013). The INSAR data covered the largest area for the project and has a 5 m (~16 ft) horizontal cell-size (Table 2-1). The LiDAR, with a 1 m (~3 ft) horizontal cell-size, captured a smaller aerial extent that chiefly focused on the Susitna River corridor (Figure 2-5). Both INSAR and LiDAR can penetrate through vegetation cover to map the ground surface beneath and can be used to create a “bare earth” model of the landscape.

The INSAR-derived DEM data was the basis for mapping lineaments at regional extents (e.g. the 100-km [~62 miles] radius), and is a significant improvement in accuracy and detail of elevation as compared to any previously available regional data in south-central Alaska, and compared to DEM models derived from typical 1:24,000-scale topographic quadrangles throughout the continental United States. However, after comparing the elevation model data along mapped lineaments to the geomorphic features observed on the ground during the field work, several trends became apparent. First, for example, what visually appear to be relatively small features on the INSAR data actually are rather large features in the field. Features such as slope breaks that appeared sharp and abrupt on hill shaded maps, generally were found to be larger than expected in overall size and relief with less abrupt and more rounded slope geometries. Considering that the investigation team’s objective was to detect and identify potential earthquake-related geomorphic features (i.e., fault rupture scarps), the INSAR-based lineament mapping (FCL 2013) may have over-mapped features that likely would not be considered tectonic in origin. Nevertheless, all lineaments were mapped impartially, and subsequently tested via field investigation and reasoning.

Secondly, some relatively small features were observed on the landscape and on the ground during the field investigation which were not captured by the INSAR data, and thus not identified as lineaments in FCL (2013). This condition is challenging to characterize because the ability of the INSAR to image small features seems to be a function of the features’ relief relative to that of the landscape (small feature in flat terrain vs. small feature in a ravine or valley) and the features’ inherent geomorphic expression (steeply sloped margins vs. gently sloped margins and also continuity or length). To mitigate this apparent resolution limitation, derivative surface elevation models from the bare earth model were analyzed during the field investigation using the ruggedized field laptop GIS platform. Slope maps (change of elevation), and slope of slope maps (change of slope), were used to highlight subtle or systematic changes in elevation or slope that accentuate features that may be generally non-apparent in traditional hillshade elevation maps. These derivative surface elevation models were locally helpful in identifying smaller landscape features such as solifluction scarps and terraces.

Overall, the field investigation highlighted the previously known limitations of the INSAR based lineament mapping, notably that the base resolution of a 5 m (~16 ft) DEM is still relatively coarse with respect to the scale of geomorphic features that might be expected to be associated with single earthquake surface ruptures. As noted in FCL (2012), surface rupture features associated with the 2002 Susitna Glacier fault rupture are subtle, but recognizable in the 5 m INSAR DEM data. Conversely, the previously mapped lineament along the Talkeetna fault trenched by WCC (1982) and discussed later in Section 4.1, is not resolved on the INSAR DEM, but does represent the type and scale of feature that would be of interest as a potential tectonic feature. This feature is evident on LiDAR data acquired in 2014 (see Section 4.1 and figures thereto). When considered together with the role of active surface modification processes (discussed below in Section 3.5), these two features show that while there may be significant limits to the preservation of small tectonic features over time periods of thousands of years due to geomorphic surface modifications, such features can be stable and preserved in the Holocene landscape. Our field observations confirm that this limitation is likely most severe in areas of more irregular and high relief terrain, and somewhat less so in areas with more gentle, rounded, and uniform slopes. In short, the terrain and the style of faulting will together affect how apparent potential fault-derived features will be in the INSAR data.

The scale of features mapped in areas where LiDAR DEM data are available is much finer than those of based on the INSAR DEM (see Section 4.1 and associated figures). Direct comparison of the field scale of these features where there is overlap of the INSAR and LiDAR data coupled with field-based investigation illustrates the scale of features that are visually identifiable from aerial reconnaissance, LiDAR, and INSAR DEM.

3.5 Role of Geomorphic Processes for Creating Apparent Lineaments

Another insight stemming from the lineament field investigation is that a preponderance of the individual lineaments mapped within many of the lineament groups are the result of glacial and/or periglacial processes. Therefore, a discussion of the various geomorphic processes and resulting landforms is warranted in order to provide a context for their extensive presence on the landscape, as well as a technical basis for evaluation of lineament groups within the project area.

Based on the field observations, the dominant erosional features observed are common in glacial and periglacial environments and include: subglacial (sub-ice) channels carved into rock or soil; solifluction-related scarps and lobes; roche moutonee, drumlins, and nivation-related scarps. The erosion-related landforms tend to produce slope breaks and linear features that are similar in landscape expression to tectonically produced lineaments. These processes are briefly described below.

3.5.1 Subglacial Channels and Basal Erosional Processes

Subglacial erosional processes appear to be significant factors in the origin of many of the larger lineament features identified through the desktop DEM analyses in FCL (2012). Unfortunately, the specific genesis of subglacial erosion that creates subglacial channels (also called meltwater channels) is generally poorly understood because their process of origination cannot be directly observed. Moreover, the classification and nomenclature for describing landforms and origins of various types of subglacial channels is relatively non-uniform and inconsistent, which further confounds clear terminology.

In essence, subglacial channels may develop by eroding upward into ice, eroding downward into the underlying substrate, or a combination of both. Channels that erode upward into ice may eventually become plugged with sediment and, when the ice recedes, remain on the landscape as eskers.

Subglacial channels that form by eroding downward under the ice into the underlying geologic substrate are relevant to this lineament evaluation because this action produces sub-linear erosional features on the landscape (Figures 3-10 to 3-12). Geomorphic characteristics common to subglacial channels include: an often abrupt beginning or termination in places where normal river channels do not start or end (e.g., across interfluves), uneven longitudinal profiles, channels that tend not to widen downstream, and steep channel side-walls oriented down slopes at a right angle to the contour lines (Gray 2001; Gao 2011). The geomorphic expression usually is a ravine that starts for seemingly no reason and then continues towards the bottom of a valley where it may terminate abruptly. Where the channels have formed in solid rock, the substrate rock typically is deeply incised or gorged, with narrow and steep-sided walls (Figure 3-11).

The subglacial channels described above may also be referred to as a tunnel valley. A tunnel valley is a large, long, valley originally cut under the margin of former continental ice sheets (Figure 3-12; Jorgensen and Sandersen 2006; Gao 2011). The processes forming the valleys appear to advantageously occupy pre-existing (open and buried) valleys for the renewed erosion. Thus, old subglacial erosion pathways may have been re-used several times. The Finger Lakes in New York State are attributed to tunnel valley processes (Jorgensen and Sandersen 2006).

Tunnel valleys appear in the technical literature under several terms, including tunnel channels, subglacial valleys, iceways, snake coils and linear incisions.

Roche moutonee (a.k.a. sheepback) landforms result from the passage of glacier ice over bedrock that creates an asymmetric erosional form as a result of abrasion on the up-ice side of the rock and plucking on the down-ice side (Ritter et al. 1995). This process generally produces isolated "knobs" of rock that may protrude through glacial drift or alluvial cover, and appear similar to a tectonically bounded or emplaced sliver because of its generally infrequent occurrence on the landscape.

Drumlins form by ice-flow and substrate abrasion or scour, and typically are elongate, linear ridges oriented parallel to the direction of ice flow (Ritter et al. 1995). On a drumlin, the steep side is facing the approaching glacier, rather than trailing it, and thus may appear as an apparent truncation if the slope is appreciably steep.

3.5.2 Solifluction

Solifluction (also called gelifluction) is a slow-rate hillslope mass wasting process that commonly occurs in periglacial environments during the thaw (i.e., summer) season. It is distinct from the frost heave process. (Frost heave is a particle's movement perpendicular to slope because of volumetric ice expansion.) The term solifluction describes the gravity-driven downslope movement of water-saturated unconsolidated surface material (regolith) that flows down slopes of moderate to very low gradient because meltwater saturates the upper layers but cannot penetrate the frozen ground beneath (Ritter et al. 1995). The process produces arcuate erosional (and scarp-like) features up-slope as well as arcuate lobate constructional landforms on the downslope. The arcuate landforms tend to produce apparent slope breaks on the landscape that may be interpreted as potential fault-related features. In many cases, it appears that solifluction related scarp-like features and slope breaks of sufficient size to be identified and mapped in the INSAR based DEM were included as individual features within the lineament groups. These occurrences are most common in landscapes with more uniform and moderate slopes, where extensive areas of solifluction features have developed. Because of similarities at the outcrop scale of the size, morphology, and continuity of these features to surface rupture features associated with large tectonic earthquakes, evaluation of lineament groups and features in these types of landscapes poses significant challenges and added uncertainty for interpretations.

3.5.3 Other Processes and Landforms

Nivation processes are difficult to define because the process includes both physical weathering coupled with hillslope erosion. In general, nivation is the acceleration and/or intensification of ground weathering and erosion associated with patches of snow that persist into the summer season in a periglacial environment (Ritter et al. 1995). Snow patches that persist in sheltered (shaded) positions on hillslopes below the altitude of permanent snow fields may produce nivation depressions or "hollows." The weathering becomes intensified in the saturated ground beneath a compacted snow patch (i.e., névé: a young, granular type of snow which has been partially melted, refrozen and compacted yet precedes the form of ice). The saturated snow mass produces a flow of water on the ground surface that erodes particles of soil beneath the snow. In addition, freezing and thawing of the snow mass can impart physical breakdown of soil as well as heave and downslope soil erosion processes.

Nivation scarps and related geomorphic features are most common and apparent in the higher elevation portions of the landscape above treeline, most often in portions of valleys most recently occupied by glacial ice. In these areas, low-level aerial and ground observation facilitated differentiation of nivation-related landforms from landforms generated by other processes. Importantly, the identification of lineaments, whether nivation-related or not, in areas most recently occupied by glaciers implies a very young age. Many of the features ultimately interpreted as nivation-related were prominent in the DEM models, but found with field observations to be much larger than credible for features of tectonic origin given their occurrence within the youngest portions of the regional landscape.

3.6 Age Datums and Detectability Limits

Understanding the Quaternary geologic history in the Susitna River basin region is relevant to understanding the geomorphic processes, resultant surficial geologic deposits, as well as relationships amongst deposits, both stratigraphically and chronologically. Quaternary stratigraphy and correlations to regional chronology form a basis to establish a geologic datum for evaluating tectonic (fault) activity during the latest Quaternary. The following section presents our Quaternary geologic and chronologic model based on the correlation of regional glacial events and timings. In addition, the results of age-dated samples collected near the dam site and their relevance to local age datum are discussed.

3.6.1 Quaternary Geologic and Chronologic Model

At their maximum extent during the Quaternary, glacial ice caps coalesced and covered essentially the entire 100 km (~62 miles) radius about the Watana dam site (Wahrhaftig 1965; Hamilton 1994; Kaufman et al. 2011). Even during the late Wisconsin or last glacial maximum (LGM) in south–central Alaska, recent regional compilations (Kaufman et al. 2011) show that the glacial extent was slightly restricted relative to the Quaternary maximum extent, but still only a few relatively high elevation or isolated areas within 100 km (~62 miles) of the Watana dam site remained ice free (Figure 3-13). Most remaining lower elevation areas in that region, such as the northwestern Copper River Basin, were largely occupied by proglacial lakes, confined by ice blockages between the mountain ice caps. In the Watana dam site area, prior investigations (e.g., Acres 1982a, 1982b) document the stratigraphic record left by alternating ice advances and glacial lakes associated with the most recent glaciations.

Age control for the late Wisconsin glacial advances in the Watana dam region is limited, and largely based on recent cosmogenic dating of moraines and landforms on either side of the Alaska Range, north of Watana dam site (Figure 3-13). Most recent age compilations (e.g., Kaufman et al. 2011; Briner and Kaufman 2008) now suggest that the timing of Oxygen Isotope Stage 2 (LGM) maximum advances in Alaska may have varied by thousands of years across the state, but retreat from the maximum extent in south-central Alaska likely started about 22 to 20 ka. Ice extent probably remained near the maximum extent for a few thousand years, with several readvances and periods of stabilization through about 15 ka. The last significant readvances of glaciers in the Alaska Range occurred between 14 to 12 ka, and 12 to 11 ka (Briner and Kaufman 2008), followed by rapid deglaciation.

Near Anchorage and in the upper Cook Inlet, about 200 km (~125 miles) to the southwest of the site, the late Wisconsin advance is locally termed the Naptowne, and occurred between about 30 to 11 ka (Reger et al. 1997). During the maximum advance, ice from the Alaska Range flowed south and southeast and filled much of the Cook Inlet at about 23 ka. Ice remained near this limit until about 19 ka, then retreated gradually to less extensive advances or still-stands until about 17 ka, when there was significant retreat. A final re-advance, which built the Elmendorf moraine complex, began after 16 ka, and extended to about 11 ka.

For fault and crustal seismic evaluations, the ages from regional glacial chronologic correlations imply that the vast majority of the landscape within about 100 km (~62 miles) of Watana dam site was covered beneath glacial ice or glacial lakes as late as about 17 ka, with a slow reduction in ice and lake extent through 12 to 11 ka. During this later period, significant ice and lakes remained in most of the glaciated valleys within the northern and central Talkeetna Mountains, and potentially included the last glacial advances of the Tsusena and Deadman Creek glacial lobes into the Watana dam site vicinity, and intervals of glacial lakes in the Watana Creek area (Figure 3-14). Thus, geomorphic surfaces on which a record of potential surface faulting might be preserved significantly prior to about 12 to 11 ka within about 100 km (~62 miles) of the Watana dam site were likely limited to isolated high peaks above the ice limits, and small ice-free areas above the limits of glacial lakes. Potential ice free areas during the later stages of the late Wisconsin advance lie mostly east of Watana Creek along either side of the Susitna River, and along the southeastern margin of the Talkeetna Mountains above the limits of Lake Ahtna in the Copper River Basin (Figure 3-13). As ice receded during the waning late Wisconsin advance, areas near Talkeetna, along the Chulitna River from Susitna River to the Broad Pass area, and the low hills and valleys southwest of the Alaska Range glaciers on Monihan Flats, but northeast of Watana dam site, may have been ice free closer to 15 ka, although some dating results from near Talkeetna (Wygal 2009; Wygal and Goebel 2011) suggest significant deglaciation may have begun much earlier.

In the middle Susitna Basin, in the Watana dam site vicinity, reconstructions of possible ice profiles suggests that LGM ice thickness near the site was at least several hundred meters, as ice caps from both the North and South Talkeetna Mountains coalesced with south-west flowing ice from the Northern Alaska Range (Figures 3-13 and 3-14), as shown by the strongly grooved landscape surface evident within the basin. Available dating results from sites in the path of ice sources on the south side of the Alaska Range (Figure 3-13) only constrain the regional LGM advance here as older than 13 to 17 ka. Dates from the northern portion of the Copper River Basin (Thorson et al. 1981; Williams and Galloway 1986) appear to suggest that these advances near LGM limits are younger than about 22 to 24 ka. As LGM ice began to recede, contributions from the Alaska Range diminished and the Northern Talkeetna Mountains ice sources became dominant, resulting in local flow to the northeast as evidenced by moraines built east of Tsusena Butte which demonstrate ice flow towards Butte and Deadman Lakes. Much of the middle Susitna Basin likely remained ice covered during this period of overall recession from the LGM, but with thinner, and increasing areas of stagnant ice (Figure 3-14).

The final stages of deglaciation in the middle Susitna Basin near the Watana dam site appear to be recorded by the large areas of stagnant ice deposits extending north from the Susitna River between Tsusena and Deadman Creeks (Acres 1982b) to Tsusena Butte (Figure 3-14). Samples for OSL dating of this last stage of deglaciation were collected in 2014 from an exposure along Deadman Creek about 4 km northeast of the Watana Dam site (Figures 3-14 and 3-15). The Deadman Creek sample site is on the edge of an approximately 100 to 200-m (~330 to 660 ft) wide geomorphic surface which extends about 1 to 2 km (0.6 to 1.2 mi) upstream along Deadman Creek; the surface is approximately 685 m (2,250 ft) elevation and is about 40 m (135 ft) above the incised creek (Figure 3-15). This surface appears to be a late stage feature in the retreat of the Deadman Creek ice lobe, and is inset below the main areas of stagnant ice features between Deadman and Tsusena Creeks. This inset surface, and the larger area of stagnation associated with the Deadman Creek ice lobe, cross-cut and thus post-date the more extensive LGM ice advance that is manifested as west to southwest directed fluted terrain south of the dam site and near Deadman Creek (Figure 3-15). We interpret the stratigraphy in this exposure to represent shallow deltaic and glacio-lacustrine sedimentation resulting from drainage impeded or ponded by late-stage stagnant ice within 1 to 2 km (0.6 to 1.2 mi) downstream on Deadman Creek. General outlines of the site geomorphic setting are shown on the project LiDAR color hillshade base on Figure 3-15).

The lower part of the Deadman Creek exposure consists of a sequence of laminated and cross-bedded fine- to medium-grained sands (Figure 3-16). Samples S1-3 and S1-4 are within this sequence of sands. Deeper in the section (lower right of photo) are some fine beds of silt to very fine silty sand that are cut by very small compaction or dewatering faults. The top of the sandy section, between S1-3 and S1-2, is oxidized and iron stained, within the upper part of the sands, and bounded by the fine sand/silt beds that comprise much of the upper part of the section in which samples S1-1 and S1-2 were collected. This finer-grained upper section is also thinly laminated, and bedded with a few 1- to 5-cm thick (0.4 to 2 inch) beds of fine-medium sand. In the upper left corner of the photo (Figure 3-16), are 10 to 20 cm diameter (4 to 8 inch) cobbles; these increase in frequency and size to the left of the exposure near the edge of the surface. We interpret the lower part of the Deadman Creek exposure as representing shallow, fluvial deltaic sedimentation in a small glacial lake with either rising lake level or restrictions on the input of the fluvial source. The upper portion of the section reflects more distal glacial lacustrine fine sedimentation, with cobbles as either local melt out from icebergs (dropstones). The overall stratigraphy of the exposure does not indicate any obvious large breaks or hiatus in deposition, and the restricted extent of the inset geomorphic surface along Deadman Creek also suggests a limited duration for deposition at the site (Figure 3-15).

Table 3-1 and Figure 3-17 show the tabulated OSL results and plot of age versus depth for the samples from the Deadman Creek exposure. (The laboratory report for the OSL analysis is provided as Appendix C). The OSL ages suggest that deglaciation and stagnation of the larger Deadman Creek ice lobe in the middle Susitna River valley must be older than about 14 to 15 ka. The ages imply that the upper and lower portions of the exposure differ in age by less than about 2 ka.

Table 3-1. Summary Results from OSL Age Dating

Sample number	Depth below ground (m)	Minimum age (ka)	Mean age (ka)	Maximum age (ka)	2-sigma (ka)
S1-1	0.43	12.38	15.09	17.80	2.71
S1-2	0.53	12.24	14.96	17.68	2.72
S1-3	0.85	12.66	15.29	17.92	2.63
S1-4	1.03	12.53	15.06	17.59	2.53

In conjunction with regional deglaciation ages of 13 to 17 ka from the Alaska Range north and northeast of site (Figure 3-13) and the upper age limits of 22 to 24 ka for LGM advances into the northern Copper River Basin (Thorson et al. 1981; Williams and Galloway 1986), the OSL ages from the Deadman Creek site indicate that deglaciation of the middle Susitna valley following the LGM was very rapid, occurring between about 15 ka to ~ 22 ka.

Furthermore, following the last late Wisconsin advances in the middle Susitna Valley prior to about 15 ka, there was rapid deglaciation and retreat of the glaciers of southern Alaska to high altitude limits and positions not far from present glacial extents (Reger and Pinney 1997). Moraines and deposits just beyond the limits of current and recently active deposits have ages of less than 2 to 1 ka (Dortch et al. 2010a), suggesting glacial extents during the Holocene have remained near present limits. Near the Watana dam site, the rapid transition to non-glacial conditions is evidenced by several radiocarbon ages on peats and bog deposits which began to accumulate in the post-glacial environment and which yield radiocarbon ages ranging up to about 11 to 10 ka (WCC 1982; Reger et al. 1990). Radiocarbon ages from the lake deposits in Copper River Basin, suggest final lowering and drainage of the large glacial lake there occurred during the same time period (Williams and Galloway 1986). Published radiocarbon chronologies from archaeological studies indicate that some parts of the Upper Susitna area may have been habitable by 12 ka (Potter 2008).

At least three Holocene tephra units are known to overlie glacial deposits in some areas near the Watana dam site. These deposits are thought to have originated from eruptions in the Tordrillo Mountains to the southwest of the Watana site (Riehle et al. 1990). Three tephra units described near the Watana site are reported to be about mid to late Holocene age, based on radiocarbon analyses of 42 samples (Dixon et al. 1983, 1985). More recent work by Brian Wygal (Wygal and Goebel 2011) suggests the older (i.e. lower) tephra observed may have been deposited 7,880 - 8,800 calendar years before present.

For fault and lineament evaluations in the Watana dam site region, the review of previous studies and research of Alaskan glacial chronologies, coupled with field observations of the type and distribution of glacial constructional and erosion landforms suggests that there are three broad age categories within which the landscape may be viewed. These are, from youngest to oldest: late Holocene, mid- to early Holocene, and post-late Wisconsin period of the latest Pleistocene. Geomorphic surfaces and deposits associated with maximum phases of the late Wisconsin glaciation, and older glaciations, were generally either modified or buried by effects of the last phases of late Wisconsin glaciation. Thus, for geomorphic evaluations of the faults and lineaments in the region, these older deposits are generally of limited use because the surface expression of older faulting has been removed. Based on the results of the OSL dating (Table 3-1), the geomorphology of the Quaternary deposits in the vicinity of the sample collection site (Figure 3-15), and the regional chronologic correlations (Figures 3-13 and 3-14), it is likely that Quaternary surfaces and deposits that were formed during the post-late Wisconsin period of the latest Pleistocene precede 15 ka.

4. OBSERVATIONS AND INTERPRETATIONS OF LINEAMENT GROUPS AND RELEVANT FEATURES

This section presents the observations of the lineament groups characteristics based on review and inspection of existing geologic mapping, geomorphic evaluation of the LiDAR data on which the lineaments are mapped, and synthesizes this information with the results of the field investigations to provide an interpretation and evaluation of the significance of the lineament group. This section also presents the observations and interpretations of other relevant features, namely the discussion of the Talkeetna fault trench locations of WCC (1982) (Section 4.2), the Susitna feature (Section 4.3), and the Watana lineament (Section 4.4).

4.1 Lineament Groups, Areas, and Reger et al. (1990) Photogeologic lineaments

The documentation under Section 4.1 discusses each of the individual lineament groups and larger areas visited during the 2013 and 2014 lineament field investigation. The groups and larger areas are depicted in detail on a series of strip maps and plates on which relevant field and office geologic and geomorphic data are compiled and evaluated (Appendix A). The lineament groups identified for field work are shown on Appendix A, Figure A0.1, and a series of supporting figures[1]. The larger areas showing the Broad Pass fault, Clearwater Mountains, northeastern Castle Mountain fault, are shown on Plates A-BP, A-CWM, and A-CME, respectively. Appendix B contains a series of figures presenting map and field data for numerous photogeologic lineaments mapped by Reger et al. (1990) on the Healy A-3 Quadrangle (see Figure B-01 and discussion below). The strip maps and plates facilitate discussion and evaluation of the data collected in the field with respect to the features' relevance to the seismic hazard evaluation for the proposed Watana dam site.

4.1.1 Lineament Group 1

Lineament group 1 is an east-northeast-trending group of lineaments defined by a series of aligned, linear to sub-linear drainages and uphill-facing slope breaks, approximately 51 km (~32

[1] Note that for ease of reference, Appendix A figure numbers correspond to lineament group numbers. For example, Figure A1.1 shows the extent of lineament group 1. The content of the strip maps and plates is customized for each lineament group and only the most relevant geologic data are shown on the most appropriate base imagery, given the local terrain and features of interest. The explanation of symbols and relevant existing geologic mapping shown on the figures has been compiled into a series of explanation sheets (Figures A0.2, A0.3, A0.4, and A0.5) that follow the index map of lineament groups and precedes the figures for lineament group 1.

miles) north of the proposed Watana dam site (Appendix A, Figures A0.1, and A1.1). Individual mapped lineament feature lengths range from approximately 200 m to 4 km (~650 feet to 2 miles), with an aggregate length of approximately 20 km (~12 miles). No previously mapped faults or lineament features coincide with the group (Figure A1.1), and no evidence of fault structure was observed during low-level aerial investigation. Along the eastern portion of the group, the morphology of the lineaments and their very linear trend across the high relief terrain suggests that any potential fault structure that may exist would have a steep dip and apparently north-down, south-up sense of motion. The feature has a similar trend to the relatively proximal Denali fault (Figure A0.1). Discrete lineaments that make up the aggregate group occur in the Cretaceous Kahiltna flysch sequence (map unit KJf, Wilson et al. 1998) and to a lesser extent, Tertiary intrusives of felsic and intermediate composition (map unit Thf). Late Quaternary deposits along the Jack River, of late Wisconsin and post-glacial age intersect the projected trace of the group 1 lineaments near the center of the group 1 ellipse. These late Quaternary deposits show no apparent expression of the lineament (Figures A1.1 and A1.2).

Observations made during aerial field investigation suggest that the topographic expressions of the lineaments within the Cretaceous Kahiltna flysch (map unit KJf), in the eastern portion of the group, may be erosional features along unmapped bedrock structure, or possibly large sackung features. In either case, the absence of continuity of the individual lineaments from steep bedrock slopes into adjacent areas of lower slopes where Quaternary deposits are present is evidence of non-tectonic origin for these features. Although the lineament group has a similar trend to the Denali fault located about 18 km (~11 miles) to the north, no previously mapped faults or lineament features coincide with the group (Figure A1-1), and no evidence of fault structure was observed during low-level aerial investigation. The lineaments that were identified in the western portion of group 1 are associated with a large, narrow, linear canyon, with no change in rock type or expression across the valley. Additionally, the lineament segments of Group 1 do not align across the Jack Creek drainage at larger (more detailed) map scales, suggesting the lineament group may represent two shorter sets of unrelated features. Based on the above evidence, the lineaments of group 1 are likely non-tectonic in origin, are judged to be primarily erosional and/or landslide features, and are not considered further.

4.1.2 Lineament Group 2

Lineament group 2 is an east-northeast-trending series of aligned, linear drainages, slope-breaks, and V-notched saddles (Figure A2.1) located approximately 46 km (~29 miles) north-northwest of the proposed Watana dam site (Figure A0.1). No previously mapped geologic faults or lineament features coincide with the lineaments of group 2, although the group has a similar trend to the relatively proximal Denali fault (located 25 km [~15 miles] to the north-northwest). No evidence of fault structure was observed during low-level aerial investigation. Individual features range in length from a few hundred meters to approximately 2 km (<985 feet to ~1 miles), with an aggregate length of approximately 12 km (~7 miles). The youngest unit expressing lineament features are Tertiary volcanic rocks (map unit Tvu), and the oldest unit is the Cretaceous Kahiltna flysch (map unit KJf) sequence (Wilson et al. 1998; Figure A2.1). Individual lineaments within the group have a clear expression in both bedrock units. Mapped Quaternary surficial sediments, fluvial deposits in several unnamed drainages, a glacial moraine, and an alluvial fan deposit show no apparent deflection or deformation where overlying the projected trace of the lineament group (Figures A2.1 and A2.2). Glacial valley orientations are orthogonal, or sub-orthogonal to the lineament group, suggesting that Quaternary glacial processes likely had little role in the formation of the features. From west to east, the mapped linear segments present both down-to-the-north and down-to-the-south apparent senses of vertical deformation with a variable scale of vertical relief ranging from less than 10 m to about 50 m (~33 to 164 ft).

Discrete lineaments within group 2 occur primarily in Tertiary volcanic rocks (map unit Tvu), with one feature showing an apparent expression in both the Tertiary and Cretaceous rocks, and an additional aligned linear drainage expressed in Cretaceous rocks (Figure A2.1). No FCL mapped lineament from group 2 has expression in Quaternary units or Quaternary landforms based on field observations. As mapped, the Wilson et al. (1998) map compilation in this area is generalized and does not accurately depict the full extent of Quaternary surficial deposits (map unit Qs) along the position of FCL-mapped lineaments. Field investigation confirmed that Quaternary surficial deposits should be mapped through the floor of the Jack River valley and on both the north and south sides of the linear drainage shown in Figure A2.2 (Photograph A) and that much of these deposits consist of till and other glacial deposits, likely of late Wisconsin age. In all instances, lineaments with clear expression in bedrock lose expression at contacts with Quaternary deposits and landforms. In the eastern portion of the lineament group, the lineament appears to consist of erosional scarps and linear drainage sections that follow the course of the Jack River. At a rectilinear bend in the river (near A on Figure A2.2), late Wisconsin glacial deposits in the valley bottom overlie the projected trace of the linear river segment, and did not show any expression indicative of deformation related to faulting. West of the Jack River, the lineament consists of discontinuous, but aligned linear slope breaks in Tertiary volcanic bedrock (map unit Tvu) separated by Quaternary units in which the lineament is not expressed. The western-most of the lineaments extends into KJf (Cretaceous Kahiltna flysch), based on the Wilson (1998) mapping, but is again separated from other lineaments by Quaternary units with no expression of the lineament. The limited and ambiguous expression of lineament features outside of the Tertiary volcanic rocks within the Kahiltna flysch, suggests that the observed trend may represent erosion along internal bedrock structure or features with the Tertiary volcanic rocks, as opposed to a through-going crustal structure. The geomorphic expression of this lineament group presents an inconsistent expression of apparent vertical displacement. Along the trace of this lineament group both down-to-the-north and apparent down-to-the-south sense of displacement is expressed. The case for lateral displacement is unlikely because of the absence of deflected drainages and other features related to lateral deformation (shutter ridges, sag ponds, etc.) along the projection of the lineament trend. Based on the field observations, notably the irregular characteristics of the lineaments along strike, lack of western continuity into the Cretaceous Kahiltna flysch units, and absence of expression in Quaternary units along the feature, the likelihood of a tectonic origin for the lineaments in group 2 is judged to be low and they are not considered further.

4.1.3 Lineament Groups 3a & 3b

Lineament group 3a is an east-west trending group consisting of a series of linear to sub-linear aligned drainages, approximately 40 km (~25 miles) northwest of the proposed Watana dam site (Figure A3a.1). Lineament group 3b, east of group 3a, consists of east-west trending lineaments manifested by a series of aligned, linear to sub-linear drainages, slope-breaks, and steep V-shaped notched canyons, approximately 27 km (~17 miles) north-northwest of the proposed dam site (Figure A3b.1).

These two groups were considered for evaluation in summer 2013 largely because they share a generally similar orientation/trajectory on the landscape and they are spatially proximal, thus introducing the possibility that groups 3a and 3b could represent a through-going (i.e. linked) structure of appreciable length. In fact, considered separately, group 3a and group 3b would have failed, or nearly failed, the lineament exclusionary criteria (Table 2-3). There are no previously mapped faults that coincide with either group 3a or group 3b lineament, however, each group is depicted (Clautice 1990; Wilson et al. 2009) with bedrock faults crossing each lineament group at high angles (Figures A3a.1 and A3b.1). The northeast trending fault in group 3b was not observed. The faults bounding Triassic metamorphic rocks (Trnm) in group 3a did appear to bracket rock types based on somewhat different surface textures.

The trend of lineaments within group 3a across the topographic contours is linear, and does not follow a pattern expected from a dipping plane intersecting the ground surface. The lineaments are expressed in mapped undifferentiated Quaternary deposits (map unit Qs – likely post glacial age) as short linear gullies tributary to Crooked Creek along the eastern part of group 3a (Figure A3a.2), however no scarp-like feature was observed in the field during low-level aerial investigation. The lineaments also are expressed in Cretaceous Kahiltna flysch sequences (map unit KJf) as a raised ridge with an apparent color contrast on either side of the ridge (Photograph B, Figure A3a.2). However, this observation could not be extended laterally to the west; the adjacent, older, Triassic metamorphic rocks (map unit Trnm) show no expression of faulting. The 3a lineaments cross several different geologic units and landforms, and are largely discordant to the likely ice flow direction. The lineaments' morphology largely are v-shaped notches and slope breaks whose scale is variable along strike of the group. Near the Crooked Creek drainage, the lineaments have both small and moderate magnitude notches. Farther west, and into the Triassic rocks, the notches become relatively larger in magnitude. The magnitude of expression at the west end of group 3a is least of the entire group.

The lineaments mapped in Quaternary (post-glacial) deposits along group 3a do not show neotectonic expression or offset. While the group 3a lineaments are mapped across several different geologic units, there is no apparent offset of mapped bedrock contacts along the trend of the lineaments. Most of the lineaments are interpreted to be either erosional in origin or related to slope processes due to their expression as short linear gulleys or presence on slopes where solifluction or nivation processes are dominant. The exception to this is the ridge in the Cretaceous Kahiltna flysch in which field observations found a color contrast (Figure A3a.2) that may be structurally-controlled, or may just as equally be stratigraphically controlled.

The lineaments within group 3b are nearly entirely within Eocene granitics (map unit Tegr, Figure A3b.1). The lineaments within group 3b are mapped along the invert of v-shaped notches, and thus the trend of the lineaments across topographic contours is nearly orthogonal. No Quaternary deposits are mapped, but ground-based observations indicate that there are youthful (Holocene) deposits in cirques and drainage valleys, as well as rock glacier deposits (Figure A3b.2). Although these are very young deposits, there is no expression of lineaments in these deposits. The lineaments are somewhat oriented parallel to ice flow direction along the eastern part of the group, but are positioned mostly in cirques and near ridgelines. Rock glaciers are present along the western part of group 3b, and interrupt the mapped lineaments without offset or deformation (Photograph D, Figure A3b.2). The morphology of the lineament is inconsistent along strike, showing north-facing slope breaks, south-facing slope breaks, as well as v-shaped notches.

The lineaments show an absence of evidence of expression in the Quaternary drainages, and in particular, the toes of rock glaciers where they interrupt the mapped lineaments. While the rock glaciers are likely no older than post-glacial, they may also be as young as early Holocene. Given the relatively large expression of the north-facing slope break along the eastern part of group 3b, it is reasonable to expect some signature in the Quaternary deposits despite their potential youthfulness.

Overall, lineaments within groups 3a and 3b are not associated with previously mapped faults, are predominantly erosional in origin, and show no evidence of offsetting Quaternary deposits. When considered individually, there is little evidence to support the lineaments as a fault structure. When considered collectively, there is little similarity in their landscape expression across the two groups to support positive interpretation of a linked, through-going crustal structure. Lineament groups 3a and 3b are interpreted to not represent an active crustal structure and no further work is deemed necessary.

4.1.4 Lineament Group 4

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) and strip maps for this group are not included herein (Figure A0). However, a limited number of low-altitude fly-overs in 2013 appear to confirm the desktop conclusion that the group 4 features are pre-Quaternary. Rock-type contrasts were observed across the previously mapped NE-trending thrust fault but no prominent tectonic geomorphology to suggest Quaternary activity was observed along strike in post-glacial surficial deposits nor in the bedrock.

4.1.5 Lineament Group 5

Lineament group 5 is an east-northeast trending lineament group defined by aligned V-shaped troughs, side-hill benches, and slope breaks, approximately 40 km (~25 miles) west-northwest of the proposed Watana dam site, near Chulitna Pass (Figures A5-1.1 and A5-1.2). The eastern extent of the lineament group coincides with a previously mapped, unnamed lineament feature (Wilson et al. 2009), however lineament group 5 does not coincide with any previously mapped faults (FCL 2013). Low altitude aerial observation found no evidence for the presence of a fault structure along group 5. Along its eastern extent, the trend of individual lineament groups is generally parallel to ice-flow direction expressed as fluted and grooved topography in a general east-west orientation. The trend of the lineaments across the topography is near straight, implying a vertical to steep geometry of a hypothetical structure. The lineaments primarily are expressed in Cretaceous turbidite rocks of the Kahiltna flysch sequence (map unit KJs) and, to a lesser extent, Tertiary granitics and Quaternary (probable late Wisconsin) glacial sediments. While the lineaments traverse different age rocks and sediments, the lineaments mapped in Quaternary sediments are restricted to likely floodplain or terrace deposits of the Indian River that could be as young as Holocene and coincide with terrace risers (Figure A5-2.2). The magnitude of the lineaments expression along strike is variable, with greater expression in the older bedrock units and substantively less expressed within the Quaternary units. The lineaments within the Quaternary deposits are relatively concordant with the ice-flow direction as expressed in the ice-scoured surfaces. There is no evidence that the ice-scoured surfaces are cross-cut or otherwise offset by the lineaments. Along the eastern extent of the group, the lineaments' morphologic expression as side-hill benches would imply an extensional-type kinematics (i.e., down-to-the-south); along the western extent the morphologic expression varies as both uphill and downhill facing scarps, linear grooves, and drainages that would imply a translational-type kinematics.

Low altitude aerial field observation revealed no evidence of lineament expression within the Quaternary deposits or surfaces. While the lineament group does traverse different geologic units and landforms suggesting a continuity of structure, the lineaments show an inconsistent kinematic expression along strike (i.e., extensional on the east, translational on the west) within the same rock unit (Cretaceous turbidites; map unit KJs) that tends to not support the presence of a tectonic structure for creating the lineaments. The lineament group is associated with a previously mapped lineament along the eastern extent, however, the lineament does not continue westerly past Indian Creek drainage. Given the above, it is likely that individual lineaments apparent origin is dominantly erosional. Along the western part of the group near Little Coal Creek, field observations indicated that a side-hill bench and linear drainage (Figure A5-2.2) likely are the result of bedded turbidite sediments dipping into the hillslope (Figure A5-1.1), with differential weathering accentuating the erosion features. The lineaments in the Quaternary sediments of Indian River valley appear to be the result of erosion along generally west-flowing creeks that are dissecting the geomorphic surfaces creating apparent scarps in the fluvial deposits. From the above, it is judged that the lineaments along group 5 are the result of bedding orientations in the Cretaceous turbidite units and elsewhere from fluvial or glacial erosion, and do not represent a tectonic fault.

4.1.6 Lineament Group 6

The northeast-trending linear drainage of Watana Creek is a prominent landscape feature; this and smaller lineaments along Watana Creek are lineament group 6 (Figure A6.1). The lineaments primarily define a northeast-trending, linear to sub-linear drainage, approximately 14 km (~9 miles) east of the proposed Watana dam site. Traces of the Talkeetna fault previously-mapped (as concealed and/or inferred) pass within the ellipse defining group 6. In addition, Watana Creek was the target of focused project-specific geologic mapping and data collection by WCC (1980, 1982) and Acres (1982a, 1982b). However, the previous studies result in a fair degree of disagreement as to the (inferred) location and character of the Talkeetna fault in the area of lineament group 6. Importantly, the published map traces (as concealed and/or inferred) are placed along the western upland margin of Watana Creek, and are not shown as crossing or intersecting Watana Creek (Figure A6.1). During multiple low altitude overflights, field evidence of a fault structure was not observed along or in the immediate vicinity of lineament group 6, and no evidence was observed along the projection of the fault trace across Delusion Creek. A shear zone is delineated by Acres (1982b) near the mouth of Watana Creek (orange line from Acres mapping shown in Figure A6.1). However, the trend and extent of the shear zone do not seem to correspond to other map traces of the Talkeetna fault. Because the lineaments are chiefly mapped along Watana Creek itself, as well as linear drainages tributary to the creek, the trend of the lineaments as mapped reveals little about hypothetical fault structure geometries. The lineaments are expressed as linear drainages or erosional gullies oriented sub-orthogonal to the Talkeetna fault trace(s), and principally are developed in late Quaternary glacial drift (till) and glacio-lacustrine (lake) deposits. Lineament group 6 occurs at a high angle to regional ice-flow direction, suggesting that Quaternary glacial processes had little influence on the formation of the feature. The lineaments themselves are thus attributed to surface erosion and drainage development on the Quaternary upland surface, with one exception. A linear feature of about 700 m length (~2,300 ft) with distinctly positive relief was observed and mapped as a lineament segment near where Watana Creek turns easterly into the uplands. This feature, parallel and nearby to the inferred locations of the Talkeetna fault, was inspected from the air and on the ground, and a shallow test pit was opened to examine the stratigraphy to better understand the origin of the feature (Figures A6.1 and A6.4). The shallow subsurface texture generally was sand with gravel, grading upward into silt, and was interpreted as an esker landform. Tephra deposits (wind-laid volcanic ash) were observed near the top of the pit, and three different tephras could be present. Discussions with project archaeologists and review of published literature indicate that the tephras likely represent the Mt. Hayes, Watana, and possibly the Oshetna tephra deposits (Dixon and Smith 1990). It is interpreted that the esker is at least a few to several thousand years old based on the presence of the tephras, but an upper age limit is undetermined at present.

There is an appreciable lack of mapped lineaments coincident with the (concealed and/or inferred) locations and orientations of published Talkeetna fault traces, even within LiDAR imagery area. The LiDAR-derived DEM data reveal an absence of scarp-like features along the map traces in Quaternary surfaces (Figure A6.1) that was confirmed during field investigation (Figure A6.2 and A6.3). The INSAR-derived DEM data also reveal an absence of lineaments in the post-glacial valley bottom sediments to the northeast of GPS waypoints 017 and 183. Field observations of Quaternary stratigraphic outcrops along Watana Creek suggest that the contact between the overlying lake and underlying till deposits is planar, unbroken, and apparently untilted (Figure A6.2). A prominent ridge consisting of bedded Tertiary sediments (map unit Tsu) appear as gently northwest-dipping (A6.3). This is generally consistent with structural data collected in Oligocene (Tertiary) outcrops along Watana Creek by WCC (1982) that was used as a basis to argue for northeast-southwest compression and related flexural deformation of the Tertiary units. Though gently northwest-dipping, the stratigraphy of the ridge appears undisrupted along its length and provides additional evidence that the Talkeetna fault likely does not run down the Watana Creek canyon. This style of deformation is inconsistent with reverse thrusting along this part of the Talkeenta fault while regional stress field data allows for the potential reactivation of this lineament as a northeast-oriented thrust fault. The lineaments mapped within group 6 are judged to be the result of erosion of tributary drainages and fluvial erosion to create terrace risers along the creeks and are not likely tectonically-related. Further, there is an absence of tectonic geomorphology along the inferred locations of the Talkeetna fault in Quaternary deposits and surfaces present along the uplands adjacent to Watana Creek.

Additional field investigation was performed along Watana Creek in July, 2014. Helicopter landings allowed geologists to inspect and analyze outcrops exposed in Watana Creek. Bedding orientation (strike and dip) data were collected from accessible exposures of stratified deposits that were present in areas mapped as undivided Tertiary sediments (e.g., Csejtey et al. 1978; Wilson et al. 2009) that may be Oligocene in age (Csejtey et al. 1978). The bedding orientations augment those collected along Watana Creek by WCC (1982). The stratified deposits generally consisted of slightly-to moderately-indurated sandstones, siltstones, and claystones, as well as thin coal beds, and commonly provided clear bedding planes used to collect orientation.

Bedding attitudes of Tertiary units in Watana Creek are generally consistent with those of WCC (1982) and show strata that dip gently to the north as well as north-northwest (Figure A6.5). Variations in individual bedding strike deviate from these general patterns at the outcrop scale, and it is not fully known if this is because: (1) the beds measured were not in original position (i.e., moved downslope), or, (2) if there are localized structural features that were not detected during the field work (i.e., tight folds). The orientation of the Tertiary bedding in Watana Creek supports tilting to the north-northwest. WCC (1982) interprets the bedding attitudes as an expression of northwest plunging anticlines and synclines; that is, northeast-southwest oriented compression with a component of tilting to the northwest. While it seems clear that the strata have been tilted to the north-northwest – similar to attitudes collected in Cretaceous rocks outcropping along the banks of the Susitna River – the development of clear fold limbs in the Tertiary sediment is less obvious.

Faulting of Tertiary deposits was observed in Watana Creek outcrop at approximately 1.5 mi (~2.4 km) and 6.3 mi (~10 km) upstream from the confluence with the Susitna River. At the outcrop 6.3 mi (~10 km) upstream from the confluence, two faults were documented that clearly off set stratigraphic markers exposed in the outcrop. The first fault, striking 065^{o} and dipping 40^{o} southeast, appeared to extend across the entire outcrop, had about 1 cm (~0.4 in) of clay gouge thickness, and produced approximately 40 cm (~16 in) of apparent vertical separation (Figure A6.6). The second fault, striking 221^{o} and dipping 27^{o} northwest, appeared to terminate against the first suggesting a subordinate structural feature that produced approximately 15 cm (~6 in) of apparent vertical separation. Because the bedding attitudes were difficult to measure due to the unstable face of the weakly indurated material, net slip along the fault plane is not estimated. The relative offset along beds separated by the first fault implies reverse (thrust) displacement (i.e., left-side up), however, the same relative offset also could be produced by lateral (strike slip) motion along a fault intersecting dipping bed. The 40^{o} dip of the fault plane also would suggest thrust movement rather than strike slip motion; oblique motion also is completely plausible. There is an absence of lineaments in the Quaternary cover overlying the outcrop (e.g., Figure A6.1 and A6.5), providing a degree of evidence that these two faults have not experienced movement within the last 12,000 years or so.

The second outcrop where faulting within the Tertiary sequence was documented is approximately 1.5 mi (~2.4 km) upstream of the mouth of Watana Creek. The cobble-rich Tertiary outcrop is distinctly different from the upstream strata in that it appears to have been deposited in a relatively higher-energy environment capable of transporting large, rounded, cobbles; perhaps laid by a debris-flow process. The outcrop generally shows a relative dip to the north. A fault zone with clay gouge was observed at the lower part of the outcrop near the waterline of Watana Creek. The fault zone is about 15 to 20 cm (~6 to 8 in) in width and has both blue and greenish clay gouge (Figure A6.7). At the outcrop, relative movement appears to be right side up; however, kinematic indicators on the fault plane (mullions) indicate a left-lateral oblique motion. Adequate surfaces to measure fault plane orientation were not present, and the estimated attitude of the fault was 245^{o} to 260^{o} strike and 65^{o} dip to the north. Significantly, there is an absence of lineaments in the Quaternary cover overlying the outcrop (e.g., Plate A5), providing a degree of evidence that this fault has not experienced movement within the last 12,000 years or so.

4.1.7 Lineament Group 7

Lineament group 7 is a northeast-oriented lineament group defined by an aligned series of linear to sub-linear drainages, faceted ridges, and saddles (Figure A7.1), approximately 28 km (~17 miles) east of the proposed Watana dam site (Figure A0.1). Mapped bedrock fault structures are depicted within the lineament group by some, but not all existing maps (FCL 2013). For example, mapping by Kline et al. (1990) shows a shear zone within lineament group 7. One of the bedrock faults juxtaposing Triassic (Nikolai) greenstone (map unit Trn) against Paleozoic volcanic rocks (map unit Pv) was indirectly observed as a color and vegetation change coincident with a topographic notch in the ridgeline (Photograph A, Figure A7.2). These are the oldest rocks within which the lineaments occur. The youngest deposits that the lineaments are mapped in are latest Pleistocene (late Wisconsin?); the lineaments transect young valley floor glacial sediments as well as elevated bedrock ridgelines. The topographic expression of the individual lineaments implies a high angle to near vertical orientation for a fault because they cut steeply across topographic contours. Along the northern part of the group, the lineaments are not mapped nor are expressed in the glacial valleys; along the southern part of the group the lineaments are oriented along the drainage direction toward the Susitna River. Aerial investigation revealed no field evidence that linear strain markers were deformed or displaced, however the glacial sediments are from rock glacier processes, and few older landforms such as moraines, eskers, or terraces were observed along this group. The expression of the lineament is inconsistent along strike with an apparent stronger expression where mapped along fluvial drainages, and no expression in WNW-oriented cirque-floors or valleys. An additional lineament feature less than 2 km [~1 mile] away from the group 7 also was inspected, although this was not formally included as part of group 7. This feature trends slightly west of north, and is expressed as a large notch near rock glacier deposits. Low altitude fly-overs allowed a visual inspection of the notch that was estimated to be about 15 meters tall (~50 ft). No corresponding notch or groove was observed in the ridgeline on projection to the north, thus the groove was probably created by non-tectonic surface processes.

Lineament group 7 does not show consistent field expression in Quaternary deposits or landforms. The largest magnitude relief along the lineament is along the south-flowing drainages, and relief is not expressed topographically across the WNW trending cirque valley floors. Because the lineament expression in Quaternary deposits is chiefly linear gullies (erosion) with no apparent difference in relief across the gulley, the expression does not suggest either normal or reverse-type faulting. A translational kinematic sense of motion cannot be ruled out; however there is little along-strike expression to assess the sense or magnitude of potential relative lateral motion. There are previously mapped faults along the mapped lineament (Wilson et al. 2009; Figure A7.1). However, there are large scale topographic changes (i.e. reverses) along the length of the fault (and lineament) that leads to an inconsistency in location, magnitude, and type of lineament expression. These inconsistencies, coupled with the fact that the Quaternary deposits in the valley floors are not disrupted, strongly indicates that erosional process of creek incision and downcutting into surface deposits along the south-flowing drainages are likely responsible for creating the mapped lineament feature. Where mapped in bedrock, lineaments of group 7 generally coincide with mapped bedrock structures within fault-line-valleys but lineaments in late Quaternary deposits are inconsistently expressed and likely relate to processes of erosion. No evidence of Quaternary deformation along the mapped lineaments was observed and no further field work is deemed necessary.

4.1.8 Lineament Group 8

The lineaments of group 8 are north-northwest-oriented features expressed topographically as aligned V- and U-shaped, linear to sub-linear drainages, aligned with several discontinuous slope breaks and linear fronts (Figures A8-1.1 and A8-2.2), approximately 38 km (~24 miles) west of the proposed dam site (Figure A0.1). The lineament group coincides with a north-trending promontory around which the Susitna River makes a prominent bend in course (Figure A8-1.1). The middle portion of lineament group coincides with an unnamed, inferred fault mapped by Wilson et al. (2009) that juxtaposes Tertiary undivided volcanic rocks (map unit Tvu) against Paleocene granite (map unit Tpgr) and also granodiorite (map unit Tgd) against turbidites of the Kahiltna flysch (unit KJs) (Figure A8-2.1). WCC lineament feature KD5-44 also coincides with lineament group 8 (FCL 2013). WCC described their feature KD5-44 as a linear stream valley north of the Susitna River, and south of the Susitna River as a linear valley (Cheechako Creek and a tributary creek) and “a shallow, broad, linear depression on the upland plateau…” (WCC 1982). No direct evidence of fault exposures were observed during ground and low level aerial investigation but indirect evidence in the form of changes in lithology across the linear valley was observed near the middle of the lineament group (Photograph C, Figure A8-2.2). The linear trend of the lineament group across the terrain suggests any potential fault that may exist has a very steep to near-vertical dip. The lineaments are expressed in ice-scoured bedrock uplands and a thin cover of glacial and colluvial deposits subject to solifluction. The bedrock ranges in age from Cretaceous-Jurassic flysch (map unit KJf) to Tertiary volcanics (map unit Tvu). The glacial deposits are likely latest Pleistocene to early Holocene (~11 to 12 ka) in age while the colluvium is latest Holocene to modern in age. The mapped lineaments transect across several different bedrock units (Figure A8-1.1 and A8-2.1). The magnitude of expression ranges from none in broad, flat-lying terrain, to 1- to 2-m-high (3- to 6-ft) scarps in solifluction-prone colluvial slopes, to deeply incised linear streams and 50- to 100-m-high (~164 to ~328 ft) linear fronts (Figures A8-2.2 and A8-2.3). The lineament group lies roughly perpendicular to the direction of glacial striae. Glacial striae north of the Susitna River do not appear consistently deformed or displaced across the trend of the lineament and, although the Susitna River does take a tight bend-in-course along the projection of some of the mapped lineaments, several small streams that cross the lineaments near GPS waypoints 177 and 195 are not consistently laterally offset or deflected (Figure A8-2.1). Aerial investigation did reveal the oxidized mafic dike on the northern canyon wall of the Susitna River that WCC (1982) observed projecting across the observed lineament trend but discovered the same ambiguous and poor exposure conditions described by WCC. The 2013 aerial investigation efforts discovered no new evidence to confirm or refute WCC's (1982) interpretation that the dike is not truncated by the linear drainage (FigureA8-2.3); ground access may be required. Based on the preponderance of east-facing bedrock escarpments, the morphology of the lineament group overall suggests down-to-the-east or dip-slip motion on high-angle faults, but a few west-facing escarpments do exist. In addition, mapped fault relations that juxtapose units (Wilson et al. 2009) along the middle of the lineament group are not entirely consistent with the contact of turbidite rocks of the Cretaceous Kahiltna flysch (map unit KJs) and Paleocene granite (map unit Tpgr) being apparently undeformed across the northern portion of the lineament (Figure A8.1).

Portions of lineament group 8 are expressed in very thin Quaternary (i.e., latest Holocene) colluvial and glacial deposits that overlie bedrock, but the lineaments are not consistently expressed in Quaternary strain markers (i.e., stream channels). In two locations, on the north side of Susitna River and along its southern extent, individual lineaments of the group appear to be overprinted by glacial or flood-derived striae (Figure A8-1.1 and A8-2.1). The orthogonal orientation of the lineaments to the regional ice-flow direction suggests that most of the lineament features likely do not result from ice scour or abrasion. However, other ice-related processes such as plucking might explain some of the short lineaments north of the Susitna River where the small east-facing (and up-ice stream-facing) knobs of turbidite rocks of the Cretaceous Kahiltna flysch (map unit KJs) might have been preferentially erodible due to the highly bedded nature of the unit. Lineament group 8 does transect different mapped geologic units but does not exhibit relative consistency of geomorphic expression along strike. For example, in the middle of the group, both east- and west-facing topographic scarps in undivided Tertiary volcanics (map unit Tvu) range up to 50 to 200 m high (~164 to 656 ft) but apparent scarps in thin colluvium overlying Tertiary granodiorite (unit Tgd) near GPS waypoints 177 and 195 are less than several meters high (Figure A8-2.2 and A8-2.3). Furthermore, the lack of spatially-connected and through-going lineaments across the ice-striated terrain north of the Susitna River is inconsistent with the magnitude of expression the deeply-incised linear streams and tall linear fronts to the south. In addition, the apparent structural kinematics (dip-slip) based on mapped contact relations compiled by Wilson et al. (2009) for the middle and southern portion of the group are not consistent with the undeformed contact relations between turbidite rocks of the Cretaceous Kahiltna flysch (map unit KJs) and Paleocene granite (map unit Tpgr) near the Susitna River and also the lack of deformation in turbidite rocks (map unit KJs) north of the river. Lineament group 8 is spatially coincident with previously mapped lineaments (feature KD5-44 of WCC (1982)) and faults (Wilson et al. 2009) but making kinematic sense of the mapped fault and unit contact relations is challenging. No positive evidence of active tectonism was observed and the discrepancy in scale in the apparent tectonic geomorphology along the group is inconsistent with a genesis by active faulting; a fault capable of producing topographic displacement on the order of 50 or more meters (~164 ft) should leave a more consistent, through-going pattern of deformation on the landscape. Overall, the evidence supports the presence of a fault-line-scarp (an erosional feature aligned with a mapped fault) along the middle and southern portions of group 8 where glacial erosion may have preferentially eroded along pre-existing faults or lithologic contacts.

4.1.9 Lineament Group 9

Lineament group 9 consists of north-northwest oriented features expressed principally as a prominent V-shaped linear drainage greater than 5 km (~3 miles) in length, along with smaller, sub-linear aligned drainages, aligned knobs, and short east-facing slope breaks (Figures A9-1.1 and A9-2.1 through A9-2.4) approximately 31 km (~19 miles) west of the dam site (Figure A0.1). The southern portion of the lineament group coincides to an inferred fault mapped by Wilson et al. (2009) that lies within the prominent linear V-shaped drainage and juxtaposes Paleocene granitics (map unit Tpgr) against turbidite rocks of the Cretaceous Kahiltna flysch (map unit KJs) (Figure A9-2.1). The lineament group also coincides with WCC fault KC5-5. WCC (1982) described the feature as a linear stream drainage north of the Susitna River and a prominent linear canyon and shallow linear depression south of the Susitna River that is fault-controlled in several locations. Indirect evidence of fault structure was observed along the prominent linear V-shaped drainage in the form of contrasting rock types (Figure A9-2.4). With the exception of the southern end, the strongly linear trend of most of the lineament group implies that any potential tectonic structure would have a steep to near-vertical dip. At the southern end of the lineament, the mapped lineaments that curve around a hill near WCC segment 4 (Figure A9-2.1) suggest that a fault in this area would have a moderate to shallowly west-dipping orientation. Individual lineaments are expressed in several Cretaceous to early Tertiary bedrock units exposed in the glaciated uplands: turbidite rocks of the Cretaceous Kahiltna flysch (map unit KJs), Paleocene granitics (map unit Tpgr), and at the contact between those units where the inferred fault trace is mapped (Wilson et al. 2009). North of the Susitna River, lineaments are expressed as short, discontinuous, and weakly-aligned, bedrock knobs, and in the southernmost portion of the group as 1- to 4-m-high (~3- to ~13 ft), east-facing slope breaks in thin colluvium overlying bedrock. The mapped lineaments do transect mapped bedrock units, but are not expressed in the limited extent of Quaternary surficial deposits present along the group. No lineaments were observed in post-glacial (early Holocene) fluvial deposits within a broad depression (Figure A9-2.1) or across the extent of a post-glacial landslide located in WCC segment 3. The scale of expression of the lineaments is variable along trend. The 1- to 4-m-high (~3- to ~13 ft), east-facing slope breaks in the south contrast with the >300-m-deep (~985 ft) linear V-shaped canyon, and the absence of any lineaments in above-mentioned late Quaternary deposits. The orthogonal orientation of the lineament group to the regional ice-flow direction (Figures A9-1.1 and A9-2.1) suggests that the lineament group as whole likely does not result from ice-flow or scour, but individual knobs in the north could relate to plucking by flowing ice. No field evidence of consistently deformed linear strain markers was observed along the lineament group during low altitude aerial or ground investigation. A sharp bend in the Susitna River exists where the lineament group projects across the river (Figure A9-1.1) but south of the river lies an apparently undeformed contact between turbidite rocks of the Cretaceous Kahiltna flysch (map unit KJs) and Paleocene granitics (map unit Tpgr), while the southern portion of the lineament group corresponds to an inferred fault mapped by Wilson et al. (2009) that juxtaposes those same rock types (Figure A9-2.1). Based on the mapped geologic contacts along the southern portion of the group, the apparent sense of offset is right-lateral with possible unknown oblique component. However, this is kinematically inconsistent with the mapping north of the Susitna River because the mapped contact between Cretaceous Kahiltna flysch (map unit KJs) and Paleocene granitics (map unit Tpgr) is apparently undeformed and undisplaced where the lineament group projects across the contact.

WCC's evaluation of their feature KC5-5 led them to recognize four segments of the feature (WCC 1982) (Figures A9-1.1 and A9-2.1). Segment 1 is the linear drainage that lies north of the Susitna River. WCC acknowledged that the drainage may be fault-controlled but WCC did not observe any evidence that conclusively confirmed or precluded a fault origin (WCC 1982). Low-level aerial investigation revealed that the drainage is only weakly linear and did not reveal any evidence to refute WCC's observations.

Segment 2 is the V-shaped linear drainage >5 km (~3 miles) in length directly south of the Susitna River. Here, WCC observed fault zones via helicopter aerial reconnaissance in three different locations running parallel to the overall lineament orientation. The fault zones are a few inches (few centimeters) to a few feet (few meters) in width, near vertical in orientation, light gray in color, and form sharp, distinct boundaries within intrusive rocks and locally separate intrusive from metamorphic rocks. No evidence to determine the sense of displacement was observed (WCC 1982). These fault zones may be similar to the zones of light-colored, fractured, and highly weathered rock in Cheechako Creek along lineament group 8 observed by both WCC and FCL during aerial inspection. One or more of these fault zone locations may lie within the view captured in photograph J of Figure A9-2.4.

Segment 3 is a broad and shallow curvilinear depression in the bedrock upland south of segment 2. Mapping completed by WCC revealed that a contact mapped by Csejtey et al. (1978) between Cretaceous argillite and greywacke metasediments on the west and Tertiary intrusive rocks on the east, which was previously thought to coincide with the depression, is too irregular to match the contact. Rather, WCC describes that the fault zone lies entirely within the Tertiary intrusive rocks (WCC 1982). However, more recent compilations of mapping (i.e., Wilson et al. 2009) show this area as turbidite rocks of the Cretaceous Kahiltna flysch (map unit KJs) (Figure A9-2), suggesting an apparent discrepancy in the understanding of the geologic units. Field investigation in July of 2013 confirmed the presence of granodiorite (presumably equivalent to Paleocene granitics; unit Tpgr) in a nearby drainage previously mapped as exposing turbidite rocks of the Cretaceous Kahiltna flysch (map unit KJs) (Figure A9-2.1 and A9-2.4), confirming the interpretation that contact relations from this ground inspection are more complicated than shown by Wilson et al. (2009).

Regardless of the bedrock lithologies present, WCC observed sediments in the broad depression which they interpreted to be approximately 40,000 to 75,000 years in age. Their aerial inspection revealed no evidence of deformation of the sediments and they interpreted that the observed fault zones had not experienced displacement within the last 40,000 years (WCC 1982). Based on an updated view of the Quaternary glacial history of the region (Section 3.6), these sediments are likely much younger, as deglaciation of this area is possibly as young as 15,000 to 11,000 years. Our low-level aerial and ground inspection confirmed the absence of any apparent deformation or lineaments observed by WCC (1982) (Figure A9-2.4).

Segment 4 consists of an alignment of east-facing linear bedrock scarps, some of which coincide with the location of several springs (Figures A9-2.2 and A9-2.3). These topographic escarpments are readily apparent in the INSAR data along the southernmost portion of the lineament group (Figure A9-2.1) and are the most suspiciously fault-like geomorphic features in the group. WCC's field investigations suggested that the scarps could relate to differential erosion controlled by jointing but that the scarps are not controlled by lithologic contacts. WCC could not identify direct evidence of faulting along segment 4 of their Fault KC5-5 but did acknowledge the segment could be fault controlled (WCC 1982). Ground access restrictions prevented thorough study of all the features but aerial inspection revealed the lineaments are generally 1- to 4-m-high, east-facing slope breaks that are each several hundred meters or more long (Figures A9-2.2 and A9-2.3). The features align in a broad curve across the topography, suggesting that any fault here would have a moderate to shallowly west-dipping orientation. Detailed review of the geomorphology along the features revealed apparent morphological and kinematic inconsistencies; in adjacent drainages both left-lateral and right-lateral apparent sense of motion indicators were observed, which is further inconsistent with the apparent west-up/east-down thrust movement suggested by adjacent features along trend and the apparent the west-dipping orientation of the features as they cross topography.

After evaluating all four segments of their Fault KC5-5, WCC concluded that together the observed features represented a fault without recent displacement, noting "the absence of any compelling evidence of recent displacement (e.g., systematic stream drainage offsets, scarps in recent sediments, or offset of youthful geomorphic units)" (WCC 1982). Low altitude aerial and ground inspection in July of 2013 of the lineaments of group 9 revealed similar evidence and concluded that the features are likely a fault-line scarp. For example, no evidence of expression in Quaternary units, landforms, or strain markers was observed. Furthermore, although a rock-type contrast does exist across portions of the lineament, the current mapping compilation may be too simplified and more irregularity of bedrock unit contacts likely exists along the linear V-shaped drainage and mapped fault. Although the lineament group does coincide with a previously mapped fault and also cuts across several bedrock units, the magnitude of expression and apparent sense of deformation observed in the field is inconsistent along trend. Lineament group 9 is interpreted to represent a fault-line scarp and not a Quaternary tectonic feature.

4.1.10 Lineament Group 10

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) that the lineament group is over 70 km (~44 miles) from the proposed dam site and is less than 40 km (~25 miles) long (Table 5-2), and likely would not appreciably contribute to the hazard calculations. Strip maps for this group are not included herein (Figure A0) but were presented as part of FCL (2013). During limited flyovers in 2013, no features were observed that suggested a need to revise those conclusions.

4.1.11 Lineament Group 11

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) suggesting that surficial processes are likely exploiting existing topographic position and/or local weaknesses in the underlying Cretaceous Kahiltna flysch bedrock to create the lineaments. Strip maps for this group are not included herein (Figure A0) but were presented as part of FCL (2013). Limited overflight of these features in 2013 appears to confirm this conclusion. In addition, the group is greater than 30 km (~19 miles) from the proposed site and is less than 20 km (~12 miles) in length (Table 5-2), and likely would not appreciably contribute to the hazard calculations.

4.1.12 Lineament Groups 12a & 12b

Lineament 12a traverses part of the southeastern-facing Paleozoic volcanic hills in the Fog Creek area, about 14 km (~9 miles) southeast of the proposed dam site (Figures A0.1 and A12a.1). Aerial and ground inspection of group 12a confirmed the presence several southeast-facing slope breaks near the lower flanks of the hillside of the northern part of the group (Figure A12a.2). There are no previously mapped faults within this group; however, field observations of color contrasts within the Paleozoic rocks (map unit Pzv) suggest the possible presence of northeast-oriented bedrock structures. No evidence of a fault was observed along the lineament group trend. A prominent notch with an uphill-facing slope break was observed within the Paleozoic rocks along the nose of a ridge (Photograph C, Figure A12a.2). The topographic expression of this lineament feature on the ridge implies a northwest-dipping structure geometry. Bedded rock exposed on the other side of the mountains within the northwest-facing cirque walls appears to have a generally northwest dip and a moderate (~45?) degree dip angle. The topographic expression of the lineaments about 1.2 km (~3/4 mile) to the north of the notch may allow an inferred northwest-dipping geometry but with a much shallower dip plane as compared to the notch feature; suggesting a substantive change in dip should the lineaments represent a structural fault. The individual lineaments mapped along the north part of the group chiefly are within probable latest Wisconsin-age glacial deposits near the valley margin, and are oriented along the ice flow direction. To the southwest, the lineaments rise in elevation and are mapped in the Paleozoic rocks (map unit Pzv) above the contact with glacial sediments (map unit Qs). There are no lineaments expressed in the Quaternary deposits along about the southern half of group 12a, and there is visual evidence that glacial moraine and kame terrace features at the southern end of the group are not offset. The relief of the lineaments along strike is variable, and generally is greater in magnitude within the bedrock than the unconsolidated deposits. However, the morphology of the features is kinematically inconsistent along strike, with south-east facing downhill slope breaks found on the lineaments in the Quaternary deposits, and an uphill facing slope break on the bedrock notch feature.

Although the individual lineaments of group 12a are mapped within late Quaternary deposits along the valley margin, there is no expression of deformation or offset of late Wisconsin landforms in kames or delta surfaces within the valley of Fog Creek directly north. Similarly, there is no expression of deformation or offset of late Wisconsin landforms in lateral moraines or delta surfaces within the Clear Valley directly south of group 12a. The individual lineaments appear to traverse both Paleozoic rocks as well as late Quaternary deposits, however, as noted above there is an inconsistent morphologic expression of those features along strike, as well as inconsistent relative structural kinematics (apparent dip, scarp direction) along the lineaments. The slope breaks within the Quaternary sediments along the northern part of the group appear to be a result of solifluction and to a lesser extent, nivation processes, and thus are dominantly erosional in origin. The observation of multiple slope breaks on the hillslope in the vicinity of the mapped lineaments, as well as the general lineament orientation being parallel to ice flow directions, suggests the lineament group was not produced by tectonic processes, rather glacial deposits that are now undergoing solifluction and nivation processes. From these observations and interpretations, it is judged that the lineaments within group 12a are the result of both past glacial processes, ongoing hillslope erosion processes, and potentially bedding relationships within the Paleozoic rocks, and do not represent a tectonic fault.

Lineament group 12b is approximately 16 km (~10 miles) southeast of the proposed Watana dam site, and is about 2 km (~1.5 miles) northwest of lineament group 12a and directly west of Mount Watana. Lineaments within group 12b are coincident with an unnamed, kinematically-undefined fault (Clautice 1990) within the Paleozoic Slana Spur volcanic rocks (map unit Pzv) (Figure A12b.1), however no direct or indirect field evidence of the fault was found from low-altitude inspection; the morphologic expression of the feature is incised drainages and a very broad and deep valley within which a small creek now flows (Photograph C, Figure A12b.2). The trend of the lineament group across topography is essentially linear, implying a vertical geometry that cuts directly across contours. The lineaments are expressed chiefly in Paleozoic rocks, however, a thin cover of Holocene regolith mantles the rocks, consisting of unmapped talus, solifluction of glacial material, colluvium, and alluvium, in which the lineaments also are mapped. The lineaments show no field evidence of offsetting or deforming those sediments. The scale of expression of the lineaments varies along strike: it is rather large at the middle and northern end of the lineament group where it is coincident with an unnamed northeast-flowing drainage; the expression decreases along the southern end of the lineament group. The middle and northern part of the lineament group is oriented parallel to a glacial ice flow from cirques toward the Susitna River. The southern part of the lineament group is less certainly assessed with respect to ice flow because of its topographic position on the landscape. None of the glacial geomorphic surfaces in Fog Creek valley (e.g. eskers, deltas) along the southwestern projection of the lineaments were observed to be offset or deformed, and no evidence of deformation was observed at the Susitna River margin along the northeastern projection. Along the south-center part of the lineament group, a northwest-facing break in slope morphology may suggest reverse-type movement (i.e. northwest vergence), however, the ends of the group do not exhibit any strong kinematic indicators.

The lineaments within group 12b did not show field evidence of expression in Quaternary deposits or landforms serving as strain markers, notably along the southwestern projection of the group into Fog Creek valley with late Wisconsin landforms. The lineament is chiefly constrained to within the Paleozoic volcanics (map unit Pzv), and is coincident with the previously mapped fault of Clautice (1990), suggesting a potential structural control and preferential erosion along the pre-existing structure. Alternatively, internal lithologic control on the geomorphic expression of the lineament (e.g. bedding) is plausible given the lack of lineament continuity beyond the Paleozoic rocks. The lineament group appears to have a variable geomorphic expression along strike, has weak kinematic indicators along strike, and has its largest surface expression in drainages flowing away from the area of kinematic indicators. In total, the field observations and data evaluation suggest that glacial and post-glacial fluvial erosional processes are a likely explanation for the origin of the lineament features. Individual lineaments may represent fault-line scarps or fault-line-valleys but due to the lack of expression in Quaternary deposits, the lineament group is not considered a Quaternary tectonic structure and no further work is deemed necessary.

4.1.13 Lineament Group 13

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). Strip maps for this group are not included herein (Figure A0.1) but were presented as part of FCL (2013). FCL (2013) interpreted that lineament group 13 was the result of erosion, but also discussed that the lineament group lies greater than 40 km (~25 miles) distant from the proposed dam site and is less than 20 km (~12 miles) in aggregate length (Table 5-2) and would therefore likely have limited contribution to the hazard calculations. During limited flyovers, no features were observed that suggested a need to revise those conclusions.

4.1.14 Lineament Group 14

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). Strip maps for this group are not included herein (Figure A0.1) but were presented as part of FCL (2013). The group is greater than 30 km (~19 miles) from the site and less than 20 km (~12 miles) in aggregate length, (Table 5-2) thus meeting lineament exclusion criteria. A limited fly-over in 2013 revealed no features that that suggested a need for additional analysis.

4.1.15 Lineament Group 15

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). Strip maps for this group are not included herein (Figure A0.1) but were presented as part of FCL (2013). FCL (2013) excluded the group from further analysis on the basis of its large distance from the proposed dam site (~43 km [~27 miles]) and short aggregate length (~6 km [~4 miles]) (Table 5-2). A limited fly-over in 2013 revealed no features that that suggested a need for additional analysis.

4.1.16 Lineament Group 16

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). Strip maps for this group are not included herein (Figure A0.1) but were presented as part of FCL (2013). This group is sub-orthogonal to the map trace of the Talkeetna fault (Csejtey, 1978; Wilson et al. 2009), directly north of the WCC trench T-2 site (Figures 2-1 and 5-3). The group was excluded from further analysis on basis on its significant distance to the proposed dam site (~60 km [~37 miles]) and relatively short aggregate length (~19 km [~12 miles]) (Table 5-2). During limited flyovers, no features were observed that suggested a need for additional analysis.

4.1.17 Lineament Groups 17a, 17b, & 17c

Lineament group 17a is a north-northwest trending lineament, approximately 24 km (~15 miles) west of the proposed Watana dam site (Figure A0.1). Lineament group 17b is a north-northwest trending lineament group, approximately 36 km (~22 miles) southwest of the proposed Watana dam site. Lineament group 17c is approximately 45 km (~28 miles) south-southwest of the proposed Watana dam site, and is the southernmost extent of lineament the 17a, 17b, and 17c series (Figures A0.1). Lineament group 17a is not coincident with previously mapped faults, however, the southerly extent of 17b and parts of 17c are (Figure A17b.1 and A17c.1). Wilson (2009) depicts a lineament coincident with 17a and another coincident with 17b. Although aerial field inspection did not find evidence to directly confirm the presence of a fault within group 17b and 17c, contrasting rock types and units were observed in the field in general consistency with previous geologic mapping, allowing the possibility of a bedrock fault structure along these groups.

Lineaments within group 17a are mapped along a northerly segment of the Susitna River, a north-trending canyon tributary, and in the Quaternary deposits south of the canyon (Figure A17a.1). No evidence of a fault was observed at the northern end of the lineament group along the south-facing wall of the Susitna River, nor along strike to the north. Low altitude aerial field inspection revealed that the lineaments in Quaternary deposits at the south end of group 17a do not show scarp-like morphologies; rather one is a discordant, small, creek drainage and the other appears to be a depositional contact of likely late Holocene grassy swale (bog) sediments against a near-surface ice-sculpted bedrock buttress (Figure A17a.2). Lineament group 17a is somewhat off-trend of lineament groups 8 and 9, and also appears to follow a bedrock jointing pattern that is expressed on the landscape. Based on the absence of compelling evidence for Quaternary tectonism, lineament group 17a is judged to not represent a tectonic fault.

As noted above, lineaments within the group 17b are somewhat coincident with previously published inferred faults and lineaments. Aerial field inspection indicated that the morphologic break in slope along the FCL-mapped lineaments at the base of the uplands near the western margin of the valley is not as sharp and abrupt in the field as implied on the INSAR-derived DEM. The most prominent morphologic feature is actually a narrow drainage that is fed by a perched lake; review of USGS topographic maps confirmed this linear feature as a creek. The trend of the lineaments across topographic contours is straight, but also parallel to contour because it is in the valley bottom; this would imply either a vertical or horizontal hypothetical fault dip geometry. The lineaments are chiefly mapped in thin glacial-derived sediments that primarily reflect erosion by small creek drainage, and are probably Holocene age. Near the south end of group 17b, the lineaments are mapped as extending out of the glacial deposits and traversing Tertiary volcanics (map unit Tvu) and Paleozoic volcaniclastic rocks of the Slana Spur formation (map unit Pzv) (Figure A17b.2) directly north of the Talkeetna River. Field investigation found no direct evidence of a fault along this trend. The lineaments appear to coincide with the trend of glacial ice flow directions that were valley parallel. The southeasterly oriented inferred fault of Csejtey (1974) also was not confirmed in the field; this area appears to be sculpted bedrock knolls that have been slightly dissected and mantled by a thin veneer of youthful glacial deposits (Figure A17b.2). South of the Talkeetna River, the southern part of group 17b coincides with a short inferred fault of Wilson (2009). Low altitude fly-overs of this area discovered a positive relief "mole track-like" features present on the ground along the FCL-mapped lineament. Ground inspection resulted in the conclusion that the feature in fact is a pro-talus rampart; a geomorphic feature constructed by talus collecting in a snow covered field that results in talus deposition a short distance away from the base of the slope (Figure A17b.3). The ground inspection supports the interpretation that glacial ice was present in the valley by the observation of an out-of-place glacial erratic. Although there may be a bedrock structure along part of this group that separates Paleozoic (map unit Pzv) and Mesozoic rocks (map unit Tvu), lineament group 17b is judged to be created at the local scale by fluvial erosion as well as in part by glacial ice erosion of the linear valley and periglacial processes.

Along part of its northern and southern ends, lineament group 17c is partially coincident with faults previously mapped by Wilson et al. (2009), although none are recognized by Csejtey (1974) and Clautice (1990). None of the faults depicted on Wilson et al. (2009) are shown extending across or displacing Quaternary glacial or moraine deposits. No evidence was found during low altitude aerial field investigation to confirm the northern (dashed and inferred) previously mapped fault in group 17c. Near the southern end of 17c, the depicted rock juxtaposition between units Tertiary volcanic rocks (map unit Tvu) and Eocene mafic volcanic rocks (map unit Tem) (i.e. bedrock fault) was not lithologically well expressed in the field with apparently similar bedded volcanic rocks exposed on either side of the canyon walls (Figure A17c.1), and the presence of the previously mapped fault is unconfirmed. The lineament trends across topography irrespective of contours in steep terrain, suggesting a near vertical geometry for a hypothetical structure. The lineaments are mapped across Tertiary volcanic rocks as well as in young (likely Holocene) rock glacier deposits; the expression within the rock glacier deposits correspond to relatively deep drainages eroded into the rock glacier deposits (Figure A17c.2). The scale of the lineaments' expression along strike varies; along the north end of group 17c cirque ridges that are traversed by previously mapped structure are not offset and little relief is expressed topographically. Along the middle of the group the lineaments are expressed as ridgeline saddles with adjacent ridge peaks standing about 75 meters (~246 ft) above the saddle whereas on the INSAR DEM the lineaments are attributed as linear v-shaped troughs. Along the south end of lineament group 17c, the relief along the lineament in the Quaternary rock glaciers is lesser than the middle part of the group, however, the relief in the rock glacier drainage is about 25 meters (~82 ft); much larger than would be expected for a relatively low-slip rate fault structure in young post-glacial deposits. While the presence of a bedrock fault cannot be ruled out along lineament group 17c, it is judged that the mapped lineament is the result of erosion into the rock glacier deposit.

Lineament groups 17a, 17b, and 17c are each independently judged as formed by erosional processes (fluvial and/or glacial) as described above, based on field observations and interpretations. Collectively, these groups do not form a continuous geologic structure based on an absence of faults observed (directly or indirectly) in the field, and the inconsistent and variable geomorphic expression of the lineaments in the landscape along 17a, 17b, and 17c as a whole.

4.1.18 Lineament Group 18

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) which concluded that the group's large distance to the proposed dam site and short overall length (Table 5-2) would likely not appreciably contribute to the hazard calculations. Strip maps for this group are not included herein (Figure A0.1) but were presented as part of FCL (2013).

4.1.19 Lineament Group 19

Lineament group 19 is a semi-arcuate, northeast-trending group of linear features that is nearly 44 km (~27 miles) long, located approximately 54 km (~34 miles) southeast of the proposed Watana dam site (Figure A0.1). This feature is defined by a series of aligned, gently-sloping linear range-fronts, slope breaks, linear valleys, and a few aligned saddles (Figures A19-1.1, A19-2.1, and A19-3.1).

Existing geologic mapping (Wilson et al. 2009; Csejtey et al. 1978) suggests that this lineament group may represent a bedrock contact zone between various Jurassic age bedrock units (mostly Trondhjemite [map unit Jtr] vs. a migmatite border zone of granodiorite [map unit Jpmu]). An inferred fault mapped by Clautice (1990) lies east of the aligned features along a parallel orientation and nearly converges with the lineament group near the northern projection of the lineament (Figures A19-1.1, A19-2.1, and A19-3.1). Indirect evidence of a fault structure was observed in the southwestern portion of the lineament where apparent rock type contrasts were observed via aerial inspection across an alignment of linear drainages (Figures A19-1.2 and A19-1.3). The trend of this rock type contrast/rock contact across the topography is very linear, suggesting that any tectonic feature present would have a near-vertical to steeply-dipping orientation. The features making up lineament group 19 are expressed in bedrock valleys, bedrock plateaus, valley-margin glacial deposits, and colluvial deposits. The ages of deposits in which lineament features are expressed ranges from the Jurassic age bedrock exposed in the linear valleys shown in Figures A19-1.2 and A19-1.3 to thin colluvial deposits of latest Holocene age. Low-level aerial inspection revealed that the lineaments of group 19 do transect several different geologic units and landforms, but are not present in the post-glacial (Holocene) alluvium of the Goose Creek or adjacent drainages (Figure A19-2.1). The magnitude of expression of the lineaments ranges from ~10-m-high (~33 ft) downhill-facing slope breaks in glacial deposits of the Black River to gently sloping ~125-m-high (~410 ft) (Photograph A, Figure A19-2.2; Photograph A, Figure A19-3.2) bedrock escarpments. The lineament group is roughly parallel to glacial ice flow directions in the Black River canyon and spatially coincident with left-lateral ice margins as mapped by Williams and Galloway (1986) (Figures A19-1.1, A19-2.1, and A19-3.1). Field inspection did not reveal any displaced or deformed linear strain markers along the lineament. The morphology of the lineament and its expression in the landscape suggests that, if it were a tectonic fault, it would be a strike-slip fault.

Low altitude aerial observations showed variable evidence of lineament expression within the Quaternary deposits along lineament group 19. Lineaments are expressed in the glacial deposits of the Black River, but not in Holocene age rock glacier and glacial moraine deposits at the head of Kosina Creek (Photographs E and F, Figure A19-1.3), nor in the Holocene-age deposits of the Goose Creek adjacent drainages (Figure A19-2.1). The lineaments in the glacial deposits of the Black River valley occur parallel to the ice-flow direction and their geomorphic position high on the left side of the valley suggests that the lineaments are most likely left lateral moraine or kame terraces.

The large magnitude of relief across the lineaments in the northeastern portion is inconsistent with the apparent lack of topographic offset across the lineaments in the southwest portion of the group. Specifically, the surfaces of the exceptionally planar bedrock plateau across which the aligned linear valleys run (Figure A19-1.1) show no evidence of the vertical displacement apparent along the lineament group to the northeast. This inconsistency in relief does not support the existence of a tectonic structure along lineament group 19. Bedrock exposures observed during ground inspection in creeks along the lineament showed evidence of pervasive jointing (Photograph C, Figure A19-3.2) which is the likely genesis of the linear troughs and swales at the northeast-most portion of the group (Photograph D). Lateral ice margins mapped by Williams and Galloway (1986) coincide with many of the mapped lineaments (Figures A19-2.1 and A19-3.1), providing a non-tectonic origin alternative. In addition, a series of sub-ice fluvial channels located just north of Goose Creek (Photograph B, Figure A19-3.1) cross the lineament and do not appear to be displaced. For these reasons, lineament group 19 is not interpreted to be the result of Quaternary tectonic faulting; a fault or bedrock contact may exist in the southwest portion of the group, but there is no direct evidence of Quaternary tectonic activity anywhere within the group. It is judged that lineament group 19 is a result of a combination of bedrock jointing and glacial and post-glacial erosion processes, and does not represent a Quaternary fault.

4.1.20 Lineament Group 20

Lineament group 20 is a northeast-trending lineament group defined by a series of sub-linear, aligned drainages, saddles, broad U-shaped troughs, and V-notched linear canyons expressed in an area of gently rolling hills and terrain of relatively modest-relief (Figures A20.1, A20.2, A20.3, and A20.4), approximately 94 km (~58 miles) southeast of the proposed Watana dam site (Figure A0.1). Some of the lineaments in this group coincide with mapped, unnamed faults with apparent vertical throw (Grantz 1960) that lie along the northeastern projection of the Castle Mountain fault (Figure A0.1, Plate A-CME). Early mapping by Grantz (1960) shows stratigraphic offsets within Tertiary (Eocene) units as well as between Tertiary (Eocene), Cretaceous, and Jurassic age rocks. However, more modern compilations (Wilson et al. 1998) show the same faults juxtaposing Jurassic-age sedimentary rocks against one another as well as Jurassic sedimentary rock units against Tertiary sedimentary units, suggesting a revised understanding of the geologic units with further study. No direct evidence of any of the mapped faults was apparent in the field during aerial or ground inspection but indirect evidence in the form of apparent rock type contrasts across mapped faults was observed near GPS way point 018 and locations to the southwest of GPS way point 018 (Figure A20.1). The trend of the lineaments across topography is very linear, suggesting any potential fault structures would be steeply dipping. Grantz's (1960) map unit Jns (Jurassic sandstone) is the oldest unit in which the linear drainages and aligned saddles occur in while the youngest map unit to express lineaments is Eocene fluviatile conglomerate and coaly sandstone (map unit Tf) (Figure A20.1). Very few Quaternary units were observed during field investigation of this group; colluvium is relatively thin and thin alluvial deposits are restricted to narrow watercourses. The area appears to be a region of erosional or residual terrane with gentle slopes with relatively non-resistant bedrock and few solifluction features. None of the mapped lineaments are concordant with glacial ice-flow directions; there is no field evidence of erosion from glacial ice within the area of the lineament group 20 (Figure A20.5) although the presence of glacial lake sediments and glacial erratics suggests the presence of glacial lakes (Figure A20.1). The magnitude of expression of the lineaments is not consistent along trend. For example, the mapped lineaments often alternate between weakly expressed and subtle slope breaks and broad troughs and deep and well-defined linear valleys. A prime example is the U-shaped swale shown in photographs A and B of Figure A20.1 which is not matched by similar features along trend to the southwest (Photograph C).

Based on the bedrock map units alone, a short fault mapped by Grantz (1960) as running through the middle of the lineament group 20 ellipse and which is mapped as displacing Eocene fluviatile conglomerate and coaly sandstone (map unit Tf) in a down-to-the-southeast sense. GPS way point 001 lies on this fault. (Wilson et al.'s (1998) compilation of the area does not include this fault, but whether this difference is due to the regional scale of their compilation, or the discovery of additional evidence to refute the fault's existence is unknown. Consequently, review of the original mapping is warranted.) As noted above, a mapped lineament feature is spatially associated with this fault where the fault passes through a saddle but the lineament is not consistently expressed along trend. Specifically, a prominent linear ridge and the geologic unit contacts within it are not obviously displaced (Photograph C) and the southeast-flowing stream valley to the north also does not express the lineament. Close inspection of the INSAR-derived DEM revealed that no separation of geologic units may exist across the fault (Figure A20.6). Grantz (1960) mapped an apparent ~100 feet (~33 m) offset in the Tf-Jns contact but a detailed slope map of the area apparently shows the basal contact of Tf with the underlying Jns in a different position than depicted by Grantz and that does not suggest any offset. Southeast of the mapped fault, Grantz's (1960) Tf-Jns contact is approximately 100 feet too low on the hillside and northwest of the fault the contact is ~100 feet too high elevation.

The prominent swale coinciding with the mapped fault may have a genesis related to spillways and wave-cut benches developed during the presence of an ice-marginal glacial lake. Glacial meltwater was likely impounded by the left lateral moraines of the Little Nelchina ice lobe to the east and by the ice in Daisy Creek to the north (Figure A20.5). Ground investigation discovered a presumably ice-rafted granitic glacial erratic in terrain mapped as Jurassic sedimentary rocks (unit Jnbc) at an elevation of ~3925 feet (at GPS waypoint 018 on Figure A20.1), about 100 feet higher in elevation than the swale shown in Photographs A and B of Figure A20.2. Williams and Galloway (1980) show a spillway transecting part of lineament group 20 at similar elevations that would have sent water over a drainage divide to Fourth of July Creek (Figure A20.5). Development of a similar spillway could be the genesis of the swale shown in Photograph A. In addition, several planar and horizontal benches at similar elevations may indicate the presence of a relatively long-lived lake, but could also relate to differential erodibility of the nearly horizontal stratigraphy in the area.

In summary, some of the individual lineaments along the northwestern margin of group 20 do appear to coincide with previously mapped bedrock faults and are likely fault-line scarps developed along bedrock faults, but the remaining lineaments are interpreted to be the result of erosion and not tectonically-related. Low-level aerial and ground inspection did not reveal any evidence for Quaternary faulting along the mapped lineaments or previously mapped faults. However, the validity of some of the faults is in question when evaluated with modern high-resolution elevation data. The mapped lineaments are not consistently expressed across the landscape and nearly all are spatially associated with erosional features. For the above reasons, no further work for lineament group 20 is deemed necessary.

4.1.21 Lineament Group 21a & 21b

Lineament group 21a is a northwest-trending small group of lineaments expressed as weakly aligned features within a terminal moraine complex, and a few topographic slope breaks and linear drainages (Figures A21a.1 and A21a.2), approximately 41 km (~25 miles) northeast of the proposed Watana dam site (Plate 1). No previously mapped fault or lineament feature coincides with the orientation of the lineament group and no direct evidence of fault structure was observed during low-level aerial investigation. However, the Mesozoic-age Honolulu thrust fault (Csejtey 1961) does cut across the lineament group but does not align or coincide with any mapped lineaments. The weakly linear alignment of lineaments across the relatively low-relief terrain (Figure A21a.1) does not constrain the geometry or kinematics of any potential tectonic structure. Lineament group 21a lies entirely with glaciated terrain at the confluence of possibly four different ice streams (Figure A21a.2) and although Cretaceous flysch is mapped nearby (Csejtey et al. 1992; Wilson et al. 2009), field inspection confirmed that most of the area has either a surficial cover of glacial moraine and/or glacial lake deposits from a series of glacial lakes (Reger et al. 1990). The youngest deposits containing lineaments are likely late Holocene linear streams while the oldest surficial deposits in which lineaments are expressed are likely latest Pleistocene glacial deposits (Reger et al. 1990). The lineaments do not cut across different age deposits or landforms; they lie almost entirely within the Quaternary deposits in the valley bottoms. Aside from a 120-meter-tall rock-cored drumlin, the lineaments all have a relatively consistent magnitude expression of < 15 meters tall and are both parallel and discordant with ice flow directions. The most prominent lineaments are three lineaments that trend highly obliquely to the rest of the group and which have morphology and position suggestive of being either a terminal moraine ridge from northwest flowing ice or an esker (Figure A21a.2). No field evidence of displaced or deformed terrace risers or moraine ridges was observed along the trend of the lineaments.

Several lines of evidence point to a non-tectonic origin for the lineaments in group 21a. Although expressed in Quaternary deposits and of a scale consistent with a low slip-rate fault, the lineaments of group 21a do not traverse across portions of the landscape of different ages which would help support the existence of through-going tectonic structure. The apparent origins of the lineaments are both constructional (terminal moraine complex and eskers) and erosional (linear streams and short slope breaks in dissected glacial moraine ridges). In addition, part of the importance of group 21a as a potential tectonic structure is the group's spatial proximity and along-trend parallel orientation with group 21b, for which a non-tectonic explanation is likely (see below). Overall, the lineaments of group 21a are few in number, weakly expressed, weakly aligned, and do not coincide with a previously mapped structure. These factors coupled with the recent dominance of both active and stagnant ice processes in the area, point to a non-tectonic, glacial origin for the lineaments of group 21a and the lineaments are not considered further.

Lineament group 21b is a northwest trending group of lineaments expressed as a series of linear slope breaks and aligned linear drainages (Figure A21b.1) located approximately 43 km (~27 miles) north-northeast of the proposed Watana dam site. Lineament group 21a is separated from group 21b by about 5 km (~3 miles). The only previously mapped fault or lineament feature that coincides with lineament group 21b is a photographic lineament mapped by Reger et al. (1990) that is discussed below and shown on Figure B-15. No fault exposures were observed during aerial and ground field investigation along lineament group 21b. The portion of the lineament group located west of Butte Creek climbs east-sloping terrain in a straight-line manner (Figure A21b.1) that suggests any potential tectonic structure would have a steep to near vertical dip and strong lateral kinematics. The lineaments of group 21b occur as downhill-facing slope breaks in mapped Quaternary glacial deposits (unit Qdt_3 of Smith et al. (1988)) and as linear streams and gulleys eroded into Cretaceous flysch, and to a lesser extent, Cretaceous granite (Csejtey et al. 1992; Wilson et al. 2009). Map unit Qdt_3 is considered to be of late Wisconsin age (11,800 to 25,000 year B.P.) (Smith et al. 1988). The mapped lineaments coincide with a concealed bedrock contact between units Ks (schist) and Kph (phyllite) of Smith et al. (1988) but cut across the map unit contacts of Wilson et al. (1998) (Figure A21b.1). Low-level aerial and ground inspection revealed the scale of the lineaments ranges from 2- to 4-m-high slope breaks (Photograph A, Figure A21b.2) to 5- to 10-m-deep linear stream channels. The lineament group is oriented perpendicular to the ice flow directions within the Butte Creek valley.

Field investigation did confirm the expression of the 3-km-long, downhill-facing slope break in Quaternary glacial deposits (Photograph A, Figure A21b.2) but did not reveal any exposures of the spatially-coincident concealed schist-phyllite contact mapped by Smith (1988). Inspection of the stream banks and terrace risers located to the west along the trend of the feature did not reveal any displaced terrace risers or surfaces (Figure A21b.3). Exposures in the left bank of

Butte Creek at GPS waypoint 009 consisted of east-southeast striking, vertically-dipping phyllite which coincide with the projection of a lineament formed by a short, low-relief downhill-facing slope break (small arrows in Photograph A, Figure A21b.2) on the adjacent strath terrace surface. More resistant, sandy beds within the phyllite are interpreted to form the short slope break along the margin of the strath terrace and serve as an analogy for the much larger lineament located upslope. For example, rather than a being formed by a tectonic fault, the 3-km-long lineament mapped from INSAR data most likely relates to the rock type contrasts mapped by Smith et al. (1988) where higher grade (and more resistant) schist lies upslope of the slightly lower grade (and less resistant) phyllite and is overlain by a thin veneer of Quaternary glacial deposits. The linear streams and gulleys to the west of Butte Creek are therefore interpreted to be serendipitously-aligned erosion features. Alternatively, the reconnaissance mapping compiled by Wilson et al. (2009) for this area may be inaccurate, and the contact relations shown by the more detailed mapping of Smith et al. (1988) may continue westward, controlling the drainage patterns to produce linear streams along the strike direction of the phyllite. In either case, the lineaments of Group 21a are judged to be non-tectonic in origin and likely relate to differential erosion along depositional contacts within bedded metasedimentary rocks.

4.1.22 Lineament Group 22

Lineament group 22 is a northwest-trending group of lineaments defined chiefly as a series of aligned, linear V-shaped troughs and slope breaks (Figure A22), approximately 27 km (~17 miles) northwest of the proposed Watana dam site (Plate 1, Figure A0.1). Group 22 spatially coincides with several northwest-trending photogeologic lineaments discussed below as features 7, 8, and 9 in the section on Reger et al.'s (1990) northwest-trending photogeologic lineaments of the Healy A-3 quadrangle. These features are depicted as extending across Quaternary glacial sediments as well Tertiary and Cretaceous intrusives that have variable strikes and dips. The lineaments are mapped in Reger et al.'s (1990) till of late Wisconsin age (unit Qd3; 9,500 to 25,000 years old) (Reger Public Data file 90-1), and are expressed in the field as linear erosional gullies. The geomorphic features east of Deadman Creek are smaller and less prominent in Mesozoic and Tertiary rocks as compared to those in Cretaceous rocks that are west of the creek, indicating an inconsistent scale of expression along strike (Figure A22.1). No field evidence of a fault was found during low-level aerial inspection, and much of the hillsides appear to be influenced by solifluction processes (Figure A22.2). The trend of the lineament on the landscape would suggest a hypothetical steeply-dipping geometry because the lineaments trend at high angles across contours. Along Deadman Creek, the lineaments are nearly orthogonal to the ice flow direction (Reger et al. 1990, sheet B), and no offsets in the lateral moraines were observed. Along the far western part of the lineament group, the lineaments are parallel to the ice flow direction.

The lineaments of group 22 show a dearth of expression in Quaternary deposits, other than being associated with two linear drainages. While the lineaments transect several different geologic units, suggesting some continuity, we find that the magnitude of expression along strike is quite variable supporting an erosional genesis to the lineaments. The absence of substantive Quaternary lineaments further supports an erosional origin. Because of its geomorphic expression as linear drainages, there is insufficient landform information to assess potential kinematics (e.g., uphill facing scarp). Because there is no fault previously mapped along this group and no evidence of a fault was observed, coupled with the field observations of hillslope processes as well as a distinct lack of faulting expression in the late Wisconsin glacial deposits, it is judged that lineament group 22 is not a fault.

4.1.23 Lineament Group 23

Lineament group 23 is an arcing group of roughly east-west-trending lineaments defined by a series of aligned slope-breaks, low mounds, and short linear ridges (Figure A23.1), approximately 62 km (~39 miles) southeast of the proposed Watana dam site. The features along the lineament trend occur entirely within mapped Quaternary glacial and lake deposits of the Copper River Basin (Williams and Galloway 1986; Wilson et al. 2009). Potential ages for these deposits range from mid to late Pleistocene for the glacial till deposits to latest Pleistocene_for the glacial lake deposits (Williams and Galloway 1986). The lineaments do not coincide with any previously mapped faults or lineaments (FCL 2013) and low altitude aerial inspection did not reveal any direct evidence of tectonic structures anywhere along the lineament, including in the near-vertical cut banks of Tyone Creek. The aligned slope-breaks, low mounds, and short linear ridges that make up the lineament group are of mostly broad and low relief, ranging in height from approximately 30 m high (~100 ft) in the west to 10 to 15 m high in the center and east portions. The orientation of the mapped lineaments is parallel to several north-south oriented drumlins mapped by Williams and Galloway (1986), and perpendicular to regional ice-flow directions, but parallel to and locally coincident with terminal moraine crests.

Several pieces of evidence beyond the spatial coincidence with the terminal Tysus Moraines of Williams and Galloway (1986) point to a non-tectonic explanation for lineament group 23. For example, no direct evidence of tectonic structures was observed during very low altitude aerial inspection, including in key exposures where the lineament alignment crosses Tyone Creek. The arcing alignment and the consistently low relief morphology of the aligned slope-breaks, low mounds, and short linear ridges does appear similar to a terminal moraine complex. The positive relief of these features suggests constructional or depositional geomorphic processes, rather than tectonic processes, may have played a role in their formation and their subtle expression could derive from being obscured by overlying glacial lake deposits. For example, the lineament group lies within published glacial lake extents and elevations in the Copper Basin for lake elevations of 975 m, 914 m , 800 m, and partly for the 775 m lake level (Kaufmann et al. 2011), suggesting Quaternary lake glacial processes may have influenced the formation of these features. The discordance of the lineaments located east of Tyone Creek with the orientation of terminal moraine ridges mapped by Williams and Galloway (1986) may result from differences in the scale and quality of the aerial photography used by Williams and Galloway (1986) compared to modern hi-resolution INSAR data. For example, the discordance could be the result of receding lake shorelines being interpreted as terminal moraines. Overall, the preponderance of evidence described above points to a genesis via glacial processes for the lineaments of group 23, and does not support a tectonic genesis. It is judged that lineament group 23 does not represent a tectonic fault, and no further work is recommended for lineament group 23.

4.1.24 Lineament Group 24

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). Strip maps for this group are not included herein (Figure A0.1) but were presented as part of FCL (2013). The lineament group is short (~15 km [~9 miles]) and lies a great distance from the dam site (~120 km [~75 miles]), and likely would not appreciably contribute to the hazard calculations (FCL 2013).

4.1.25 Lineament Group 25

This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). Strip maps for this group are not included herein (Figure A0.1) but were presented as part of FCL (2013). The lineament group was interpreted to be the result of erosional and depositional processes (FCL 2013), chiefly the apparent alignment of several large, curvilinear glacial valleys. During limited flyovers, no features were observed that suggested a need to revise those conclusions.

4.1.26 Lineament Group 26

Lineament group 26 is a northwest-trending lineament group expressed as a series of aligned slope-breaks, U-shaped troughs, and linear drainage segments (Figure A26.1), approximately 2 km (~1 miles) west of the proposed Watana dam site (Figure A0.1). Much of the lineament follows an unnamed tributary to the Susitna River that lies directly west of Tsusena Creek. Previously mapped bedrock structures, lineaments, or faults are not coincident with or near this lineament group. Similarly, field evidence of fault structures were not observed along this lineament group during low altitude aerial inspection. The trend of the lineaments across topography implies a hypothetical near vertically-oriented geometry because the lineaments cut across topographic contours at high angles. South of the Susitna River, the lineaments are mapped in glacially-sculpted terrain that shows geomorphic landforms indicative of stagnant ice (e.g. eskers). The thickness of unconsolidated deposits on the south side of the river seems to be relatively thin. At the confluence of the Susitna River with Tsusena Creek, the lineament is mapped across Quaternary glacial outwash deposits that overlie bedrock. North of the Susitna River, the lineaments principally are mapped in an entrenched drainage in whose upper banks are exposures of glacial outwash that overlies lacustrine and fluvial deposits. The lineaments are mapped as cutting across Tertiary volcanics and intrusives as well as Quaternary sediment, however field observations did not find evidence to validate presence of a lineament(s) expression in the bedrock or sediment. The scale of the expression of the lineaments along strike is variable, with little to no apparent relief across lineaments on the south side of the river. The lineament group is relatively discordant with the ice flow direction. An esker deposit on the uplands south of the Susitna River trends sub-oblique to the lineaments' projection and showed no evidence of being offset or deformed based on low-altitude flyovers (Figure A26.2). Assessment of kinematics of the lineament morphology is indeterminate because there a near absence of geomorphic expression of tectonic-related features.

The aerial reconnaissance traversed along both banks of Tsusena Creek at the intersection with LG-26 to look for evidence of faults or faulting, and found no evidence although the tree cover was relatively thick and exposures were limited in extent (Figure A26.3). The aerial traverse also inspected the canyon where bedrock ridges are aligned roughly perpendicular to the creek valley would intercept the projection of the lineaments. The bedrock ridges show no evidence of a fault, based on lack of color contrasts, lack of lithologic contrasts, and lack of unusual notches or slope breaks along the ridge crest. A ground landing was made in an attempt to hike to the rim of the creek valley for visual observation from the ground; however tall and dense alder trees prevented a meaningful traverse. Additional inspections of the Quaternary surficial deposits show no evidence of tectonic geomorphology; neither in the LiDAR nor in the aerial reconnaissance. The morphology of the drainage and its position on the landscape suggest that it may have originally formed from meltwater of the last retreat of ice, and subsequent down cutting and drainage basin elongation as a consequence of adjustment to the base level of the Susitna River. Ground traverses were made along parts of LG-26 south of the Susitna River, slightly west of the western extent of the lineament group "bubble" (Figure A26.3) (Waypoints 14S35 and 14S36) where a cluster of short lineaments were mapped on shallow to at-ground-surface bedrock. The bedrock was jointed porphyritic andesite with evidence of glacial fluting (Figure A26.3). Subtle slope breaks as well as taller slopes were observed during the ground traverse, but collectively did not align to form a continuous or compelling topographic feature. The morphologic expression of the lineaments mapped adjacent to the west margin of LG-26 are attributed to glacial scour as well as jointing in the bedrock.

The lineament group does not show evidence of expression in late Quaternary units or landforms, including the outwash deposits at the confluence of the Tsusena Creek and Susitna

Rivers. The glacial deposit that seems to overlie the lake deposits along the upper banks of the unnamed drainage also appears to have a horizontal basal contact (Figure A26.2). While the lineament group is mapped across different geologic units, there is very little consistency of expression north of the Susitna River as compared to the south. North of the river, the lineaments appear to be dominantly erosional based on their mapped position at the bottom of a sub-linear canyon. South of the river, the lineaments that are mapped largely follow ice-flow directions. The few that are not concordant with ice-flow direction seem to be related to near-surface bedrock that is expressed as drumlin-like landform features. Because of the absences of previously mapped structures or faults, the lack of field evidence of faults, and the apparent positive evidence for non-faulting or displacement vis-à-vis the undeformed esker deposit (>11 ka in age), it is judged that the lineament group is erosional in origin and likely does not represent a fault structure.

In summary, no evidence – on the ground or from the air – was revealed that would contradict this study's initial interpretation and conclusion that lineament group LG-26 is erosional in origin and does not represent a fault structure.

4.1.27 Lineament Group 27

Lineament group 27 is a northeast-trending series of aligned lakes and subtle topographic troughs/swales that project towards a large and linear U-shaped valley (Figures A27-1.1 through A27-3.1), approximately 80 km (~50 miles) southeast of the proposed Watana dam site (Figure A0.1). This group is expressed in mapped Quaternary sediments within the Copper River Basin and partially coincides with the mapped Sonona Creek fault (Williams and Galloway 1986; Wilson et al. 2009), although no fault exposures were directly observed in the field during aerial and ground reconnaissance. The geometry of any potential tectonic structure is difficult to resolve with certainty because the linear trend of the lineament across the very low relief (i.e., basically flat) portion of the Copper River Basin could result from several fault geometries. The lineament is expressed in late Quaternary glacial drift and glacial lake deposits as a series of aligned lakes, linear lakes and swales, vegetation lineaments, low-relief (~2-m-high) ridges, all of which project toward a 1 km right stream deflection in Tyone Creek (Figures A27-3.1 and A27-3.2). These lineament features were not mapped throughout all the Tolson Creek Moraine complex of Williams and Galloway (1986) but do exist in the glacial lake deposits (and underlying basal till under the center of the ice lobe?) located to the east. Williams and Galloway's (1986) depiction of the Sonona Creek fault is somewhat equivocal regarding the constraining age of potential faulting; they show the fault as truncating, cutting across, and also terminating into different ridges of the Tolson Creek moraine complex. The magnitude of lineaments' expression is relatively consistent along strike as shallow, ~2- to 3-m-deep lakes and ~2-m-high linear ridges, but the apparent sense of displacement is not consistent. In some locations (Photograph D, Figure A27-3.2) the apparent sense of displacement is south-down/north-up, whereas elsewhere the apparent displacement is south-up/north-down, and at other locations there is no discrete topographic expression of any displacement. The orientation of the lineament group is roughly perpendicular to the northwest-flowing ice in the Copper River Basin, but parallel to ice flowing down a northeast-trending segment of the Oshetna River Valley. No observations of displaced linear strain markers such as moraine ridges or terrace risers were found during low-level and ground investigation or from desktop analysis of the INSAR data. This suggests that the ~1 km (~0.6 miles) of apparent right-lateral stream deflection cannot be due to lateral fault motion, but it does not eliminate the possibility of stream deflection due to damming or diversion by a south-facing topographic scarp created by a north-up/south-down sense of vertical movement.

Field investigation revealed that the very few lineaments mapped in the western half of the group within the broad glacially-sculpted Oshetna River valley (Figures A27-1.1 and A27-2.1) are either rock or drift drumlins or coincide with ice-marginal features such as kame terraces, and are not likely tectonically related. The most prominently expressed features of group 27 are located in the eastern portion of the group amongst features that appear to be derived from stagnant ice (Figure A27-3.1) and coincide with the mapped Sonona Creek fault, but these aligned lakes, linear lakes and swales, and vegetation lineaments do not appear to transect across features of different ages. Specifically, ground investigation and aerial inspection of the Tolson Creek moraines did not reveal any lateral or vertical deformation along the projection of the mapped fault—only the presumably younger areas of ice-related deposition contained lineaments. The expression of lineaments in a portion of the landscape judged to be the youngest, and the absence of observed deformation (lateral or vertical) in the adjacent Tolson Creek Moraines, which are older, is inconsistent with an origin by faulting. (If the youngest portions of the landscape express prominent tectonic geomorphology, the older portions would likely also show evidence of recent tectonic activity too.) However, the lineament group's orientation does align with an apparent regional structural grain in the landscape, based on the orientation of the Castle Mountain fault 30 km to the south. Field investigation did not reveal any definitive evidence to strongly refute nor strongly support the presence of the mapped portion of the Sonona Creek fault and a late Pleistocene/early Holocene earthquake event cannot be refuted.

The initial Susitna-Watana PSHA (FCL, 2012) included the Sonona Creek fault as a seismic source based on the mapping of Williams and Galloway (1986) that depicts a late Quaternary faulted moraine. The aerial and ground field observations from this study did not verify this feature, however, the field data are not sufficiently detailed or extensive to preclude the potential of a latest Pleistocene to early Holocene co-seismic surface rupture. This would require developing a new detailed map along the Sonona Creek fault trace and confirmation of the relative age relationships of the presumed unfaulted deposits in that area. The Sonona Creek fault was not a significant contributing seismic source in the FCL (2012) PSHA evaluation due to its low slip rate and distance (~70 km) from the Watana site. Based on the 2013 field observations, the Sonona Creek fault should likely be retained in the seismic source model, but with an updated source characterization which considers a weighted non-tectonic interpretation of this lineament suggested by the new field observations. Reasons for maintaining this feature in the seismic source model are: (1) it is depicted on a previous publication as a late Quaternary fault, and, (2) the present study scope does not provide sufficient field evidence to positively refute its existence. In the absence of further field studies of the Sonona Creek fault, inclusion of a non-tectonic alternative for this fault would encompass a broad range of alternative interpretations within the crustal source model. No further field studies of the Sonona Creek fault or features in lineament group 27 for the Watana dam seismic hazard evaluation are recommended.

4.1.28 Broad Pass Area Faults

The Broad Pass area includes, for this investigation, the northeast-trending northwest-dipping thrust fault previously mapped by Csejtey (1961), approximately 56 km (~35 miles) northwest of the proposed Watana dam site, along the western extent of the Chulitna River valley (Figure A0.1, Plate A-BP); as well as other bedrock faults mapped within and near the Chulitna valley (e.g., Honolulu thrust fault of Csejtey (1961)); and most recently several northeast-southwest oriented faults depicted by Wilson et al. (1998)). Faults oriented approximately northeast-southwest in this area are likely favorably oriented for (re)-activation in the existing crustal stress field near the Denali fault. A strong fabric of northeast-trending glacial features characterizes the geomorphology in the Chulitna valley, with numerous landforms such as drumlins, and glacial striae occurring throughout the valley. Existing geologic mapping (Wilson et al. 1998) depicts pre-Quaternary faults that apparently place Paleozoic and Mesozoic rocks against each other, or Paleozoic and Mesozoic rocks against Tertiary sedimentary rock units. These older rocks are in turn overlain by Quaternary glacial and fluvial sediments that are no older than late Wisconsin age.

Several locations were investigated as part of the assessment of previously mapped faults in the Chulitna River valley (Plate A-BP). Faults mapped as bounding Tertiary units could not be confirmed due to lack of exposure (e.g., Figure A-BP.1). A ground traverse was made orthogonal to the mapped fault and no exposures were present and a fault was not observed during the hike. Low altitude fly-overs of the partly-forested, partly-wetland surface of the Chulitna valley found no evidence of Quaternary faulting, and the surficial geomorphology observed was uninterrupted and undeformed. Exposures of Quaternary terrace units exposed along the western bank of the West Fork of the Chulitna River appear to be chiefly fluvial in origin and show lenticular beds that are not entirely planar in geometry. On the east side of the

West Fork of the Chulitna River, an important outcrop exposes late Quaternary till that unconformably overlies Tertiary sediments with an apparently horizontal basal contact geometry for the length of the exposure (Figure A-BP.1). Similar contact relations and horizontal geometries were observed in the East Fork Chulitna River and several tributaries. This observation argues that the till deposit has not experienced tectonic deformation since its emplacement, supporting an interpretation of no late Quaternary or post-glacial faulting.

Other locations within the Chulitna River valley were visually inspected (Plate A-BP; Figures A-BP.2 and A-BP.3). Field investigation found no evidence to directly confirm the faults as mapped. In all instances, late Quaternary cover overlying the fault appeared undisturbed and not offset. Based on the extensive glacial ice features that are prevalent in the valley, the late Quaternary deposits and landforms are probably from the last glacial maximum. The lineaments mapped within the Chulitna River valley are oriented along the direction of ice flow, and generally are located along the margins of geomorphic features (e.g. drumlins, kettle edges) that are genetically related to glacial flow and related processes. Thus, none of the lineaments mapped in this area are considered tectonic in origin. The field evidence did not directly confirm the previously mapped pre-Quaternary faults, nor did it confirm faulting of Tertiary deposits at locations inspected. However, observations of field exposures and late Quaternary surficial deposits showed no evidence of faulting.

4.1.29 Clearwater Mountains

FCL (2013) identified the Clearwater Mountains as an area of interest because the western extent of the Broxson Gulch fault lies within the Clearwater Mountains, and was inferred as Quaternary-active by Nokelberg et al. (1994). Conceptually, the region could be analogous to the area around the Susitna Glacier fault, where a WSW-trending fault splays from the Denali fault and results in southward-directed uplift on a north-dipping fault. West-southwest trending fault splays may be favorably oriented for (re)-activation within the existing crustal stress field and if active would potentially provide a structural connection between the Denali fault and the Talkeetna thrust fault. In order to better understand the potential genesis of the Clearwater Mountains and potential connections between the Broxson Gulch fault and Talkeetna thrust fault, Plate A-CWM displays the area surrounding the Clearwater Mountains. The potential junction of the Broxson Gulch fault and Talkeetna thrust faults lies approximately 83 km (~52 miles) northeast of the proposed dam site.

Several different iterations of geologic mapping exist for the area of the southern Clearwater Mountains and these data are described in detail by FCL (2013). For the purposes of the current discussion, it is sufficient to reiterate that three maps in particular demonstrate the range of depictions of the faults in the area: Smith (1981), Silberling at al. (1981), and Csejtey et al.

(1992). Importantly, the three maps show different configurations for the potential junction of the Broxson Gulch, Black Creek, and Talkeetna thrust faults in the Pass Creek area (Plate A-CWM). Smith et al. (1981) show the Talkeetna thrust fault as a continuation of the Broxson Gulch fault, which together truncate the Black Creek fault. Silberling et al. (1981) also show the Talkeetna thrust fault as a continuation of the Broxson Gulch fault but do not present mapping of the Black Creek fault. In contrast, Csejtey et al. (1992) shows the Broxson Gulch fault continuing westward as the Black Creek fault and the Broxson-Black Creek fault system as truncating the Talkeetna thrust fault. Based on their own work, and upon review of previous work, including the work of Nokleberg et al. (1994), O'Neill et al. (2001) conclude that the Black Creek/Broxson Gulch fault truncates the Talkeetna thrust fault, and that the Broxson Gulch fault and Talkeetna thrust faults are not kinematically or structurally related.

Based on the results of FCL (2013), two specific areas within the Clearwater Mountains were deemed candidates for field inspection (Plate A-CWM): 1) the junction area of the Talkeetna thrust, Broxson Gulch thrust, and Black Creek faults (lineament group CMW1) and, 2) a collection of lineaments on the south side of the Clearwater Mountains (lineament group CMW2).

Lineament group CWM1 does contain a few lineaments that lie proximal to mapped faults in the saddle between the Windy Creek and South Fork Pass Creek valleys (Plate A-CWM, Figure A-CWM.1) and in other locations along the Black Creek fault (Plate A-CWM). In the saddle between the Windy Creek and South Fork Pass Creek valleys, the trend of most mapped lineaments across the terrain was somewhat inconclusive while the trends of others suggested the potential geometry of fault structures would be steeply dipping. Indirect evidence of fault structure was observed in several locations in the high elevation bedrock terrain above the valley floor in the form of contrasting rock-type juxtapositions (Figure A-CWM.1 and A-CWM.2) that corroborate the general locations of the mapped faults. The FCL-mapped lineaments are expressed as linear gullies and streams in both late Cretaceous to early Jurassic bedrock and glacial deposits, broad and shallow U-shaped linear troughs in glacial deposits, and locally as side-hill benches within latest Pleistocene glacial deposits on the margins of the valleys. The lineaments do not appear to cut across different geologic units and have a consistent magnitude of expression. The lineaments are both discordant and concordant with glacial ice-flow directions; some lineaments may be expressing the ice-limit elevations at the bedrock-glacial moraine contact (Figure A-CWM.1). No field evidence of deformed Quaternary-age linear strain markers along the trend of mapped lineaments or faults was observed during aerial inspection. Furthermore, no evidence of through-going tectonic geomorphology was observed along the mapped lineaments in the saddle between the Windy Creek and South Fork Pass Creek valleys, nor any expression of deformation in the Quaternary sediments of the north-trending glaciated valleys across which the Black Creek fault cuts (Figure A-CWM.2).

The FCL-mapped lineaments in the area of group CWM2 do not coincide with previously mapped faults, lie at elevations below the maximum ice elevation, and are oriented mostly parallel to the direction of ice flow (Plate A-CWM). The lineaments are expressed as side-hill benches within Quaternary glacial deposits (and spatially coincide locally with kame terraces) (Figure A-CWM.3) and as downhill-facing scarps in areas subject to solifluction. The magnitude of expression varies from relatively broad side-hill benches 10s of meters wide and 100s of meters long, to smaller topographic scarps with only a few meters of relief that are difficult to trace laterally in thick vegetation. Extensive low-level and ground investigation revealed that the lineaments are not laterally continuous across different geologic units or landforms; eskers and post-glacial alluvial fans are not apparently deformed along the projection of the lineaments (Figure A-CWM.3). No evidence of displaced or deformed linear strain markers was observed.

In summary, some mapped lineaments mapped by FCL (2013) in the central Clearwater Mountains area coincide with previously mapped bedrock faults but no evidence of deformed or displaced Quaternary deposits was observed. No field evidence of Quaternary activity along the mapped traces of the Talkeetna thrust, westward extension of the Broxson Gulch, or Black Creek faults was observed and consequently the specific geometries and contact relationships between these three faults were not evaluated in the field. The lineaments mapped along the southern slopes of the Clearwater Mountains are interpreted to be of non-tectonic origin. The geomorphology on the southern slopes of the Clearwater Mountains is heavily influenced by glacial processes and the presence of left-lateral moraine deposits. Field investigation did not reveal any through-going and laterally continuous aggregations of individual lineaments or tilted tectonic markers (such as shorelines or terraces) at the southern foot of the mountains that could be definitively linked to a tectonic origin. Post-glacial landforms and deposits did not express any lineaments and appear undeformed.

4.1.30 Castle Mountain Fault Extension

The Castle Mountain fault is a Quaternary seismogenic structure, as well as a major structural boundary which was included as a seismic source in the initial Watana Dam PSHA evaluation (FCL, 2012). The eastern extent of the Castle Mountain fault, as mapped in the Alaska Quaternary fault and fold database (i.e., Koehler et al. 2012), bifurcates to the east toward the Copper basin, ending in two splays (Plate A-CME). The northern splay ends at an unnamed glacial valley west of Caribou Creek; and the southern splay ends at the confluence of Billy Creek, and the larger Caribou Creek drainage. Northeast of the mapped end of the southern splay of the Castle Mountain fault, along Billy Creek, a group of lineaments projects to the northeast along a trend similar to the Castle Mountain fault (Plate A-CME). Lineament features aligned with the Castle Mountain fault could potentially increase the overall rupture length of the fault, and may extend slightly closer to the Watana dam site than previously mapped.

Field evidence for faulting observed during low altitude aerial and ground inspection included: apparent bedrock type juxtapositions, bedrock color change associated with alteration zones, and deformation of bedrock units. All apparent evidence was observed in bedrock and no linear expression or evidence of faulting was observed in Quaternary deposits, although Quaternary deposits were scarce. The mostly straight to overall gently arcuate trend of the lineaments across high-relief mountainous terrain occur within a swath of parallel to sub-parallel features. The landscape in this swath exhibits a clear northeast-trending structural grain which suggests a steeply dipping structure(s) within a zone of deformation. To the southwest, the lineaments coalesce and join the right-lateral Castle Mountain fault. Considering the oblique orientation of these faults to the east-west trending right-lateral Castle Mountain fault system, the kinematics of these features can be implied as being right-lateral oblique with a larger vertical component than lateral. Observed lineament features occur in multiple bedrock lithologies, including: the Jurassic Talkeetna (Jtk), the undivided Chinitna and Tuxedni Formations (Jtxc), and Naknek Formations (Jn), Cretaceous Matanuska Formation (Km), Tertiary Chickaloon Formation (Tch) and undifferentiated Tertiary volcanic rocks (Tvu) (Plate A-CME). These features are only expressed in upland bedrock terrain and slopes and do not occur in alluvial deposits or glacial landforms. The orientation of these lineaments is perpendicular to regional ice-flow direction. It is unlikely that glacial processes played a major role in the formation of these lineaments.

Quaternary deposits in the vicinity of the Castle Mountain fault extension lineament group have limited spatial coverage and most commonly occur as fluvial deposits found within in narrow canyons. Bubb Creek, Flume Creek, Greta Creek, and other unnamed drainages intersect, and are nearly orthogonal to, the lineament alignment and mapped features of Csejtey et al. (1978). Each waterway is relatively narrow with little to no Quaternary deposits. The Little Nelchina River valley is a broad glacial valley, and it provides the best exposure of continuous, flat-lying, and undeformed Quaternary terraces across the lineaments and mapped features. The scale of aligned features such as saddles, linear U- and V-shaped valleys, side-hill benches and breaks-in-slope remain consistent along strike and across variable terrain. Although a core group of lineaments within this group coincide with mapped faults, others do not. The mapped lineaments that do not coincide with previously mapped faults are attributed to be linear drainages (erosion features) and lineaments related to structural grain of the bedrock (lithologic control). The fault-related lineaments appear to be related to the Castle Mountain-Caribou fault systems of late Cenozoic age (Csejtey et al. 1978). Because of limited exposure of Quaternary deposits and the segmented and splayed characteristics of the mapped faults in this area, it is difficult to declare that all segments of this fault exhibit no Quaternary activity. No definitive evidence was encountered that precludes a scenario where this segment of aligned features ruptures as an extension of the Castle Mountain fault. If the group of aligned features acts as an extension of the Castle Mountain fault, the group of features could extend the fault by approximately 21 km (~13 miles) to the northeast of the current mapped extent of the fault as shown in Koehler et al. (2012). Based on the observations that these features are clearly related to faulting of late Cenozoic age, we suggest adding this segment of fault-related features to the crustal seismic source model as a northeast extension of the Castle Mountain fault rupture scenario.

4.1.31 North-South Features near Talkeetna River-Susitna River Confluence

This area was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) on the basis of the features' large distance (i.e., >70 km [>40 miles]) to the proposed dam site and their poor expression in the surrounding Quaternary sediments and Tertiary granodiorite outcrops as manifested in the INSAR data. This group was not visited during the 2013 field inspections and no observations were made that suggested a need for additional analysis. A plate showing available geologic data for this group is not included herein but was presented as part of FCL (2013).

4.1.32 Photogeologic Lineaments Mapped by Reger et al. (1990) in the Healy A-3 Quadrangle

In addition to investigation of the lineaments mapped by FCL (2013), lineaments appearing in Reger et al. (1990) were also evaluated in the field. In their study, Reger et al. (1990) mapped geologic units, glacial features, glacial lake shorelines, faults and lineaments within the extent of the Healy A-3 quadrangle. These features are presented in several thematic map sheets and described in the associated report. In the report, Reger et al. (1990) mention that "several photogeologic lineaments transect or offset moraines…" and are "likely candidates for active faults." Reger et al. (1990) describe one specific lineament as intersecting an east facing cirque in the headwaters of Butte Creek and being coincident with an offset cirque floor. Three lineament groups mapped by FCL (2013) and evaluated as part of this study (groups 21a, 21b, and 22) fully or partly overlap the Reger et al. (1990) map area (Figure B-01). None of the features identified in these three lineament group areas are interpreted to be associated with late Quaternary faulting. However, closer examination of the Reger et al. (1990) map showed a number of locations where the map depicted faults and solid lines either through or extending into Quaternary units. Based on these observations and the statements in the associated text, the features shown on the Reger et al. (1990) map were highlighted for further field review.

Lineaments and faults appearing in Reger et al. (1990), Sheet 1 of 2, were digitized as shapefile lines at a scale of 1:63,360, or better, and attributed appropriately. The locations where these lineaments and faults were mapped across or extended into Quaternary units were identified, saved as shapefile points and given a feature number (Figure B-01). The line and point shapefiles were loaded into an ArcGIS-enabled ruggedized field laptop with real-time GPS tracking. Field investigation of each feature was conducted via helicopter overflight with limited ground inspection, using the evaluation process described in Section 2 and Section 3. Discussion of these features follows below, but due to the large number of features shown by Reger et al. (1990), figures presenting the map and field data for the features are presented as Appendix B.

Feature 1:

Feature 1 is a northeast trending photo-lineament mapped over orthogneiss and migmatite (TKgm) bedrock in its central and northern portions. The southern portion of the lineament is mapped over Quaternary age landslide (Qct) and rock glacier (Qcg) deposits in a narrow south facing cirque (Figure B-02). Low altitude aerial inspection of this location revealed that the mapped trace of the lineament is coincident with a linear alignment formed by the toe of a rock glacier advancing downslope from the eastern cirque wall. The lineament is enhanced because it is in close proximity, and parallel to, the axial drainage channel. Additionally, the lineament is absent in the Quaternary sediments on the valley floor of the down-drainage intersecting valley. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 2:

Feature 2 is a northwest trending photo-lineament mapped over a quartz monzonite gneiss (TKqmg) and paragneiss (TKpng) bedrock ridge. The lineament is terminated in Wisconsin age till (Qd3) at its northwest extent (Figure B-03). The mapped trace of the feature overlies obliquely oriented linear glacial striations within the bedrock. Low altitude aerial inspection revealed no clear linear expression in the terrain with the same orientation as the mapped trace of Feature 2. Quaternary deposits at the northwest and southeast extent of this feature were visually inspected, and no evidence of linear expression was observed. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 3:

Feature 3 is a west-northwest trending photo-lineament mapped across Wisconsin age till (Qd3), moraine (Qm3), and abandoned meltwater channel alluvium (Qac) deposits (Figure B-04). Low altitude aerial inspection revealed that this feature correlates with linear expressions related to glacial features rather than tectonic features. The western and central segments of this lineament are coincident with two prominent breaks-in-slope on the northeastern margin of a U-shaped glacial valley. The eastern portion of the feature is coincident with a linear to semi-arcuate moraine. In addition, the lineament has no expression within the Qac deposits near the center of the mapped trace. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Features 4 & 5:

Features 4 and 5 are mapped as sub-parallel northwest striking faults across a broad Kahiltna argillite, sandstone, and siltstone (KJs) bedrock ridge (Figure B-05). Both of these faults are depicted as intersecting Wisconsin age till (Qd3) deposits on the flanks of the ridge. A clear expression of these faults was not observed in the bedrock during low altitude aerial inspection. In addition, the Quaternary (Qd3) deposits were observed to have no linear expression or fault related deformation. Expressing no Quaternary-aged deformation, these features are not considered to be active structures.

Feature 6:

Feature 6 is an arcing north-northwest trending photo-lineament mapped across granodiorite (Tgdf) bedrock and Quaternary age paludal (Qs) and Wisconsin age till (Qd3) deposits (Figure B-06). The central portion of the mapped lineament correlates to a prominent break in slope and juxtaposing bedrock and Quaternary deposits. The northern extent of the lineament is expressed by a subtle west facing slope and linear valley. The southern extent is mapped over the crest of a bedrock knob and has no clear expression. Low altitude aerial inspection revealed that this lineament exhibits an opposite sense of vertical displacement in the north (apparent down-to-the-west) compared to the middle and southern segments (apparent down-to-the-east), an unlikely combination of geomorphic expressions for a tectonic feature with vertical displacement. Geomorphic expression indicative of oblique or strike-slip faulting was not observed. Additionally, this lineament has no expression within Quaternary deposits. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 7:

Feature 7 is a sinuous east-northeast trending photo-lineament mapped over quartz monzonite gneiss (TKqmg), quartz monzonite (Tqm) bedrock, and Wisconsin age till (Qd3) deposits (Figure B-07a/b). A pegmatite vein is mapped, unbroken, across this feature at its intersection with the Feature 8 lineament. Low altitude aerial inspection revealed that linear expression within the Quaternary deposits was observed to be a linear drainage (western segment) and an alignment of solufluction lobes (eastern segment). In aggregate, this lineament is a collection of aligned and unrelated non-tectonic features: linear drainages, linear erosional features, and aligned solufluction lobes. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 8:

Feature 8 is a slightly arcing west-northwest trending photo-lineament mapped over a quartz monzonite gneiss (TKqmg) bedrock ridge and Wisconsin age till (Qd3) deposits (Figure B-07a/b). The mapped trace of Feature 8 intersects Feature 7 on the eastern flank of the bedrock ridge. On the western side of the ridge, the feature intersects the northern extent of a mapped fault that has no expression in Quaternary deposits. Two pegmatite veins are mapped unbroken across this feature. This lineament is made prominent by a very large southwest facing topographic scarp along a linear drainage on the west side of the ridge, and a linear drainage on the eastern side of the bedrock ridge. Low altitude aerial observations revealed that the topographic scarp is approximately 10-20m in height and likely an erosional feature related to solifluction. The scarp has a limited extent and is not expressed in any other bedrock segment or Quaternary deposit along Feature 8. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

The western portion of this mapped feature (from the fault intersection to the west) corresponds with the FCL mapped lineaments of lineament group 22 discussed above.

Feature 9:

Feature 9 is a northwest trending photo-lineament that is mapped over Wisconsin age till (Qd3), alluvial fan (Qaf), and moraine (Qm3) deposits (Figure B-08). The eastern portion of this lineament is the same feature as the lineaments included in FCL lineament group 22 discussed above. Low-altitude aerial inspection revealed that feature is formed by an alignment of non-tectonic glacial features: linear moraine, solufluction features, and glacial striations in the bedrock on the valley margin slopes. At one location near the center of its mapped trace, the lineament is overprinted with a Quaternary age alluvial fan. No trace of the lineament was observed within the alluvial fan deposit. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 10:

Feature 10 is a long (~10.5-km) north-northwest trending photo-lineament mapped over Tertiary quartz monzonite (Tqm) and granite (Tgr) bedrock, and Wisconsin age till (Qd3) and alluvium (Qa) deposits (Figure B-09a/b). Low altitude aerial inspection showed that the lineament is mostly composed of linear drainages, linear moraines, and breaks in slope. The breaks in slope in the north and south display an opposite sense of displacement (down-to-the-east) than the middle slope (down-to-the-west), an argument against a through-going, tectonic feature with vertical displacement. Geomorphic features indicative of oblique or strike-slip faulting were not observed. Alluvial deposits within the intersecting glacial valley (southern portion of the trace) and the glaciated plain (mid to northern segment of the trace) show no clear evidence of linear expression. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 11:

Feature 11 is a northwest trending photo-lineament mapped over Tertiary granite (Tgr) and quartz monzonite (Tqm) bedrock and over Wisconsin age till (Qd3) and Quaternary landslide (Qct) and rock glacier (Qcg) deposits (Figure B-10). Observations made during low altitude aerial inspection showed that the mapped trace of this lineament is coincident with an alignment of moraine crests and linear erosion features. The lineament was not observed in any of the intersecting Quaternary deposits. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 12:

Feature 12 is an east-northeast trending photo-lineament mapped in Quartz Monzonite (Tqm) bedrock and Quaternary age rock glacier (Qcg) deposits (Figure B-10). The western and central segments of this lineament are coincident with linear drainages (erosion features). In its eastern extent, the mapped trace of the lineament is coincident with the linear flank of a rock glacier over an older rock glacier. Observations from low altitude aerial inspection and existing data indicate that this feature is likely non-tectonic in origin.

Feature 13:

Feature 13 is a north-northwest trending fault mapped in Basalt, Rhyolite, and Agglomerate (Tvfa) bedrock and terminates at Quaternary age rock glacier (Qcg) and Quaternary landslide (Qct) deposits (Figure B-11a). The mapped trace is intermittent within the Quaternary deposits, and dike swarms (Tgr-d) are mapped unbroken across the project path of this feature. Observations from low altitude aerial inspection showed no expression of faulting within Quaternary deposits. Expressing no Quaternary-aged deformation, these features are not considered to be active structures.

Feature 14:

Feature 14 is a north-northwest trending photo-lineament mapped in Basalt, Rhyolite, and Agglomerate (Tvfa) bedrock and Quaternary age landslide (Qct) and rock glacier (Qcg) deposits (Figure B-11a). This feature is along strike with, and appears to be mapped as a possible northern extension of, the Feature 13 fault. This lineament is formed by a linear drainage within a rock glacier in a narrow, south facing, cirque and an aligned saddle. Low altitude aerial inspection observed no evidence for faulting along this linear alignment. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 15:

Feature 15 is a north-northwest trending fault mapped in Basalt, Rhyolite, and Agglomerate (Tvfa) bedrock and Quaternary glacial till (Qd) deposits (Figure B-11a). Low altitude aerial inspection observed the fault in bedrock outcrops on the mountain slopes and through a saddle. No expression of the fault or fault related deformation was observed in Quaternary (Qd) deposits in the valley floor or in an overlying rock glacier. Expressing no Quaternary-aged deformation, these features are not considered to be active structures.

Feature 16:

Feature 16 is a northwest trending fault juxtaposing Tertiary quartz monzonite (Tqm) against Cretaceous Kahiltna argillite, sandstone, and siltstone (KJs) bedrock and over Quaternary landslide (Qct) and till (Qd) deposits (Figure B-11a/b). This fault is along strike with, and north of, the Feature 15 fault. The two features are separated by a glacial valley. Low altitude aerial and ground inspection observed evidence of faulting in bedrock at a ridgeline saddle near photograph location C, confirming the presence of the fault along the mapped trace. The Quaternary deposits (Qct, Qd) on the floor and lower flank of the glacial valley were observed, and no linear expression or evidence of tectonic deformation was observed. Expressing no Quaternary-aged deformation, these features are not considered to be active structures.

Feature 17:

Feature 17 is a northeast trending photo-lineament mapped in Kahiltna argillite, sandstone, and siltstone (KJs) bedrock and across Quaternary landslide (Qct) and an unlabeled unit (late Wisconsin till and/or moraine?) (Figure B-12a/b). The mapped trace of the lineament crosses the till and moraine (?) deposits, however no clear through-going linear expression was observed during low altitude aerial inspection. The mapped trace is most likely defining aligned and subtle slopes and drainages within the Quaternary deposit. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 18:

Feature 18 is a northwest trending photo-lineament mapped in Kahiltna argillite, sandstone, siltstone (KJs) bedrock and Wisconsin age till (Qd3), and an unlabeled unit (late Wisconsin till and/or moraine?) (Figure B-12a/b). The mapped trace of the lineament is coincident with a topographic break-in-slope (apparent down-to-northeast) in bedrock. This lineament is parallel/sub-parallel, and along strike to the northwest, to a (down-to-northeast) normal fault mapped by Reger et al (1990). The two features are separated by a northeast trending glaciated valley. Low altitude aerial inspection observed an apparent fault exposure in bedrock at a topographic break-in-slope along the ridgeline. This evidence indicates that this lineament is likely a continuation of the fault trace mapped to the southeast. The Quaternary deposits between Features 18 and 20 were inspected and found to be undeformed and lacking any linear expression. Expressing no Quaternary-aged deformation, these features are not considered to be active structures.

Feature 19:

Feature 19 is a northeast tending photo-lineament mapped in unlabeled unit (late Wisconsin till and moraine?) (Figure B-12a/b). Low altitude aerial inspection showed that the mapped linear trace correlates with a vegetated linear drainage. The lineament is made more prominent by the color contract between the vegetation and the surrounding rocky ground surface. Observed to be an erosional feature, this lineament is likely non-tectonic in origin and not considered further.

Feature 20:

Feature 20 is a northwest striking photo-lineament mapped across orthogneiss and migmatite (TKgm) bedrock and Quaternary age undifferentiated colluvium (Qc) deposits (Figure B-12a/b). Low altitude aerial inspection confirmed that the mapped linear trace correlates with a linear drainage and has expression only in bedrock. No linear expression was observed in Quaternary deposits along the projected path of the feature. Lacking evidence of Quaternary age deformation, this feature is not considered to be an active structure.

Features 21:

Feature 21 is a northwest trending photo-lineament mapped over quartz monzonite (Tqm) bedrock and morainal deposits of Late Wisconsin age (Qm3) (Figure B-13). Low altitude aerial inspection showed that this lineament is composed of a collection of aligned features. The northern and central segments of this feature are a bedrock ridge crest leading to a linear drainage. The southern extent, in Quaternary deposits, was observed to be the crest of a debris flow levee which bounds the linear drainage. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 22:

Feature 22 is an east-northeast trending photo-lineament mapped within a deposit of colluviated till of Illinoian age (~120 to 170 ka) (Figure B-14a). Low altitude aerial reconnaissance observed no clearly defined linear expression to correlate with the mapped lineament. It is likely that the mapped trace represents a color contract created by glacial till along the crest of a low-relief ridge separating two drainages. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 23:

Feature 23 is an east-northeast trending photo lineament mapped across paragneiss (TKpgn) bedrock and morainal deposits of late Wisconsin age (Qm3), and till of Illinoian age (Qd2) (Figure B-14a/b). This lineament is to the east of, and along strike with, Feature 22. The two features are separated by a broad landscape mantled with Qd2. Low altitude aerial inspection observed that the mapped trace of the lineament correlates with topographic scarps and linear solifluction features. Along strike, the topographic scarps were observed to express opposing expressions of vertical displacement (down-to-northwest and down-to-southeast), an unlikely combination of geomorphic expressions for a through-going tectonic feature with vertical displacement. Geomorphic expression indicative of strike-slip or oblique faulting was not observed. No linear expression or scarps were observed within the intersecting Quaternary deposits. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 24:

Feature 24 is a northwest trending photo-lineament mapped in paragneiss (TKpng) bedrock for most of its length except for the northern extent where it is mapped within Quaternary age talus (Qct) deposits (Figure B-15). Reger et al. (1990) describes this lineament as one which corresponds to an offset in the floor of an east-facing cirque, the floor of which is mapped as Tkpgn. Low altitude aerial inspection of the lineament revealed that in bedrock the mapped trace consists of an alignment of variably-scaled, linear swales more likely related to glaciation rather than active tectonics. In the Quaternary deposits, the lineament corresponds to a linear drainage. Scarps and vertical displacement were not observed in the cirque floor described by Reger et al. (1990) and no evidence of tectonic origin was noted for this feature. Field observations and existing data indicate that this feature is likely non-tectonic in origin

Feature 25:

Feature 25 is an angled northwest trending photo-lineament. The lineament is mapped over paragneiss (TKpgn) bedrock and late Wisconsin age till (Qd3) (Figure B-15). Low altitude aerial inspection revealed that the mapped trace is coincident with a shallow linear drainage that is highlighted by an apparent vegetation color contrast. Being an erosional feature, these field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 26:

Feature 26 is an east-to-west trending photo lineament mapped over bedrock for its entire trace except for the far western end (Figure B-16). At this location, it is mapped over Quaternary age talus deposits before it terminates against a bedrock knob in the center of the cirque. Visual inspection of the lineament via low altitude aerial inspection revealed no clear linear trace through the talus deposits. Within the cirque, the only along-strike linear trend is attributed to a linear drainage incised into bedrock.

Feature 27:

Feature 27 is an east-to-west trending photo-lineament mapped over paragneiss (TKpgn) bedrock in its middle portion and Quaternary talus (Qct) deposits on its eastern and western extents (Figure B-16). Within bedrock, no continuous linear features were observed that correspond with the mapped trace of Feature 27. Within Quaternary talus, the only linear expressions observed via low altitude aerial inspection were related to linear drainages. Field observations and existing data indicate that this feature is likely non-tectonic in origin.

Feature 28:

Feature 28 is a north-northwest trending photo-lineament mapped over orthogneiss and migmatite (TKgm) bedrock and Quaternary age colluviated till (Qdc3) (Figure B-17). During low altitude aerial inspection, the feature was observed to be characterized by a shallow linear trough oriented at an oblique angle to linear solifluction features and moraines, possibly indicating that this feature is related to bedrock structure. However, it has no expression in overlying Quaternary deposits or within adjacent Quaternary till deposit to the southeast. Lacking evidence of Quaternary age deformation, this feature is not considered to be an active structure.

4.1.33 Summary of Reger et al. (1990) Lineaments

This study evaluated 28 locations where photo-lineaments and faults, appearing in Reger et al. (1990) Map 1, intersect Quaternary deposits to determine if any of these features display morphology indicative of post-glacial surface rupture and faulting. The aerial reconnaissance of these 28 features did not identify evidence of post-glacial surface rupture associated with these features. The prominence of these features on some aerial photography, linear traces, and local topographic expression can be explained through juxtaposition of different rock types with physical or erosional contrasts, linear erosion features along existing bedrock structures or down slopes, and/or linear features associated with glacial landforms such as moraines and eskers. In addition to the visual inspection of these features, Dr. Reger was contacted, and through personal communication (Reger, 2013), commented that he does not believe that any linear features identified in Reger et al. (1990), Map 1 are related to active faulting. This study also judges that Reger et al. (1990) lineaments are not the result of late Quaternary faulting (Figure 4-5).

4.2 Discussion of the Talkeetna Fault Trench Locations of WCC (1982)

The Talkeetna fault was recognized as a major tectonic feature near the Watana dam site by Kachadoorian and Moore (1979) and WCC (1982) although no evidence of Quaternary faulting was located during either investigation. FCL (2012, 2013) reached similar conclusions, based on the initial literature review for seismic source characterization (FCL, 2012) and subsequently based on field reconnaissance and lineament mapping using LiDAR-derived DEM’s. The WCC (1982) investigations included paleoseismic trenching at two locations along the suspected map trace of the Talkeetna fault: trench T-1 and trench T-2. Trench T-1 is located directly southwest of the Fog Lakes, and lies about 9 mi (15 km) southwest from the proposed dam site, although the trench location was not directly atop the map trace (Figures 4-1A and 4-1B). Trench T-2 is located much farther to the southwest, about 40 mi (65 km) from the proposed dam site, and is slightly west of the confluence of the Talkeetna River and Iron Creek.

4.2.1 WCC Trench T-1

Low altitude aerial inspection and ground walking was performed along the WCC trench T-1 site to confirm the location of the trench and observe the geomorphology in the area (Figures 4-1B and 4-1C). The slightly west of north-facing break-in-slope (“scarp”) is a geomorphic feature that could be interpreted to be the result of either a northwest-dipping normal fault or a potential southeast-dipping, reverse to oblique-slip fault. The scarp is approximately 550 feet (167 m) in length, approximately 6.7 feet (2.0 m) tall over 5.5 feet (1.7 m) lateral distance, and trends 067 degrees azimuth (N67E) (Figures 4-1 through 4-4).

Mapping of lineaments based on LiDAR in the T-1 vicinity shows features that are oriented generally along margins of abandoned melt-water channels, along the margins of contemporary westerly-oriented drainages, and features local to the trench site. Along projection of the scarp to the immediate southwest, are low, linear mounds (Figures 4-1B and 4-2) that are approximately 17 feet (5.2 m) in relief over 28 feet (8.5 m) of lateral distance. These are interpreted as constructional geomorphic features based on concave-down mound morphology with symmetrical slopes; possibly the remnants of an esker. Along projection to the northeast, a lineament is mapped along a roughly north-facing break in slope (Figure 4-1B), however this feature has arcuate to cuspate morphology along its margin and a broader, flat surface directly above the slope break. This suggests that the lineament feature to the northeast is a terrace-type feature that experienced erosion along is margin to produce the cuspate morphology. The T-1 slope break is geomorphically unique in the area, and no other features have the same scale, morphology, or orientation along the projected bearing of the scarp.

From subsurface excavations, WCC (1982) concluded that the gravelly outwash deposits exposed in trench T-1 were not faulted (a fault was not identified in the trench T-1), and the “slightly disrupted” bedding and clast orientations at the slope break was explained as collapse of the sediment related to the melting edge of a late Wisconsin ice margin. The scarp is located near a geomorphic transition from older, topographically higher, west-sloping dissected kame terrace proximal to the mountain front to a lower, possibly inset, landform characterized by abandoned channels that carried west-flowing glacial meltwater (i.e. outwash) (Figure 4-3). This geomorphology supports the interpretation that the scarp trenched likely is an ice-marginal feature and was not formed by surface fault rupture.

Recent geologic mapping by Twelker et al. (2014) as part of the Talkeetna Mountains C-4 quadrangle map updates the T-1 trench site and broader area geology at 1:50,000-scale based on field mapping, analysis of gravity and electromagnetic data, and mineralogic analysis. Key conclusions from their mapping effort are that the Talkeetna fault is not expressed in bedrock geology as a single, continuous fault. Rather, it is now characterized from geophysical-based bedrock interpretation and mapping as a series of complex, high angle, northeast-trending fault strands, and strands of the Talkeetna fault themselves appear to be cross-cut and truncated by north-northwest trending bedrock faults providing evidence suggesting that the Talkeetna fault is not active in the contemporary stress regime.

4.2.2 WCC Trench T-2

A brief aerial inspection of the WCC paleoseismic trench T-2 area was performed to confirm, to the extent practical, the location of the excavation, and observe the geology and geomorphology at the location. No distinct features were associated with the excavation site (e.g. tree lines, backfill mounds), so the exact trench spot was only approximately located. In general, there are linear topographic grooves along the mapped location of the Talkeetna fault (Figure 4-5). In this area, the fault juxtaposes Cretaceous sedimentary rocks (map unit KJs) on the northwest against Paleozoic volcanic rocks on the southeast. The northeast projection of the fault is shown as terminating at a hill composed of intrusive Tertiary volcanics (map unit Tvu) that were dated at slightly older than 50 Ma (Csejtey 1978). WCC (1982) observed that these volcanic rocks have not been displaced. Our field inspection confirms the conclusion that the volcanic rocks show positive evidence of no displacement (Figure 4-5), indicating that the fault, at least in this locale of the study area (40 mi [65 km] southwest of the dam site), shows evidence of no movement since volcanic emplacement (early Eocene, Csejtey et al. (1978)).

4.3 The Susitna Feature

The Susitna feature was evaluated during the lineament mapping and criteria analysis presented in TM-8 (FCL 2013), and was removed from consideration as a seismo-tectonic element because of those desktop analyses. Parts of the Susitna feature were examined during 2013 investigations because a number of lineament groups were mapped as cross-cutting the feature (e.g. LG-16, LG21b, LG-22); the lineaments mapped trend sub-perpendicular to the Susitna feature, and are not displaced where they overlie the projection of the Susitna feature. However, to address comments received from the Board of Consultants, additional inspection was completed during the 2014 field season. For completeness, this section provides brief background on the history of how the Susitna feature was identified and then discusses the field observations, evidence and interpretations.

The Susitna feature was originally labelled by Gedney (1975) as a topographic lineament observed on 1:1,000,000-scale LANDSAT imagery. The following text is excerpted from Gedney (1975):

> "In the interests of the present study, the most significant aspect to the mosaic is a dominant NE-SW striking structural grain of the Talkeetna Mountains-Alaska Range complex. It is apparent that several strong lineaments intersect the Denali fault from the southwest. The most striking of these follows the southeast margin of the Alaska Range and intersects the Denali fault near Windy. A second lineament parallels this some 60 km to the east and intersects the Denali fault in the depression occupied by the Susitna glacier. This lineament, which we originally noticed on the LANDSAT (at that time, ERTS) imagery and temporarily dubbed the "Susitna fault" has since been confirmed in the field as being a genuine fault on the basis of rock differentiation, age dating, and seismicity."

It is not known to the authors of this report the specific basis for Gedney's statement of confirmation of the Susitna fault. However, we suspect it is the 1:250,000-scale map presented in Turner and Smith (1974) (Figure 4-6) because of proximity in time of publication. Turner and Smith (1974) depict the Susitna fault on their geologic map as an approximately 70-mile-long (~112 km) feature starting at the mouth of Tsusena Creek at the Susitna River and extending northeasterly to the Susitna Glacier, based on thermal geochronology data that suggested a difference in rock cooling rates in plutonic units on either side of the Susitna Glacier, and which was interpreted as a manifestation of Cenozoic fault throw. The feature is represented as a combination of dotted line patterns, dashed line patterns, and solid line patterns (Figure 4-6). The map explanation is silent on what these line patterns specifically represent, but are interpreted by this study to correspond to concealed, inferred, and certain designations, respectively, based on geologic convention. The lengths of the concealed, inferred, and certain lines are approximately 35 mi (~56 km), 25 mi (~40 km), and 10 mi (~16 km), respectively. Relative displacement is not indicated on the map, but the map explanation depicts the line as "high angle", suggesting strike slip style. The location where the Turner and Smith (1974) fault is mapped as "certain" corresponds with offset of their map unit Tkm (Cretaceous migmititic intrusive rocks with pervasive directional fabric and intermediate composition). However, Csejtey et al. (1978) report an absence of physical field evidence for the purported Susitna feature. Kachadoorian and Moore (1979) completed field work in 1978 to evaluate this and other features in the region, and state that they "found no conclusive evidence for a fault or active faulting along the inferred trace of the Susitna fault but rather landsliding, slumping, solifluction, and soil creep." (Kachadoorian and Moore 1979, p. 16). Woodward Clyde Consultants (WCC 1982) increased the length of the Susitna feature by extending the line southwesterly from the confluence of Tsusena Creek and the Susitna River along Stephan Lake and continuing along the Talkeetna River. WCC (1982) evaluated geomorphic features along the lineament and also completed a paleoseismic trench excavation across a prominent scarp (at location S1 on Figure 4-7) and concluded that the scarp is not related to faulting but rather is of glacial origin. Subsequent geologic mapping by Cloutice (1990) and Reger et al. (1990) directly contradicts Turner and Smith's (1974) geologic mapping basis for fault juxtaposition along the postulated Susitna fault. Reger et al. (1990) do not depict the Susitna feature as a photo-geologic lineament and the map shows no direct evidence to support faulting or offset of late Pleistocene glacial till deposits or kame-esker deposits (Reger map units Qd3 and Qk, respectively).

This study completed a helicopter over flight of the Susitna feature in 2014, as well as ground observations at and near the former paleoseismic trench site (Figures 4-7 and 4-8). The former 1980s trench site was recognized by a line of green grass oriented orthogonal to the slope break. At the trench site, the topographic scarp is about 13 to 16 feet tall (~4 to 5 m). A number of scarps of similar morphology are present along the same general trend, as well as distributed at slightly higher and lower elevations suggesting it is not a unique or anomalous feature on the landscape. It is noted that the WCC (1982) S-1 trench site is located slightly west of the trace of the Susitna feature because of an absence of topographic scarps along the Turner and Smith (1974) map trace.

This study also walked the crest of a glacial moraine that traverses the postulated Susitna feature, located approximately 1.75 miles (~2.8 km) to the north of the S-1 trench site, to better observe the geomorphology of the landforms (Figure 4-8; photo C). The Quaternary moraine deposit, generally late Wisconsin age (Reger et al. 1990), shows an absence of visually-detectable offsets along the intersection of the map trace of the Susitna feature providing positive evidence that the moraine has not been faulted.

Because of the number and distribution of similar topographic scarps in the vicinity, their alignment in the valley-parallel direction, and that the relatively recent geologic mapping that does not support stratigraphic evidence of faulting, this study concludes that the scarps near the former WCC (1982) trench site were formed by erosion or slope processes, and are not from a tectonic origin. Moreover, based on this study's lineament mapping and analysis, coupled with 2014 field investigations, and in light of previous investigative findings, the data do not support evidence for the existence of a Susitna fault, and the Susitna fault feature is discarded as a tectonic lineament or fault-related feature in the vicinity of the planned Watana Dam site.

4.4 Watana Lineament

A feature known as the "Watana lineament" was proposed first by Gedney and Shapiro (1975) on the basis of interpretation of 1:1,000,000-scale Landsat and 1:250,000-scale and Side-Looking Airborne Radar imagery. At those scales, the feature corresponds to as a series of east-west trending, relatively linear segments of the Susitna River. 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. Furthermore, the Watana feature is not recognized in geologic mapping by Lahr and Kachadoorian (1975), Csejtey et al. (1978), Kachadoorian and Moore (1979), Williams and Galloway (1985), or Wilson et al. (1998).

This current study found an absence of geomorphologic expression (neo-tectonic or other) along the proposed Watana lineament, consistent with conclusions of WCC (1980). This study maps a number of lineaments both on the north and south sides of the Susitna River, however, these lineaments and their orientations are attributed glacial ice flow or erosion and do not align with the proposed Watana lineament. Several lineaments that were mapped as sub-parallel to the Susitna River were inspected during low-altitude reconnaissance and judged to be from caribou tracks at the heads of steep gullies. Direct or indirect geologic evidence of a crustal structure (i.e., fault) along this postulated lineament is absent. During the WCC (1980) seismic investigation, "virtually no evidence of a major through-going lineament was observed." Additionally, WCC (1980) found "no morphologic expression of the lineament was observed on the landscape approximately 10 km (6 mi) upstream of the proposed site", based on the Gedney and Shapiro (1975) map. The presence of the Watana lineament beneath the Susitna River appears to be further excluded based on the interpretation of drilling of 2 angled borings beneath the Susitna River from opposing banks in 2014 (MWH 2015a).

5. DAM SITE AREA FAULT RUPTURE INVESTIGATIONS

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 based on the seismotectonic conditions observed in the Talkeetna Block because the source dimensions of these structures requires features having significant persistence 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.

5.1 Sub-regional Map 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 in the dam site area. 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 linear continuity for the Talkeetna fault south of the Susitna River (Twelker et al. 2014).

Existing regional geologic mapping that depicts both the dam site and the general 5 to 10 mile vicinity 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 leads to several areas of general disagreement between 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 in this earlier work. Previous dam site-specific geologic mapping was, by definition, highly focused and of limited aerial extent. The authors of this report believe that, based on our field mapping work to date, the Acres (1982b) map generally best reflects both the dam site geology and the 5 to 10 mile vicinity in a consistent and reasonably accurate framework that is used as a base to display additional outcrop-based geologic observations. However, the Acres map, like the maps of Csejtey et al. (1978) and Wilson et al. (2009), does not include several large and prominent outcrops in this area. Thus, for the immediate dam site vicinity, a number of details remain relatively poorly understood, such as the ages and timing of plutonism, intruding dikes, and/or volcanic flows. This undeveloped framework is a missing element for the assessment of potential cross-cutting relationships, and the identification of the youngest set of features at the site.

5.1.1 Mapping Approach

Field investigations by this study 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 were 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). These data are compiled and presented on Figure 5-1 (A and B) using the Acres (1982b) map as a base. The following describes the measurements and patterns of ductile deformation observed in the study area.

Geologic observations by this study, marked with red dots or strike and dip symbols, are shown on Figure 5-1A and 5-1B in order to add detail, and to identify prominent outcrops that seem to be un-recognized in previous mapping. It is not intended to provide a new and comprehensively revised geologic map, nor is that within the scope of the present study. Rather, the intent is to indicate confirmation or disagreement with existing mapping, and to provide a level of transparency as to where outcrop are present or absent, and from which locations outcrop-based interpretations are possible.

The Acres (1982b) base originally was presented at a scale of 1 inch equal to 1 mile (1:63,360). Because of its vintage, there are apparent registration inaccuracies and map artifacts. We have elected to allow the geologic boundaries and units in the map remain unadjusted, preserving the original mapping scheme and honoring the original map scale. For example, the sedimentary rocks exposed along the Susitna River are generally accepted as part of the Cretaceous sequence of the Kahiltna formation (i.e., Kalbas et al. 2007). These rocks are shown on Acres (1982b) as map unit Kag: Cretaceous argillite; on Wilson's (2009) map these same rocks are shown as map unit Kjf: Jurassic-Cretaceous flysch. The annotations on Figures 5-1A and 5-1B maintain Acres (1982b) classification scheme for clarity purposes to avoid potential confusion with other abbreviations. The annotations are based on field observations either directly on the ground or, at times, from aerial hover when physically accessing the outcrop was not feasible. The strike and dip data are all collected from outcrop locations, and the red dot is omitted from the map figure for clarity. A small number of observation points were made from the air. Long sections of the south side of the Susitna River have limited to no outcrop or exposures because of vegetation and regolith cover. Adequate exposures on the south side of the Susitna River generally are located at the confluence of tributary creeks, and seemingly erosion-resistant Cretaceous rocks. However, the field traverses along the Susitna River and Watana Creek provided somewhat limited structural insight because they capture only a one-dimensional traverse characterization of a three-dimensional volume.

The following sections describe evidence of folding and faulting in Mesozoic (i.e., Triassic) rocks and Cenozoic (i.e., Cretaceous and Tertiary) rocks based on the sub-regional transects along the Susitna River and Watana Creek. Orientation data are reported in strike, dip format using azimuth and degree units and the right-hand rule convention. Dip directions may be included in this text for specificity. Fault locations are represented as blue strike and dip symbols on Figures 5-1A and 5-1B.

5.1.2 Susitna River Transect Results

Bedding attitudes of Cretaceous rocks were collected from outcrops chiefly exposed between Deadman Creek and the unnamed tributary directly upstream (Figures 5-1A and 5-1B). A lesser number of attitudes were collected near the downstream vicinity of the dam site, and outcrops exposed on the uplands. Where strike and dip are not shown, the rocks either are crystalline, or the Cretaceous outcrops were covered or inaccessible because of river water levels.

Cretaceous bedding dips relatively gently (e.g., 14 degrees) near Watana Creek, and steepen to the west such that near Deadman Creek the bedding is 60 to 75 degrees inclined down to the northwest. Thus, bedding is most steeply tilted directly adjacent to the eastern extent of the magmatic intrusions (Figures 5-1A). Bedding attitudes dip overall to the northwest with modest to gentle folding. The attitudes demonstrate northwestward tilting with a component of lateral (east-west) oriented compression that produced asymmetric anticline-syncline pair whose hinge lines are oriented northeast.

Downstream of the dam site, the Cretaceous rocks are again present and have bedding that dips principally to the west and northwest, up to 26 degrees. The data in this area include those from FCL (this study), as well as measurements compiled from WCC (1982) and Acres (1982b). There is good agreement with the relative strikes and dips, indicating repeatability of attitude measurements, with the exception of the FCL–measured 11 degree dip to the southwest. This appears spurious given the other measurements in the vicinity, and may be rejected. West of the mouth of Tsusena Creek, measurements in the Cretaceous rocks exposed in an unnamed gully reflect bedding that dips south (FCL, this study) or southwest (Acres, 1982b). Given the sparseness of orientation data in the area, it is difficult to ascribe a structural reason for this apparent change in bedding attitude. However, taken at face value, the strike and dip data may infer the presence of a synclinal axis oriented in the northeast direction, consistent with observations upstream.

The upper reservoir area lies mainly in Wrangellia terrain rocks mapped as Triassic basaltic metavolcanic rocks by Csejtey et al. (1978), Triassic basaltic metavolcanic rocks and slate by Acres (1982b), and Triassic Nikolai greenstone (Wilson, 2009). The Triassic rocks, by their age and distance of travel from origin to docking with North America, have a longer and more complex tectonic history. An exposure of Triassic rocks near the east-side mouth of Watana Creek (map unit TRvs, Figure 5-1B) shows a near vertical, striking 030 and dipping 79 degrees SE (Figure 5-2). Narrower shear features in the fault zone have strikes ranging from 030 to 038, with near vertical dips. The likely sense of motion was strike slip, based on the vertical attitude of the fault. Magnitudes of offset could not be determined because piercing points were not identified. Slightly upstream, a low angle shear was found striking 231 to 242, and dipping 48 to 52 NW. Downstream from the mouth of Watana Creek along the south bank of the Susitna River, a shear was found in an outcrop of Triassic rocks exposed by slope erosion (Figure 5-1, Figure 5-3). Two orientations measured on the shear plane are 140, 45 SW and 130, 53 SW. No other expression of this feature was found in the field or in the LiDAR data.

Apparent Tertiary units were observed on the south bank of the Susitna River that seem to be the downstream extent of exposed Tertiary (Figure 5-1). These rocks are substantially different from the Tertiary deposits observed in Watana Creek, and seem to consist of a type of volcaniclastic rock. Visual observations suggest that it might be a lithic ash-flow tuff with matrix supported rounded granules, although the precise volcanic classification has not been determined. A sample of the rock was collected for potential absolute dating. A shear was uncovered in these Tertiary volcanic rocks during the transect having 140^{o}, 45 SW orientation (Figure 5-4). Kinematic indicators were sought but not observed in the exposure, and as a consequence, relative sense of movement is not known.

Two minor faults were identified in the Cretaceous rocks along the north bank of the Susitna River at approximately 3.5 mi (5.6 km) upstream of Deadman Creek (Figure 5-1, Figure 5-5). The two faults (referred to as S1 and S2 for discussion) were separated laterally by a distance of about 50 m (~165 ft), with S1 being the downstream fault exposure. The faults have roughly northwest-southeast strike and southwest dip. The measured strike and dip of the fault plane are: 123, 42 S (S1) and 120, 32 S (S2). Striations on the fault plane were clear, and at S1 is a trend and plunge of 315, 10; at S2 trend and plunge measurements were 315, 04, and 310, 00. The striations indicate horizontal (i.e., strike slip) movement along both faults, which is somewhat unexpected given the moderate dip of the fault planes. Observations of offset dipping beds at the faults provides a left lateral sense of motion for both faults, as beds in the hanging wall are down relative to the beds in the footwall. Bed separation measured on the fault plane was 10 cm (~4 in) on fault S1 and also 10 cm (~4 in) on fault S2. Net slip estimated based a dipping bed offset by the fault indicates less than 1 m of net slip; hence these are considered minor faults.

5.1.3 Watana Creek Transect Results

The Watana Creek sub-regional transect is described from upstream to downstream (north to south), and characterizes folding and faulting of semi-consolidated to lithified Tertiary strata. Old faults observed in Mesozoic (i.e., Triassic) rock in limited outcrops also are described.

Bedding orientations in Watana Creek show two general orientations, with the change between the two located at a sharp bend in Watana Creek at approximately 6.5 mi (~10.5 km) upstream from the confluence with the Susitna River, where the creek flows around a prominent ridge extending into the valley bottom. Upstream of the bend, three measurements show generally east and southeast dips of 10 degrees or less. Downstream from the bend, the bedding dips are mostly to the north and northwest (Figure 5-1B).

Downstream from the bend, three domains of bedding attitude are apparent along Watana Creek. These are: (1) those north of the bend; (2) bedding attitudes southwest of the bend and upstream from confluence of Watana Creek and Delusion Creek; and, (3) bedding attitudes downstream of the confluence of Watana Creek and Delusion Creek. Two measurements near the mouth of Delusion Creek, one collected by WCC (1982) and one collected by this study, do not make reasonable sense with respect to the laterally adjacent attitudes, considering the field observations. That is, the data would require very tight folding over short distances or faulting and reversal of dip direction – a condition that was not observed in the field. We interpret these two data points as outliers, and disregard them from the analysis. The structural inflection between domain 1 and domain 2 appears reasonable because the 2 degree northwest dip directly south of the bend supports a general flattening of bedding.

Domain 1 contrasts 2 and 3 with bedding that dips in the easterly direction, however the dips are relatively flat (3 to 10 degrees) making it difficult to confidently resolve the strike direction. Within domain 1, Tertiary bedding attitudes appear to form a gentle anticline with a hinge line trending 065, and plunging 09 degrees down from vertical. Domain 2 bedding has a mean pole-to-plane line with a trend and plunge of 142, 80; that is, sub- northeast-southwest striking beds with a 10 degree dip to the northwest. Within domain 2, the pattern of flexural deformation is complex and obvious fold limbs are not easily recognized. Domain 3 has bedding with a mean pole-to-plane vector that has a trend and plunge of 178, 67, respectively; essentially an east-west bedding strike with a 23 degree dip to the north. The 215, 37 NW measurement on Tertiary strata along the Susitna River coupled with the 269, 19 N measurement on Watana Creek may represent an anticlinal hinge line trending and plunging north-northeast (Figure 5-1B).

The orientation of the Tertiary bedding in Watana Creek broadly indicates tilting to the north-northwest. WCC (1982) interpreted the bedding attitudes as an expression of northwest plunging anticlines and synclines; that is, northeast-southwest oriented compression with a component of tilting to the northwest. While it seems clear that the strata have been tilted to the north-northwest – similar to attitudes collected in Cretaceous rocks outcropping along the banks of the Susitna River – the development of clear fold limbs within the Tertiary sediment along Watana Creek is less obvious.

Minor faulting of Tertiary deposits was observed in Watana Creek outcrop at approximately 1.5 mi (~2.4 km) and 6.3 mi (~10 km) upstream from the confluence with the Susitna River (Figure 5-1B). At the outcrop 6.3 mi (~10 km) upstream from the confluence, two faults were documented that clearly off set stratigraphic markers exposed in the outcrop (Figure 5-6). The first fault, 065, 40 SE, appeared to extend across the entire outcrop, had about 1 cm (~0.4 in) of clay gouge thickness, and produced approximately 40 cm (~16 in) of apparent vertical separation. The second fault, 221, 27 NW, appeared to terminate against the first suggesting a subordinate structural feature that produced approximately 15 cm (~6 in) of apparent vertical separation. Because the bedding attitudes were difficult to measure due to the unstable face of the weakly indurated material, net slip along the fault plane is not estimated. The relative offset along beds separated by the first fault implies reverse (thrust) displacement (i.e., left-side up), however, the same relative offset also could be produced by lateral (strike slip) motion along a fault intersecting dipping bed. The dip of the fault plane also would suggest a dip slip, rather than strike slip motion; oblique motion also is completely plausible.

The second outcrop where faulting within the Tertiary sequence was documented is approximately 1.5 mi (~2.4 km) upstream of the mouth of Watana Creek (Figure 5-1B, Figure 5-7, Figure 5-8). The cobble-rich Tertiary outcrop is distinctly different from the upstream strata in that it appears to have been deposited in a relatively higher-energy environment capable of transporting large, rounded, cobbles; perhaps laid by a debris-flow process. The outcrop generally shows a relative dip to the north. A fault zone with clay gouge was observed at the lower part of the outcrop near the waterline of Watana Creek. The fault zone is about 15 to 20 cm (~6 to 8 in) in width and has both blue and greenish clay gouge. At the outcrop, apparent relative movement shows right-side up along the fault; however, kinematic indicators on the fault plane (mullions) indicate a left-lateral oblique motion. Suitable surfaces to measure fault plane orientation were not present, and the estimated strike of the fault was 245 to 260, and dipping 65 to the north.

A fault exposed in Triassic rock was observed at the lower reach of Watana Creek proximal to a fault in Tertiary cobbles (Figure 5-1B, Figure 5-7, Figure 5-9). The narrow fault appears vertical with a visually estimated northeast (045) strike. The outcrop could not be reached due to water depth. The likely sense of motion is strike slip, based on the vertical attitude of the fault.

5.2 Dam Foundation Geologic Features

Based on recent site mapping (Figure 5-10) and re-interpretation of previous mapping (Acres, 1982b), 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 in MWH (2015a) and summarized below, were evaluated for their significance as potential fault rupture hazards.

5.2.1 Geologic Feature GF4

This feature consists of GF4A and GF4B along the right abutment underlying part of the foundation footprint and intersecting related appurtenant structures. Geologic mapping and drilling in 2012 to 2014 have helped refine the interpretation of GF4 on the north bank (MWH 2015a) compared to the mapping from the 1980s. The mapping performed in 2014 (Figure 5-10) indicates that the continuity and persistence of GF4A and GF4B (named by Acres 1982b) cannot be reliably traced from the south bank to the north bank (MWH 2015a). GF4B is described as multiple discrete fracture zones, or branches, along the right abutment that are orientated in the northwest-southeast direction. A north-south trending fracture zone from this feature is shown to extend from the south bank across the Susitna River and then along the right bank. The north-south feature cross-cuts GF5 where they are shown to intersect in the river (Figure 5-10). The fracture zones (which may contain minor shear zones) are correlated to several prominent gullies immediately upstream of the dam right abutment that are as much as 40 to 50 ft. wide. Although the gullies appear wide at the surface, mapping and drilling suggests that the fracture zones are narrower. While fracture zones are not readily observed at the ground surface, several fracture zones and broken core are observed in the rock core from DH12-3, which is believed to cross several fractures zones comprising GF4B on the north abutment. Additional information describing the rock core conditions and observations is found in MWH (2015a). The azimuth of the primary northwest-trending branches of GF4B is approximately 315˚ (313 to 318) and is consistent with the orientation of primary jointing (Joint Set 1) that ranges between 270^{o} and

330° azimuth with joint spacing of 4-inches to 4-feet (MWH 2015a). The north-south trending fracture zone orientation is variable along map trace, ranging from 343° to 353°; consistent with Joint Set 3 that ranges 340° to 020° in azimuth and averages 350° (MWH 2015a). The subsidiary fractures that branch off from the north-south feature on the right abutment are 330° azimuth and qualify as Joint Set 1 but approaches the azimuth of Joint Set 3. Each of the features from GF4A and GF4B appear to be steeply dipping to vertical.

5.2.2 Geologic Feature GF5

Geologic feature 5 is located downstream of GF4. GF5 consists of multiple fracture zones with some minor shear zones that underlie the dam footprint on the lower right abutment just downstream of GF4B. While depicted as about 2,250 feet in length and extending across the Susitna River to the south bank (Figure 5-10), GF5 projects away from the dam footprint on the left abutment. The GF5 trends in the northwest-southeast (310° to 320°) orientation and is consistent with the orientation of Joint Set 1. The structures are assumed to be steeply dipping, and are anticipated to be encountered in the dam and other appurtenant structures of the right abutment. This feature is depicted as approximately 435 feet long with an approximate strike of 305 degrees where is it intersects the dam foundation footprint (Figure 5-10). 2012 boring DH 12-4 indicates a 4.2 ft zone of residual soil and moderately to highly weathered rock (altered diorite) that includes 1.1 feet of soft, moist, light gray, silty clay at 74.2 to 75.3 feet depth (MWH 2015b); downhole logging indicates northwest-southeast trend (303°) with a 86° to the southwest dip (MWH 2015b); still consistent with Joint Set 1 and also suggesting some correlation between features observed in the subsurface rock core with the mapping of geologic features on the dam site geology map.

5.2.3 Other Features in the Dam Foundation

Two features are mapped as also intersecting or partially intersecting the dam foundation footprint; both are located downstream of GF5. The first unnumbered feature downstream from GF5 is a shear exposed in a narrow gully on the north bank approximately 320 ft. downstream of GF5 (Figure 5-10). This feature is shown as only partially intersecting the dam foundation; however it is depicted as extending along both the right and left abutments and, by extrapolation, projects through the footprint. During field mapping, a shear zone was identified on the north bank oriented approximately 290° and dipping about 70° to the southwest (MWH 2015a). The shear zone is approximately 9-inches wide and contains brecciated diorite and a 2-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 rock that is 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 (MWH 2015a). The azimuths of the map trace of this feature and field measurements are consistent with Joint Set 1, that is, a range of 270 to 300^{o}, with an average azimuth of 300^{o}. Inclined drill hole DH14-12 was advanced through this feature at a sub-perpendicular orientation in late September 2014. The rock logs document a shear feature from 75.2 to 85.2 ft depth in the hole, with 1-inch thick gouge at 77.3 ft. Review of the rock core photographs (MWH 2015b) reveals an apparent clayey material present at about 76.5 to 77.5 ft depths; the core directly above and below this zone is broken and it appears that a 10-ft thick shear zone over-represents the thickness of the probable shear feature. Estimates using trigonometry suggest that the intersection of the inclined drill hole and the unnamed shear feature mapped at the surface would be no greater than about 82 feet depth, assuming a vertical plane for the shear feature as mapped (Figure 5-10). It is permissible, but not conclusive, that the shear recorded in rock core log DH14-12 correlates with the feature documented by the surface geologic mapping. Drill hole data for the corresponding map trace feature on the south bank of the river does not exist.

The second unnumbered feature is located about 550 feet downstream from GF5 along the north abutment near the river shoreline. This feature is mapped as approximately 3,300-feet in length, with an approximate strike of 310 degrees. The orientation of this feature is consistent with the azimuth range of joint set (JS) 1. Locally, near the downstream footprint toe along the north bank of the Susitna River, the feature is depicted as less than 10-ft wide shear zone on the geologic map (Figure 5-10). Along the south abutment, field observations (MWH 2015a) also indicate this feature is characterized as a joint, consistent with the map depiction in this location as a fracture zone. Although outcrop evidence for this feature to be considered a major shear zone is lacking, it is depicted (relative to the other features) as intersecting a substantive part of the foundation footprint. Because of the feature's map trace extent, this feature is treated as a potential plane of weakness for the fault rupture evaluations.

5.2.4 Geologic Feature GF1

Early site investigations identified a zone of fractured and sheared rock, with a prominent exposure in the cliffs along the north side of the Susitna River about 0.5 mi upstream of, but not traversing, the dam site (USACE 1979; Acres 1982a). The structure is referred to as GF1 in Acres (1982b) and Harza-Ebasco (1984). This feature, about 550 feet in outcrop width, strikes northwest-southeast (approximately 315^{o}) and dips 70 to 75 degrees to the northeast, and appears also to be expressed as a shear structure in Tsusena Creek (WCC 1982).

The geomorphology of the GF1 is clearly expressed along the steep north bank of the Susitna River, and consists of near-vertically oriented dikes of diorite that are separated by weaker zones that have been deeply eroded. As observed in the field (MWH, 2015a), the weaker zones have contributed to the erosion of steep gullies which are separated by intact rock ridges. In addition, the GF1 also exhibits lateral rock-type changes between diorite and andesite porphyry; some gullies appear to be located at the apparent contact zone between the two rock types. One gully inspected in the field revealed a narrow, fracture that was in-filled with loose river alluvium. The fracture orientation was 327^{o}, with a 77^{o} northeast dip. The upstream part of GF1 also coincides with a steep, narrow gulley that is a 10 ft. wide shear/alteration zone that forms the contact between the diorite and a large mafic dike. Along the south bank of the Susitna River, GF1 has no such geomorphic expression of vertical bedrock ridges and eroded gullies. The shear feature exposed in bedrock along Tsusena Creek along the northwest projection of GF1 also completely lacks a geomorphic expression of vertical bedrock ridges and eroded gullies. Geomorphic expression of GF1 is similarly absent along the projection of GF1 beneath the Quaternary deposits which mantle the uplands between the Susitna River and Tsusena Creek, as well as to the southeast of the Susitna River.

GF1 was judged to be a short (~2 mile long) fault without “recent” displacement by WCC (1982). A subsequent geotechnical evaluation of the feature by Harza-Ebasco (1984) included detailed geologic mapping and geotechnical drilling and concluded that the northwest striking feature is not a “through-going structure,” but rather a zone of closely spaced fractures, some with slickensides and clay infilling suggestive of “minor shearing,” but with no evidence of “major faulting.” The southeastern projection of GF1 would extend beneath the area of the Fog Lakes. Detailed lineament mapping on LiDAR in this area demonstrates an absence of geomorphic features in the northwest-southeast orientation; perpendicular to regional ice flow direction. The dominant trend of lineaments is in the northeast-southwest directions indicating positive evidence of non-displacement by a northwest-southeast trending direction.

5.2.5 Other Relevant Observations

Apparent discrete shear zones are on the south (left) side of the Susitna River about 550 feet upstream of the dam footprint (Figure 5-10). The shear zones are described with widths of “several inches” and consisting of “crushed rock-breccia and clay gouge” that strike northwest and dip moderate to steeply southwest (MWH 2015a). However, at least one outcrop location along the south shoreline of the Susitna River, a felsic dike is exposed that cross-cuts the shears in an uninterrupted fashion without offset. This observation suggests positive evidence of no movement along the northwest oriented shear post-emplacement of the dike, however additional instances of this type of evidence need to be identified to develop an unequivocal position.

5.2.6 Comparison to Previous Fault Investigations

Previous fault investigations undertaken include studies in the 1970's by the U.S. Army Corps of Engineers (USACE), and studies in the 1980's by Woodward Clyde Consultants (1980, 1982) and Acres (1982b). A summary of the results of the previous faults studies is presented in the paragraphs below as a comparison to this current study.

Regional lineament mapping of the Talkeetna Mountains area was first conducted by Gedney (1975) under the auspices of the Army Corps of Engineers (Alaska District) in coordination with the National Aeronautics and Space Administration (NASA) to support geologic hazard studies for then-planned hydroelectric facilities. The regional mapping was conducted on 1:1,000,000-scale Landsat images: photographic images taken from space-based satellites. Initiated in 1972 by NASA, the Landsat program (formerly called Earth Resources Technology Satellite [ERTS]) represented cutting-edge technology for desktop interpretation of large areas of unexplored, remote, wilderness. Criteria for drawing lineaments based on Landsat photo-images were loosely defined (Gedney 1975), but generally included length, sharpness of the feature, and investigator's judgment. The Landsat mapping was followed by localized mapping of less-pronounced lineaments using 1:250,000-scale side-looking airborne radar images (SLAR). The work identified dominant northeast-southwest striking structural grain in the Talkeetna Mountains-Alaska Range complex, with secondary shorter and abruptly truncated lineaments in the northwest orientation, and postulated the existence of a northeast striking Susitna feature. Faults were not identified at the dam site by Gedney (1976), although it was recognized that the geological mapping near the dam site was "very incomplete".

The USACE performed geologic mapping in the dam site area concurrently with subsurface drilling during spring and early summer of 1978, in situ testing, and geophysical surveys (USACE 1979). The mapping at the dam site revealed vertical to near vertical shear features and fractures that generally were consistent with their findings from exploratory drilling. The investigations found that the two most significant features at the dam site were upstream and downstream of the site footprint (i.e., GF1 and GF7). Other shorter features (joints, shears) were mapped showing northwest strikes and vertical dips, but none of the features were mapped as extending or continuing across the Susitna River. USACE (1979) indicated that fracture patterns including both joints and local shears were mapped in the vicinity of the dam site. The reported dominant orientation of fractures is northwest, but subordinate trends were noted. Major joints sets were reported as N50^{o}W (310 azimuth) and minor joint sets are N30^{o}E (060 azimuth). Fractures zones were reported as tight or re-cemented with calcite or silica. Narrow shear zones were reported to have some thin clay gouge coatings with slickensides. USACE (1979) reported that no major shear zones were encountered in a borehole drilled beneath and across the river. The USACE recognize that the geologic features at the dam site may have been produced by cooling of intrusional magma, unloading (surface erosion, melting ice), or regional tectonic deformation, however the USACE report (1979, Section D) is silent as to the significance of the shorter features mapped in the dam site footprint (i.e. specific origin, activity).

At the request of the USACE, the U.S. Geological Survey conducted a reconnaissance of the geology of the proposed Devil's Canyon and Watana dam site areas in mid to late summer of 1978 (at the time, two impoundments were envisioned). The report (Kachadoorian and Moore 1979) "did not uncover any evidence for recent or active faulting along any of the known or inferred faults", but acknowledged that the reconnaissance geologic observations were curtailed by limited duration and adverse weather. Features assessed by the Kachadoorian and Moore (1979) work include, among others, the Susitna feature, the Talkeetna fault, and faults expressed in Jurassic/Triassic rocks near Watana Creek. Faults were not identified at the dam site during the course of the Kachadoorian and Moore (1979) investigation, although the authors considered their report preliminary and recommended additional (unspecified) geologic studies.

Woodward Clyde Consultants completed faulting investigations for the proposed Watana site area and analyzed the landscape for evidence of potential faults and "recent" faulting by completing lineament mapping within a 100 km (~62 mi) radius around the proposed Devils Canyon and Watana sites (WCC 1980, 1982). These efforts also consisted of detailed field investigations, including paleoseismic trenching, on a selected subset of lineaments. In the WCC studies, the term "recent" was applied to rupture of the ground surface within the past 100,000 years (100 ka). From the WCC evaluation, 13 "significant" features closer to the site(s) were selected for additional study on the basis of their potential effect on ground motion and surface rupture considerations (WCC 1980). The 13 features selected for additional study were the subject of detailed field studies in 1981-1982; four features were considered by WCC for the Watana site (Susitna feature, Watana lineament, Talkeetna fault, and geologic feature 1). None of the significant features assessed in the WCC (1980, 1982) studies were judged to have "recent" displacement; therefore, the features were considered not to be potential seismic sources that could cause surface rupture through the site (WCC 1982).

Acres (1982b) completed detailed investigations at the dam site, including geologic mapping, exploratory drilling and in situ testing, geophysical surveys, air photo interpretation, and analysis to evaluate the site foundation as well as potential quarry and borrow areas; the details of those studies are summarized in geotechnical reports. Acres (1982b) completed site mapping that identified seven northwest-trending geologic features in the immediate dam site vicinity; the two most pronounced were geologic feature 1 and 7, upstream and downstream of the dam site. Small, localized fractured, sheared, and altered zones were mapped, and "no evidence of recent faulting was found" (Acres 1982b). Further, Acres (1982b) contended that the localized sheared, fractured, and altered zones were likely to be encountered during excavations, however Acres considered that those features are of limited extent. It was further concluded that although localized zones of sheared and fractured rock were encountered in borings, no evidence of major faulting was found either in the riverbed or within the dam site area.

Collectively and individually, none of the previous studies revealed evidence for a major structural fault within the proposed dam foundation.

5.3 Summary of Dam Foundation Fault Rupture Evaluation

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 sub-regional evidence of Quaternary faulting, or lack thereof;
- 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.

5.3.1 Regional Evidence

The evaluation of potential crustal seismic sources has not identified any specific features with evidence of late Quaternary faulting within at least 40 km 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 Quaternary faulting (Fugro, 2013; this study). The area along the Susitna River, and extending at least 3 mi (~5 km) 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 provided 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 15,000 years, the time since deglaciation of much of the area (Section 3.6.1), there is positive evidence against major surface fault rupture within the dam site region (>25 mi (~40) km radius).

Over longer time frames, 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. Based on crustal seismic features elsewhere in similar tectonic settings, recurrent large earthquakes, 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, and blind faults tend to occur near these features of uplift. 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 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). As an example, the Susitna Glacier fault, which was the "blind" initiating fault plane of the 2002 Denali earthquake, ruptured the ground surface near the base of south-facing mountains that have about 1,500 feet of relief, illustrating the premise that blind faults produce noticeable long-term topographic uplift near the "buried" fault tip even if the ground expression of surface rupture is not present. No such high-relief topography is present at the dam site to postulate the presence of a blind fault beneath 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 subhorizontal 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. 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 3-7). 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 (Figure 2-5A; Figure 4-5).

The contemporary stress regime of the Talkeetna Block is illustrated by the recent seismicity recorded by the Watana Seismic Network (Figure 5-11, panel A). These earthquakes illustrate that, the primary modes of tectonic deformation appear to involve right-lateral strike slip structures with east-northeast strikes (subparallel to the closest portion of the Denali and Castle Mountain faults), and with dip slip or compressional shortening along structures with NE strikes or elongations (roughly perpendicular to the regional direction of crustal shortening). The average P-axis calculated from 15 focal mechanisms shown on Figure 4-1A is oriented NW-SE (Figure 5-11, panel B), similar to maximum shortening direction shown by Cole et al. (2007) for the Denali fault north of Watana dam site (Figure 3-7), Figure 5-11 (panel C) compares orientations of fault sets that might result if the simple shear model of Cole et al. (2007) is rotated to differing indicators of the regional compression direction. As shown in Figure 5-11 (panel D), the primary geologic structural features at the Watana dam site, generally strike northwest-southeast, parallel to the direction of maximum compression.

Structures with northwest-southeast orientations, generally favored as thrust faults or folds by the simple shear model, would be oriented roughly parallel to the overall regional 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 high-angle faults, or potentially lessor amounts of extensional deformation along structures with northwest strikes. Because regional evidence suggests the dam site region is dominated by compression (Figure 5-11), 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.

As shown on Figure 5-12 (top panel), the earthquake focal mechanism data can be further evaluated with respect to longitudinal changes in P-axis azimuth for the recent Watana Seismic Network Talkeetna Block earthquakes recorded near the dam site. Figure 5-12 (top panel)shows the average strike of the bounding faults of the Talkeetna Block plotted with the P-axis azimuths from earthquake focal mechanisms, the Cole et al. (2007) maximum compression direction, and GPS derived directions. The best-fit line to the P-azimuth data shows a clear trend of counter-clockwise rotation of the mechanisms within the Talkeetna Block over the roughly 200-km longitudinal interval spanned by these data. Extending the fault plane orientations from the simple shear model of Cole et al. (2007) across the region (dashed lines on Figure 5-12 (top panel)) based on trend of the focal mechanism P-axis data, illustrates the potential influence of strike-slip vs reverse motion on faults oriented parallel to the Denali and Castle Mountains faults within the Talkeetna Block, with increasing tendencies to reverse faulting to the east. The western extent of the 2002 Denali earthquake and the reverse-oblique surface ruptures of the Susitna Glacier fault lie at the east edge of data and models shown in Figure 5-12 (top panel).

Figure 5-12 (bottom panel) illustrates strikes of faults, lineament groups, and dam site geologic features evaluated for this study compare to the simple shear model developed from Figure 5-12 (top panel). The strikes of the western-most features, such as faults near Broad Pass, would appear to be oriented to favor reverse or thrust motion. Features within lineament groups 8, 9, and 17, would favor strike-slip motion on the SS2 plane. The Talkeetna fault would be favored as a contractional structure, presumably with moderate SE or NW dip. However, field observations of faults along this trend near the Susitna River, Watana Creek, and Fog Creek (Section 5.2) suggest that the dominant structures exposed here are high-angle, with indications of strike-slip motion, consistent with movement in the mid-Tertiary, as suggested by (Ridgeway and Trop 2007; Figure 3-6). Geologic features and joint sets at the Watana dam site (JS3, GF1, and JS1) mostly straddle the presumed direction of maximum compression and all high-angle features. Joint set 2 is also high-angle, and strikes nearly perpendicular to the maximum compression direction. Within the simple shear model shown here, faults with these orientations are typically second or third order structures, activated usually near fault step-overs and transfer zones, which are absent in the dam site area based on the existing mapping and transects developed for this study (Section 5.2). Thus, development and activity of the dam site features primarily in association with a stress field influenced by the mid-Tertiary igneous activity in the region is favored.

5.3.2 Sub-Regional 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 exposure near the Watana dam site. These transects demonstrate that the most significant crustal fault structure in the area is the northeast-striking, fault-bounded Tertiary-age basin along Watana Creek. 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 on the order of a few kilometers or more. 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 >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. These data are consistent with existing mapping which shows that the Talkeetna fault does not appear to offset or significantly displace plutonic rocks to the southwest of the Watana dam site (e.g., WCC 1982; Figure 2-5A). 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).

The 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. Field observations and mapping along the Susitna River, several kilometers upstream and downstream of the Watana dam site, 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.

5.3.3 Watana Dam Site

Prior investigations (USACE, 1979; Acres, 1982b; Harza-Ebasco, 1984; MWH, 2015) have concluded that the structural geologic features that might intersect foundation footprints of the proposed Watana dam have chiefly northwest strikes, and are dominantly steeply dipping to vertical.

Recent mapping (MWH, 2015) also shows the orientation of discontinuities and narrow shear features mapped at the site chiefly have northwest strikes and steep, vertical to near-vertical dips. 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. Additionally, recent mapping (MWH, 2015) that the 1980s depiction of dam site conditions likely over-represented the extent and magnitude of these geologic features, and the contemporary studies have not identified physical evidence to support the presence or through-going continuity of many of those features. In addition, many of these features have characteristics consistent with the dominant joint set at the dam site (Joint Set 1; average strike of 300 degrees). Thin or narrow shears or shear zones are documented at various depths in the angled borings drilled in 2012 and 2014, and commonly are associated with mineralogic infill (i.e., calcite) or "healing". Visible shear zones are identified in outcrop near the lateral margins of the igneous pluton (i.e., GF 1 and GF 7) and similar features are absent from the surrounding Kahiltna sequence suggesting the shears may be related to emplacement of the igneous diorite bodies and/or subsequent hydrothermal alteration.

The geologic feature 1 of Acres (1982b) (Figure 5-10) remains the most significant feature identified in the dam site vicinity. This feature is approximately 0.5 miles upstream of the site, and does not intersect the foundation or abutments and thus is not a factor in the surface fault rupture hazard for the dam.

In summary, investigations to date regarding the presence of faults at the dam site indicate:

(1) northwest-oriented joints (270° to 330° strike, 300° average strike, near vertical), fractures, and narrow, apparently discontinuous shears in the dam foundation dominate,

(2) a lack of evidence to support the presence of substantial, or “major”, faults or through-going shears that are depicted in the foundation,

(3) evidence of north-south or east-west orientations is rare to absent, and borings that cross beneath the Susitna River from opposing sides demonstrate an absence of major east-west oriented structures beneath the Susitna River.

(4) GF 1 is the most significant shear zone feature in the dam site area, but there is positive evidence against displacement of the overlying Quaternary deposits. Further, GF 1 does not contribute to the surface fault rupture hazard at the dam site because there are no facilities planned to be located along this feature.

(5) none of these geologic features show evidence of geomorphic expression in the Quaternary deposits that are present in the uplands along the projection of the features mapped at the dam site. This indicates that although minor or narrow shear features may be present in the drilling logs, there is evidence to support the absence of surface displacement along these features in the last 15,000 years (Section 3.6.1).

6. SUMMARY OF FINDINGS

6.1 Lineament Evaluations

The purpose of the lineament mapping and evaluation is to identify potential seismic sources (i.e., crustal faults) that could appreciably contribute to the seismic hazard at the proposed hydroelectric project and affect dam design.

The results of our field investigations did not identify any specific features with evidence of late Quaternary faulting within at least 40 km (~25 mi) of the Watana dam site. For most of this area, the time and detection limits of the imagery and field investigations imply post-glacial time limits of about 12,000 to 15,000 years, and detection of surface offsets of more than about 1 m extending over several kilometers. For the area near Watana dam site where detailed LiDAR data was the basis for this evaluation, potential detection limits of surface fault displacements are much lower (about 0.5 m over several hundred meters).

All lineament groups targeted for field work received a low-altitude aerial observation and ground inspection was completed at selected locations where features of interest were identified. Based on these investigations, the lineament groups are placed into three categories:

- Lineament groups in category I were not advanced for field observations, but where convenient, brief fly-overs were performed to visually confirm their placement in category I, and no further field investigations are suggested. In general, most lineament groups not considered for further evaluation were generally isolated, short features at distances greater than 30 km from the dam site, or other features for which the lineament mapping provided little geologic or geomorphic evidence as potential Quaternary faults (FCL 2013).

- Category II lineaments are judged to be: 1) dominantly erosional in origin, 2) related to rock bedding or jointing, or 3) to a lesser extent, a result of constructional geomorphic processes. This category is subdivided in to categories IIa and IIb. Category IIa lineament groups are those which are not evidently associated with bedrock faults. Category IIb lineament groups that do appear to be associated with bedrock faults (Category IIb). For both categories no further field investigations are suggested.

- Category III includes lineament groups that have justifiable basis for consideration or inclusion as crustal seismic sources in an updated seismic source model. No further field investigation is suggested.

The overall evaluation and grouping of the lineament groups and features are summarized in Table 6-1 below. Table 6-2 presents a summary of lineament data, observations, and evaluations from the detailed discussions in Section 4.0.

Table 6-1. Summary of Lineament Groups and Areas

Category	Category Description	Lineament Groups
I	Lineament groups that were not advanced for field investigation in 2013 based on FCL (2013) desktop evaluations. Most were not rigorously inspected during field activities.	4, 10, 11, 13, 14, 15, 16, 18, 24, 25, North-South Features near Talkeetna River-Susitna River Confluence
IIa	Lineament groups evaluated during 2013-2104 field studies, and judged to be non-tectonic (dominantly erosional, depositional, or jointing/bedding in origin). No further field investigation is recommended for evaluation as potential crustal seismic sources.	1, 2, 3a, 3b, 5, 12a, 17a, 21a, 21b, 22, 23, 26, select Reger et al. (1990) features, Susitna feature, Watana lineament
IIb	Lineament groups evaluated during 2013-2014 field studies, and also judged to be of non-tectonic origin, but which appear to be spatially associated with previously mapped bedrock faults. No evidence of Quaternary faulting was observed, and no field investigation work is recommended for evaluation as potential crustal seismic sources	6, 7, 8, 9, 12b, 17b, 17c, 19, 20, Broad Pass area, Clearwater Mountains area, select Reger et al. (1990) features, Talkeetna fault at T-1 and T-2
III	Lineament groups that have defensible justification based on current field investigations for consideration or inclusion as crustal seismic sources in an updated seismic source model.	27 (Sonona Creek fault), Castle Mountain extension

Category I includes several lineament groups not advanced for further field study based primarily on distance from the site considerations derived from the evaluations in FCL (2012, 2013).

Many of the lineament groups investigated are judged to be dominantly erosional in origin, or to a lesser extent, related to rock bedding or jointing, are not associated with tectonic faults, and are thus assigned to Category IIa (Table 5-1). These include features in lineament groups 1, 2, 3a, 3b, 5, 12a, 17a, 21a, 21b, 22, and 23. Most of the Reger et al. (1990) photolineament features fall in Category IIa as well. A second set of lineament groups do appear to be coincident with previously mapped pre-Quaternary (i.e. bedrock) faults, but are also interpreted as erosional in origin as no evidence was found for offset or deformation of Quaternary deposits or surfaces. These are assigned to Category IIb, and include lineament groups 7, 8, 9, 12b, 17b, 17c, 19, 20, the remaining Reger et al. (1990) features, lineaments in the Broad Pass area, and lineaments in the Clearwater Mountains area.

Category III lineaments have defensible justification for consideration or inclusion as crustal seismic sources in an updated seismic source model, and consist of lineament group 27 (Sonona Creek fault) and lineaments of the Castle Mountain extension. Despite the apparent absence of geologic evidence for late Quaternary faulting in the broader region, updates to the seismic source model (FCL 2012) may consider inclusion of portions of some new sources. Such an updated source model would consider the findings and limitations from this evaluation, seismicity recorded since 2012, and other data, although some seismic sources may be constrained to very low slip rates as defined by this crustal seismic study.

Part of lineament group 27 is shown on previously published maps as offsetting Quaternary moraine landforms (i.e. Sonona Creek fault; Figure A27-3.1) and this relationship could not be confirmed nor refuted during aerial and ground field inspection. However, field investigation showed no justification for laterally extending the fault farther than already mapped. Because the Sonona Creek fault was previously included in the preliminary PSHA as a seismic source (FCL 2012), and did not result in significant contributions to the seismic hazard at the Watana site due to its low slip rate and distance from the site (~ 70 km), there is little value for further field investigation of this lineament group. Based on the new field data, the updated seismic source characterization for the Sonona Creek fault should include an alternative evaluation in which the Sonona Creek fault is considered non-tectonic in order to fully represent the potential uncertainty associated with this fault.

The Castle Mountain extension area includes several lineaments along mapped bedrock structures which appear to constitute a northeastern extension of this known Holocene active fault (Koehler et al. 2012). While Quaternary deposits of appreciable extent and age along these lineaments are lacking, the sharpness of geomorphic expression within the bedrock units was notable. Based on these two observations, it is prudent to consider the lineaments as part of the Holocene-active fault system, and include this within the alternatives considered for an updated crustal seismic source model. Castle Mountain fault provided modest contributions to the total hazard for the Watana site (FCL 2012), and extension of the Castle Mountain system to the northeast would increase the total fault length of this system and result in minor reduction in the closest distance to the Watana site (~100 km in FCL 2012). Based on the results from this study, an updated seismic source characterization might consider alternative seismic source models which include potential northeastern extensions of the Castle Mountain fault.

6.2 Surface Fault Rupture Evaluations

Synthesis of regional geology and seismology, sub regional transects, and site data all indicate that major faults, typical of active crustal seismic sources capable of primary surface rupture associated with major earthquakes in the contemporary tectonic environment, are absent from the

Watana dam site area. The evaluation of potential crustal seismic sources has not identified any specific features with evidence of late Quaternary faulting within at least 40 km of the Watana dam site. This is consistent with the observations that the reservoir area is structurally coherent with lack of pervasive penetrative deformation.

Geomorphic and geologic data similarly suggest that potential “blind” sources, located at shallow crustal depths and capable of producing significant rates of long term vertical deformation, are also absent in the site area.

Given the absence of primary seismogenic structures with appreciable rates of surface deformation in the immediate site area, it is inferred that the potential for secondary faulting on structures at the dam site is also absent or negligible.

Site data, while not yet complete, continues to build the argument for the absence of major faults in the dam foundation footprint. Recent field mapping implies less continuity of foundation structures that have been previously depicted, therefore reducing their potential significance. Such features, regardless of their orientation, would be the most likely candidates for secondary reactivation, even if undisclosed crustal seismic sources are near-by.

Shallow crustal deformation in the nearby region of Watana dam site appears to be characterized by near-horizontal maximum compressive stresses oriented northwest-southeast, based on nearby GPS vectors and earthquake focal mechanisms. Strain ellipse deformation concepts suggest that the likelihood of reactivating northwest-oriented features under existing conditions is low because of their near parallelism with compressive stress. Additional analysis would be needed to evaluate if and how these features might respond to reservoir loading, fully-loaded reservoir conditions, or fluctuating reservoir conditions.

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 25 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.

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. 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 Limitations of Study

Two primary conditions introduced limitations to this evaluation of surface fault rupture hazard at the dam site: (1) absence of long-term tectonic strain gauge(s) at the dam site, and, (2) extensive regolith (talus, colluvium, soil) mantling the valley walls that limits bedrock exposures.

The presence of tectonic strain gauges, in many cases, allows the estimation of magnitudes past deformation (that is, tilting or faulting) that may be used to evaluate (probabilistically) potential future tectonic deformation. Geomorphic surfaces such as fluvial terraces, marine terraces, pediments, or paleoshorelines record long-term tectonic deformation because they tend to be relatively planar and extensive and the age of the feature usually can be constrained. Other geologic features may also serve as strain gauges, such as stratigraphic marker horizons. For example, offset stratigraphy can be analyzed to help understand past faulting, such as cumulative displacement, or frequency of faulting. Thus, strain gauges help evaluate magnitudes of past deformation, and coupled with an understanding of strain gauge age, can help place constraints on long term average slip rates or age of last known fault movement. The dam site footprint is located in chiefly igneous diorite rock, with lesser amounts of volcanic andesite. Because of the rock origin as minerals crystallizing cooling from a melt, the rocks do not have an internal structure or marker horizons in the same way that a sedimentary rock does. Thus, a strain gauge intrinsic to the dam site rocks does not exist to help constrain amounts of past fault displacement, long term rates of faulting, or age of last faulting of the features in the dam site proper. Quaternary deposits overlying the dam site abutments along the projection of the site geologic features provide a late Quaternary strain gauge for about the past ~15,000 years. However, the site conditions are inadequate to evaluate if the features at the dam site have experienced appreciable amounts of pre-latest Quaternary displacement (offset) in the geologic past, and, if so, what constraints might be placed on those displacement magnitudes, and over what time periods might it have occurred.

The second primary limitation is the general lack of useful exposures, particularly on the south side of the Susitna River in the site area that would help the ability to correlate and evaluate the cross-river extent of geologic features previously mapped. Steep slopes coupled with heavy vegetation and extensive regolith development cover much of the terrain, limiting rock exposures as well as physical access. Because the outcrop-based data are only intermittently exposed along the field transects in the dam site area, this evaluation relies primarily on the interpretations and descriptions developed by the site investigation team regarding the potential continuity and scale of geologic features at the dam site. Those findings are supplemented by the FCL field observations made jointly and independently during 2014 site visits. Because of the limitations of outcrop and data extents at feasibility investigation level, it should be recognized that the existing site engineering geology investigations, on which the assessment of site surface rupture hazard is built, may by necessity include potentially conservative assessments regarding the continuity and scale of geologic features such as faults and shears that may be present in the dam foundation. This type of conservatism is needed to ensure adequate structural stability within the framework of dam foundation analyses, but will generally overstate the potential geologic continuity and context as evaluated for purposes of assessing the geologic history of features in the dam foundation. The extent of this limitation on this assessment can only be resolved when the level of investigations at the site, principally through development of much more extensive exposures of rock conditions across the foundation footprint, has been expanded.

Table 6-2. Lineament Data Summarized from Section 4.0

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
1	N	--	51	20	Late Quaternary deposits along the Jack River, of late Wisconsin and post-glacial age intersect the projected trace of the group 1 lineaments near the center of the group 1 ellipse. These late Quaternary deposits show no apparent expression of the lineament. No evidence of fault structure was observed during low-level aerial inspection.	The absence of continuity of the individual lineaments from steep bedrock slopes into areas adjacent areas of lower slopes where Quaternary deposits are present is evidence of non-tectonic origin for these features. The lineaments of group 1 are likely non-tectonic in origin, are judged to be primarily erosional and/or landslide features.	IIa
2	N	--	46	12	Mapped Quaternary surficial sediments, fluvial deposits in several unnamed drainages, a glacial moraine, and an alluvial fan deposit show no apparent deflection or deformation where overlying the projected trace of the lineament group. In all instances, lineaments with clear expression in bedrock lose expression at contacts with Quaternary deposits and landforms.	Based on the irregular apparent throw of the lineaments along strike, lack of western continuity into the Cretaceous Kahiltna flysch, and absence of expression in Quaternary units along the feature, the likelihood of a tectonic origin for the lineaments in group 2 is judged to be low. The limited and ambiguous expression of lineament features outside of the Tertiary volcanic rocks within the Cretaceous flysch, suggests that the observed trend may represent erosion along internal bedrock structure.	IIa
3a	N	--	40	12	The lineaments mapped in Quaternary (post-glacial) deposits along group 3a do not show neotectonic expression or offset. While the group 3a lineaments are mapped across several different geologic units, they appear erosional in origin. The exception to this is the ridge in the Cretaceous Kahiltna flysch in which field observations found a color contrast (Figure A3a.2) that may be structurally-controlled, or may just as equally be stratigraphically controlled.	Lineaments within groups 3a and 3b are not associated with previously mapped faults, are predominantly erosional in origin, and show no evidence of offsetting Quaternary deposits. When considered individually, there is little evidence to support the lineaments as a fault structure. When considered collectively, there is little similarity in their landscape expression across the two groups to support positive interpretation of a linked, through-going crustal structure.	IIa
3b	N	--	27	19	No Quaternary deposits are previously mapped, but ground-based inspection indicate that there are youthful (Holocene) deposits in cirques and drainage valleys, as well as rock glacier deposits. Although these are very young deposits, there is no expression of lineaments in these deposits. The morphology of the lineament is inconsistent along strike, showing north-facing slope breaks, south-facing slope breaks, as well as v-shaped notches.	Lineaments within groups 3a and 3b are not associated with previously mapped faults, are predominantly erosional in origin, and show no evidence of offsetting Quaternary deposits. When considered individually, there is little evidence to support the lineaments as a fault structure. When considered collectively, there is little similarity in their landscape expression across the two groups to support positive interpretation of a linked, through-going crustal structure.	IIa
4	Y	Unnamed fault of Wilson et al. (2009)	23	11	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013)	A limited number of low-altitude fly-overs in 2013 appear to confirm the desktop conclusion that the group 4 features are pre-Quaternary. Rock-type contrasts were observed across the previously mapped NE-trending thrust fault but no prominent tectonic geomorphology to suggest Quaternary activity was observed along strike in post-glacial surficial deposits nor in the bedrock.	I
5	Y	Partial coincidence with an unnamed lineament of Wilson et al. (2009)	40	23	Along its eastern extent, the trend of individual lineament groups is generally parallel to ice-flow direction expressed as fluted and grooved topography in a general east-west orientation. There is no evidence that the ice-scoured surfaces are cross-cut or otherwise offset by the lineaments. Along the eastern extent of the group, the lineaments' morphologic expression as side-hill benches would imply an extensional-type kinematics (i.e., down-to-the-south); along the western extent the morphologic expression varies as both uphill and downhill facing scarps, linear grooves, and drainages that would imply a translational-type kinematics.	While the lineament group does traverse different geologic units and landforms suggesting a continuity of structure, the lineaments show an inconsistent kinematic expression along strike within the same rock unit (Cretaceous turbidites) that tends to not support the presence of a tectonic structure for creating the lineaments. It is judged that the lineaments along group 5 are the result of bedding orientations in the Cretaceous turbidite units and elsewhere from fluvial or glacial erosion, and do not represent a tectonic fault	IIa

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
6	Y	Talkeetna thrust fault of Csejtey et al. (1978); WCC, (1982); and Wilson et al. (2009)	14	17	Previous studies result in a fair degree of disagreement as to the location and character of the (inferred) Talkeetna fault in the area of lineament group 6. The lineaments are expressed as linear drainages or erosional gullies oriented sub-orthogonal to the Talkeetna fault trace(s), and principally are developed in late Quaternary glacial drift (till) and glacio-lacustrine (lake) deposits. Field observations of stratigraphic outcrops along Watana Creek show evidence of minor faulting in Tertiary units, but the Quaternary strata indicated the contact between the overlying lake and underlying till deposits is planar, unbroken, and apparently untilted.	The lineaments mapped within group 6 are judged to be the result of erosion of tributary drainages and fluvial erosion to create terrace risers along the creeks and are not likely tectonically-related. Minor faulting of early- to mid-Tertiary deposits was documented but these appear to be secondary faults, subordinate geologic structures relative to a terrane-bounding fault/suture zone with no evidence of geomorphic expression in LiDAR data or in late Quaternary strata.	IIb
7	Y	Unnamed shear zone of Wilson et al. (2009), a mapped thrust fault (Turner and Smith 1974; Belkman et al. 1975; Kachadoorian and Moore 1979; and Clautice 1990), and a northeast-trending anticline axis Csejtey et al. (1978)	28	17	The lineaments transect young valley floor glacial sediments as well as elevated bedrock ridgelines. There was no field evidence that linear strain markers were deformed or displaced, however the glacial sediments are from rock glacier processes, and few older landforms were observed along this group. The expression of the lineament is inconsistent along strike with an apparent stronger expression where mapped along fluvial drainages, and no expression in WNW-oriented cirque-floors or valleys.	The geomorphic inconsistencies, coupled with the fact that the Quaternary deposits in the valley floors are not disrupted, strongly indicates that erosional process of creek incision and downcutting into surface deposits along the south-flowing drainages are likely responsible for creating the lineaments. Lineaments of group 7 generally coincide with mapped bedrock structures within fault-line-valleys but lineaments in late Quaternary deposits are inconsistently expressed and likely relate to processes of erosion. No evidence of Quaternary deformation was observed.	IIb
8	Y	Coincidence with feature KD5-44 of WCC (1982); Partial coincidence with an unnamed fault of Wilson et al. (2009)	38	26	The lineaments are expressed in ice-scoured bedrock uplands and a thin cover of glacial and colluvial deposits subject to solifluction. Glacial striae north of the Susitna River do not appear consistently deformed or displaced across the trend of the lineament and several small streams that cross the lineaments are not consistently laterally offset or deflected. Aerial inspection did reveal the oxidized mafic dike on the northern canyon wall of the Susitna River that WCC (1982) observed projecting across the observed lineament trend but discovered the same ambiguous and poor exposure conditions described by WCC.	Lineament group 8 does not exhibit relative consistency of geomorphic expression along strike. The apparent structural kinematics (dip-slip) based on mapped contact relations (Wilson et al. 2009) for the middle and southern portion of the group are not consistent with the undeformed contact relations between turbidite rocks of the Cretaceous and Paleocene rocks near the Susitna River, and also the lack of deformation in turbidite rocks north of the river. The evidence supports the origin as a fault-line-scarp (an erosional feature aligned with a mapped bedrock fault).	IIb
9	Y	Coincidence with feature KC5-5 of WCC (1982); Partial coincidence with an unnamed lineament and an unnamed fault of Wilson et al. (2009)	31	24	The mapped lineaments transect mapped bedrock units, but are not expressed in the limited extent of Quaternary surficial deposits present along the group. No lineaments were observed in early Holocene fluvial deposits within a broad depression or across the extent of a post-glacial landslide. Although a rock-type contrast does exist across portions of the lineament, the current mapping compilation may be too simplified and more irregularity of bedrock unit contacts likely exists. The magnitude of expression and apparent sense of deformation observed in the field is inconsistent along lineament group trend.	Based on the mapped geologic contacts along the southern portion of the group, the apparent sense of offset is right-lateral with possible unknown oblique component. This is kinematically inconsistent with the mapping north of the Susitna River because the mapped the contact there between Cretaceous Kahiltna and Paleocene granitics is apparently undeformed and undisplaced where the lineament group projects across the contact. No evidence of expression in Quaternary units, landforms, or strain markers was observed. Lineament group 9 is interpreted to represent a fault-line scarp and not a Quaternary tectonic feature.	IIb
10	N	--	70	27	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) that the lineament group is over 70 km (~44 miles) from the proposed dam site and less than 40 km (~25 miles) long, and likely would not appreciably contribute to the hazard calculations.	During limited flyovers, no features were observed that suggested a need to revise those conclusions.	I
11	Y	Coincidence with an unnamed lineament and an unnamed fault of Wilson et al. (2009)	40	18	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) suggesting that surficial processes are likely exploiting existing topographic position and/or local weaknesses in the underlying Cretaceous Kahiltna flysch bedrock to create the lineaments.	Limited overflight of these features in 2013 appears to confirm this conclusion. In addition, the group is greater than 30 km (~19 miles) from the proposed site and is less than 20 km (~12 miles) in length, and likely would not appreciably contribute to the hazard calculations.	I

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
12a	N	--	14	12	The individual lineaments mapped along the north part of the group chiefly are within probable latest Wisconsin-age glacial deposits near the valley margin, and are oriented along the ice flow direction. A prominent notch with an uphill-facing slope break was observed within the Paleozoic rocks along the nose of a ridge. The topographic expression of this lineament feature on the ridge topography implies a northwest-dipping structure geometry, similar to bedded rock exposed on the other side of the mountains. The morphology of the features is kinematically inconsistent along strike, with south-east facing downhill slope breaks found on the lineaments in the Quaternary deposits, and an uphill facing slope break on the bedrock notch feature.	There are no lineaments expressed in the Quaternary deposits along about the southern half of group 12a, and there is visual evidence that right-lateral moraine and kame terrace features at the southern end of the group are not offset. There is no expression of deformation or offset of late Wisconsin landforms in kames or delta surfaces within the valley of Fog Creek directly north. Multiple slope breaks on the hillslope in the vicinity of the mapped lineaments, as well as the lineament orientation parallel to ice flow directions, suggests the lineament group was produced by glacial deposits that are now undergoing solifluction and nivation processes. It is judged that the lineaments within group 12a are the result of both past glacial processes, ongoing hillslope erosion processes, and potentially bedding relationships within the Paleozoic rocks, and do not represent a tectonic fault.	IIa
12b	Y	Unnamed fault of Clautice, (1990)	16	11	The lineaments are expressed chiefly in Paleozoic rocks, however, a thin cover of Holocene regolith mantles the rocks. The morphologic expression of the feature is incised drainages and a very broad and deep valley within which a small creek now flows. None of the glacial geomorphic surfaces in Fog Creek valley (e.g. eskers, deltas) along the southwestern projection of the lineaments were observed to be offset or deformed, and no evidence of deformation was observed at the Susitna River margin along the northeastern projection. The lineament group appears to have a variable geomorphic expression along strike, has weak kinematic indicators along strike.	The lineament is chiefly constrained to within the Paleozoic rocks, and is coincident with the previously mapped bedrock fault, suggesting a potential structural control and preferential erosion along a pre-existing weakness. Internal lithologic control on the geomorphic expression of the lineament also is plausible given the lack of lineament continuity beyond the Paleozoic rocks. The evaluation suggests that glacial and post-glacial fluvial erosional processes are a likely explanation for the origin of the lineament features. Individual lineaments may represent fault-line scarps or fault-line-valleys, but due to the lack of expression in Quaternary deposits, the lineament group is not considered a Quaternary tectonic structure.	IIb
13	Y	Coincidence with unnamed fault of Wilson et al. (2009)	67	15	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) . Also, because of the large distance from the site, the group would therefore likely have limited contribution to the hazard calculations.	During limited flyovers, no features were observed that suggested a need to revise the conclusions of FCL (2013).	I
14	Y	Coincidence with unnamed fault of Wilson et al. (2009)	62	18	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). The group is greater than 30 km (~19 miles) from the site and less than 20 km (~12 miles) in aggregate length, thus meeting lineament exclusion criteria.	A limited fly-over revealed no features that that suggested a need for additional analysis.	I
15	Y	Coincidence with unnamed fault of Wilson et al. (2009)	43	6	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) due to its large distance from the proposed dam site (~43 km [~27 miles]) and short aggregate length (~6 km [~4 miles]).	During limited flyovers, no features were observed that suggested a need for additional analysis.	I
16	Y	Partial coincidence with an unnamed lineament of Wilson et al. (2009)	60	19	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). The group was excluded from further analysis on basis on its significant distance to the proposed dam site (~60 km [~37 miles]) and relatively short aggregate length (~19 km [~12 miles]).	During limited flyovers, no features were observed that suggested a need for additional analysis.	I
17a	Y	Unnamed lineament of Wilson et al. (2009)	24	11	Field investigation revealed that the lineaments in Quaternary deposits at the south end of group 17a do not show scarp-like morphologies; rather one is a small, discordant, creek drainage and the other appears to be a depositional contact of likely late Holocene grassy swale (bog) sediments against a near-surface ice-sculpted bedrock buttress.	Lineament group 17a appears to follow a bedrock jointing pattern that is expressed on landscape, and potentially enhanced by fluvial erosion. Based on the absence of compelling evidence for Quaternary tectonism, lineament group 17a is judged to not represent a tectonic fault.	IIa

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
17b	Y	Unnamed lineament of Wilson et al. (2009); and dashed fault of Csejtey (1974)	30	20	The most prominent morphologic expression of the lineaments is a narrow creek drainage that is fed by a perched lake. The lineaments appear to coincide with the trend of glacial ice flow directions that were valley parallel. No direct evidence of a fault along this trend was found in the field.	The ground inspection supports the interpretation that glacial ice was present in the valley. Although there may be a bedrock structure along part of this group that separates Paleozoic and Mesozoic rocks, lineament group 17b is judged to be created at the local scale by fluvial erosion as well as in part by glacial ice erosion of the linear valley and periglacial processes.	IIb
17c	Y	Unnamed fault of Wilson et al. (2009)	45	8	The lineaments are mapped across Tertiary volcanic rocks as well as in young (likely Holocene) rock glacier deposits; the expression within the rock glacier deposits correspond to relatively deep drainages eroded into the rock glacier deposits. None of the faults depicted on Wilson (2009) are shown extending across or displacing Quaternary glacial or moraine deposits.	Along the south end of 17c group the relief along the lineament in the Quaternary rock glaciers is lesser than the middle part of the group, however, the relief in the rock glacier drainage is about 25 meters (~82 ft); much larger than would be expected for a relatively low-slip rate fault structure in young post-glacial deposits. While the presence of a bedrock fault cannot be ruled out along lineament group 17c, it is judged that the mapped lineament is the result of erosion into the rock glacier deposit.	IIb
18	Y	Partial coincidence with two unnamed faults of Wilson et al. (1998)	52	10	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) which concluded that the group's large distance to the proposed dam site and short overall length would likely not appreciably contribute to the hazard calculations.	This group was not visited during the 2013 field inspections and no observations were made that suggested a need for additional analysis.	I
19	Y	Partial coincidence with unnamed fault of Clautice (1990)	54	44	The lineaments of group 19 transect several different geologic units and landforms, but are not present in the post-glacial alluvium of Goose Creek or adjacent drainages. The magnitude of expression of the lineaments ranges from ~10-m-high (~33 ft) downhill-facing slope breaks in glacial deposits of the Black River to gently sloping ~125-m-high (~410 ft) bedrock escarpments. Bedrock exposures in creeks along the lineament showed evidence of pervasive jointing. The lineament group is roughly parallel to glacial ice flow directions in the Black River canyon and spatially coincident with left-lateral ice margins.	The large magnitude of relief across the lineaments in the northeastern portion is inconsistent with the apparent lack of topographic offset across the lineaments in the southwest portion of the group. Specifically, the surfaces of the exceptionally planar bedrock plateau across which the aligned linear valleys run show no evidence of the vertical displacement apparent along the lineament group. It is judged that lineament group 19 is a result of a combination of bedrock jointing and glacial and post-glacial erosion processes, and does not represent at Quaternary fault.	IIb
20	Y	Partial coincidence with unnamed normal fault of Wilson et al. (2009) and fault mapped by Grantz (1960)	94	14	No direct evidence of any of the mapped faults was apparent in the field but indirect evidence in the form of apparent rock type contrasts across mapped fault traces. There is no field evidence of erosion from glacial ice within the area of the lineament group. The mapped lineaments often alternate between weakly expressed and subtle slope breaks and broad troughs and deep and well-defined linear valleys.	Low-level aerial and ground inspection did not reveal any evidence for Quaternary faulting along the mapped lineaments or previously mapped faults. Some of the individual lineaments along the northwestern margin of group 20 do appear to coincide with previously mapped bedrock faults and are likely fault-line scarps developed along bedrock faults, but the remaining lineaments are interpreted to be the result of erosion and not tectonically-related.	IIb
21a	N	--	40	12	Lineament group 21a lies entirely with glaciated terrain at the confluence of possibly four different ice streams. Field inspection confirmed that most of the area has either a surficial cover of glacial moraine and/or glacial lake deposits from a series of glacial lakes. No field evidence of displaced or deformed terrace risers or moraine ridges was observed along the trend of the lineaments. The lineaments of group 21a are few in number, weakly expressed, weakly aligned, and do not coincide with a previously mapped structure.	The lineaments of group 21a do not transect portions of the landscape of different ages which challenges the existence of through-going tectonic structure. The apparent origins of the lineaments are both constructional (terminal moraine complex and eskers) and erosional (linear streams and short slope breaks in dissected glacial moraine ridges. Limited and poor expression of lineaments coupled with both active and stagnant ice processes in the area, point to a non-tectonic glacial origin for the lineaments of group 21a.	IIa

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
21b	N	Coincides with a photographic lineament mapped by Reger et al. (1990)	42	12	The lineaments occur as downhill-facing slope breaks in mapped Quaternary glacial deposits (unit Qdt_3 of Smith et al. (1988)) and as linear streams and gulleys eroded into Cretaceous flysch, and to a lesser extent, Cretaceous granite. Map unit Qdt_3 is considered to be of late Wisconsin age (11,800 to 25,000 year B.P.). The lineament group is oriented perpendicular to the ice flow directions within the Butte Creek valley. Inspection of the stream banks and terrace risers located to the west along the trend of the feature did not reveal any displaced terrace risers or surfaces.	Field investigation did confirm the expression of the 3-km-long, downhill-facing slope break in Quaternary glacial deposits but did not reveal any exposures of the spatially-coincident concealed schist-phyllite contact mapped by Smith (1988). The group 21b lineament most likely relates to the rock type contrasts mapped by Smith et al. (1988) where higher grade (and more resistant) schist lies upslope of the slightly lower grade (and less resistant) phyllite and is overlain by a thin veneer of Quaternary glacial deposits. The lineaments of Group 21a are judged to be non-tectonic in origin and likely relate to differential erosion along depositional contacts within bedded metasedimentary rocks.	IIa
22	N	Spatially coincides with several northwest-trending photogeologic lineaments from Reger et al. (1990)	27	17	The lineaments are mapped in Reger et al.'s till of late Wisconsin age (unit Qd3; 9,500 to 25,000 years old) (Reger Public Data file 90-1), and are expressed in the field as linear erosional gullies. Much of the hillsides appear to be influenced by solifluction processes. Along Deadman Creek, the lineaments are nearly orthogonal to the ice flow direction, and no offsets in the lateral moraines were observed.	The lineaments of group 22 show a dearth of expression in Quaternary deposits, other than being associated with two linear drainages. While the lineaments transect several different geologic units, suggesting some lateral extent, we find that the magnitude of expression along strike is highly variable. Because there is no fault previously mapped along this group and no evidence of a fault was observed, coupled with the field observations of solifluction processes as well as a distinct lack of faulting expression in the late Wisconsin glacial deposits, it is judged that lineament group 22 is not a fault.	IIa
23	N	--	62	17	The features along the lineament trend occur entirely within mapped Quaternary glacial and lake deposits of the Copper River Basin. The lineaments do not coincide with any previously mapped faults or lineaments (FCL 2013) and low-level aerial inspection did not reveal any direct evidence of tectonic structures anywhere along the lineament, including in the near-vertical cut banks of Tyone Creek. The orientation of the mapped lineaments is parallel to several north-south oriented drumlins, and perpendicular to regional ice-flow directions, but parallel to and locally coincident with terminal moraine crests	The arcing alignment and the consistently low relief morphology of the aligned slope-breaks, low mounds, and short linear ridges does appear similar to a terminal moraine complex. The positive relief of these features suggests constructional or depositional geomorphic processes, rather than via tectonic processes, may have played a role in their formation. The lineament group lies within published glacial lake extents and elevations in the Copper Basin. The evidence points to a genesis via glacial processes, and does not support a tectonic genesis. It is judged that lineament group 23 does not represent a tectonic fault.	IIa
24	Y	Partial coincidence with lineament of Wilson et al. (2009)	120	14	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) that the lineament group is short (~15 km [~9 miles]) and lies a great distance from the dam site (~120 km [~75 miles]), and likely would not appreciably contribute to the hazard calculations.	This group was not visited during the 2013 field inspections and no observations were made that suggested a need for additional analysis.	I
25	N	--	23	32	This lineament group was not advanced for field work in 2013 based on the desktop analysis of FCL (2013). The lineament group was interpreted to be the result of erosional and depositional processes, chiefly the apparent alignment of several large, curvilinear glacial valleys.	During limited flyovers, no features were observed that suggested a need to revise those conclusions.	I
26	N	--	16	13	Neither direct nor indirect field evidence of fault structures was observed along this lineament group. South of the Susitna River, the lineaments are mapped in glacially-sculpted terrain that shows geomorphic landforms indicative of stagnant ice. North of the Susitna River, the lineaments principally are mapped in a linear drainage in whose upper banks are exposures of till that overlies lacustrine and fluvial deposits. The lineament group is relatively discordant with the ice flow direction. Assessment of kinematics of the lineament morphology is indeterminate because there a near absence of geomorphic expression of tectonic-related features.	An esker landform on the south side of the Susitna River appears to be continuous where it extends across the mapped lineament, indicating no deformation since its emplacement. Because of the absences of previously mapped structures or faults, the lack of field evidence of faults, and the apparent positive evidence for non-faulting or displacement vis-à-vis the undeformed esker deposit (>11 ka in age), it is judged that the lineament group is erosional in origin and does not represent a fault structure. However, ground access for this lineament group was restricted during the 2013 field investigations, and due to the close spatial proximity to the dam site, this lineament group warrants additional study to confirm the absence of bedrock structure along these features.	IIa

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
27	Y	Coincidence with Sonona Creek fault mapped by Williams and Galloway (1986)	62	50	The lineament is expressed in late Quatermary glacial drift and glacial lake deposits as a series of aligned lakes, linear lakes and swales, vegetation lineaments, low-relief (~2-m-high) ridges, but the apparent sense of displacement is not consistent along the lineament group. Williams and Galloway's (1986) depict the Sonona Creek fault as truncating, cutting across, and also terminating into different ridges of the Tolson Creek moraine complex. Ground investigation and aerial inspection of the Tolson Creek moraines did not reveal perceptible lateral or vertical deformation along the projection of the mapped fault	The expression of lineaments in a portion of the landscape judged to be the youngest, and the absence of observed deformation (lateral or vertical) in the adjacent Tolson Creek Moraines, which are older, is inconsistent with an origin by faulting. Field investigation did not reveal any definitive evidence to strongly refute nor strongly support the presence of the mapped portion of the Sonona Creek fault. The field observations from this study favor a non-tectonic interpretation for this feature, but are not sufficiently strong to rule out the potential of late Quaternary faulting.	III
Broad Pass Fault Area	Y	Coincidence with dashed faults mapped by Csejtey (1961) and Wilson et al. (1998)	56	Several; various lengths	A strong fabric of northeast-trending glacial features characterizes the geomorphology in the Chulitna Valley, with numerous landforms such as drumlins, and glacial striae occurring throughout the valley. Existing geologic mapping depicts pre-Quaternary faults that apparently place Paleozoic and Mesozoic rocks against each other, or Paleozoic and Mesozoic rocks against Tertiary sedimentary rock units. These older rocks are in turn overlain by Quaternary glacial and fluvial sediments that are no older than late Wisconsin age. Several locations were investigated as part of the assessment of previously mapped faults in the Chulitna River valley. Faults mapped as bounding Tertiary units could not be confirmed due to lack of exposure.	Low altitude fly-overs of the partly-forested, partly-wetland surface of the Chulitna valley found no evidence of Quaternary faulting, and the surficial geology and geomorphology observed was uninterrupted and undeformed. This argues that the deposit has not experienced tectonic deformation since its emplacement, supporting an interpretation of no late Quaternary or post-glacial faulting. The lineaments mapped within the Chulitna River valley are oriented along the direction of ice flow, and generally are located along the margins of geomorphic features (e.g. drumlins, kettle edges) that are genetically related to glacial flow and related processes. Thus, none of the lineaments mapped in this area are considered tectonic in origin.	IIb
Clearwater Mtns Area	Y	Coincidence with faults mapped by: Smith (1981), Silberling at al. (1981), and Csejtey et al. (1992)	63	Several; various lengths	The lineaments are both discordant and concordant with glacial ice-flow directions; some lineaments may be expressing the ice-limit elevations at the bedrock-glacial moraine contact. No field evidence of deformed Quaternary-age linear strain markers along the trend of mapped lineaments or faults was observed. Field investigation did not reveal any through-going and laterally continuous aggregations of individual lineaments or tilted tectonic markers (such as shorelines or terraces) at the southern foot of the mountains that could be definitively linked to a tectonic origin. Post-glacial landforms and deposits did not express any lineaments and appear undeformed.	Indirect evidence of fault structure was observed in several locations within the core of the Clearwater Mountains in the high elevation bedrock terrain above the valley floor in the form of contrasting rock-type juxtapositions that corroborate the general locations of the mapped faults. No field evidence of Quaternary activity along the mapped traces of the Talkeetna thrust, westward extension of the Broxson Gulch, or Black Creek faults was observed. The lineaments mapped along the southern slopes of the Clearwater Mountains do not coincide with previously mapped faults and are interpreted to be of non-tectonic origin, and likely is originated by glacial processes and the morphology of left-lateral moraine deposits.	IIb
Castle Mtn extension	Y	The Castle Mountain fault is a Quaternary seismogenic structure (Koehler et al. 2012)	100	21	Field evidence for faulting observed during low-level aerial inspection includes: apparent bedrock type juxtapositions, bedrock color change associated with alteration zones, and deformation of bedrock units. All apparent evidence was observed in bedrock and no linear expression or evidence of faulting was observed in Quaternary deposits, although Quaternary deposits were scarce. Quaternary deposits in the vicinity of the Castle Mountain fault extension lineament group have limited spatial coverage and most commonly occur as fluvial deposits found within in narrow canyons. Because of the limited exposure of the Quaternary deposits and the segmented and splayed characteristics of the mapped faults in this area, it is difficult to declare that all segments of this fault exhibit no Quaternary activity.	Although a core group of lineaments within this group coincide with mapped faults, others do not. The mapped lineaments that do not coincide with previously mapped faults are attributed to be linear drainages (erosion features) and lineaments related to structural grain of the bedrock (lithologic control). No definitive evidence was encountered that precludes a scenario where this segment of aligned features ruptures as an extension of the Castle Mountain fault. If the group of aligned features acts as an extension of the Castle Mountain fault, it could extend the fault by approximately 21 km (~13 miles) to the northeast of the current mapped extent of the fault as shown in Koehler et al. (2012). Based on the observations that these features are clearly related to faulting of late Cenozoic age, we suggest adding this segment of fault-related features to the crustal seismic source model as a northeast extension of the Castle Mountain fault rupture scenario.	III

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
North-South Features near Talkeetna River-Susitna River Confluence	Y	Unnamed, normal faults are identified in previous mapping by Wilson et al. (1998; 2009)	85	43	This area was not advanced for field work in 2013 based on the desktop analysis of FCL (2013) on the basis of the features' large distance (i.e., >70 km [>40 miles]) to the proposed dam site and their poor expression in the surrounding Quaternary sediments and Tertiary granodiorite outcrops as manifested in the INSAR data.	This group was not visited during the 2013 field inspections and no observations were made that suggested a need for additional analysis.	I
Reger's (1990) Photogeologic Lineament Features							
R1	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	20	2.25	At its southern extent, this lineament is mapped across Quaternary age landslide (Qct) and rock glacier (Qcg) deposits within a narrow south facing cirque. On the ground, this lineament is expressed as a mild inflection in the slope angle. Down drainage, to the south, the lineament has no expression in the valley floor sediments.	This linear feature is coincident with the linear toe of a rock glacier advancing downslope from the eastern cirque wall. The linear trace through the Quaternary deposits shows no evidence of being caused by a tectonic feature.	IIa
R2	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	25	1	A northwest trending photo-lineament mapped over a quartz monzonite gneiss (TKqmg) and paragneiss (TKpng) bedrock ridge and terminated in Wisconsin age till (Qd3) at its northwest extent. The mapped trace of the feature overlies obliquely oriented linear glacial striations within the bedrock. No clear linear expression with the same orientation as the mapped lineament was observed in the terrain. Quaternary deposits at the northwest and southeast extent of the mapped lineament were visually inspected, and no linear expression was observed.	It appears likely that the lineament represents a collection of small and unrelated linear features such as: vegetation lineaments, glacial features, joints/bedding rather than having a tectonic origin.	IIa
R3	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	25	3	A west-northwest trending photo-lineament mapped across Wisconsin age till (Qd3), moraine (Qm3), and abandoned meltwater channel alluvium (Qac) deposits. The western and central segments of this lineament are coincident with two prominent breaks-in-slope on the northeastern margin of a U-shaped glacial valley. The eastern portion of the feature is coincident with a linear to semi-arcuate moraine. The lineament has no expression within the Qac deposits near the center of the mapped trace.	The mapped lineament is expressed by two prominent slope breaks and a linear trace coincident with a moraine crest. This evidence indicates that the mapped trace correlates with glacial features and is likely non-tectonic in origin.	IIa
R4 & R5	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	28	1	A clear expression of these sub-parallel faults was not observed in the bedrock during low altitude aerial inspection. Intersecting Quaternary (Qd3) deposits were observed to have no linear expression or fault related deformation.	Lacking evidence of Quaternary age deformation, these features are not considered to be active structures.	IIa
R6	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	34	4.5	The central portion of the lineament correlates to a prominent break in slope and juxtaposing bedrock and Quaternary deposits (apparent down-to-east). The northern extent of the lineament is expressed by a subtle west facing slope and linear valley. The southern extent is mapped over the crest of a bedrock knob and exhibits an apparent down-to-east sense of motion. No expression of the lineament was observed within Quaternary deposits.	The inconsistent expression of apparent vertical displacement along the mapped trace and a lack of geomorphic expression indicative of strike-slip faulting suggest that a tectonic origin is highly unlikely. This lineament appears to represent a collection of unrelated features.	IIa

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
R7	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	27	5	A sinuous east-northeast trending photo-lineament mapped over quartz monzonite gneiss (TKqmg), quartz monzonite (Tqm) bedrock and Wisconsin age till (Qd3) deposits. A pegmatite vein is mapped, unbroken, across this feature at its intersection with the Feature 8 lineament. Linear expression within the Quaternary deposits was observed to be a linear drainage (western segment) and an alignment of solufluction lobes (eastern segment)	In aggregate this lineament is a collection of aligned and unrelated non-tectonic features: linear drainages, linear erosional features, and aligned solifluction lobes.	IIa
R8	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	29	5	A slightly arcing west-northwest trending photo-lineament mapped over a quartz monzonite gneiss (TKqmg) bedrock ridge and Wisconsin age till (Qd3) deposits. On the western side of the ridge, the feature intersects the northern extent of a mapped fault that has no expression in Quaternary deposits. Two mapped pegmatite veins are mapped, unbroken, across this feature. This lineament is made prominent by a very large southwest facing topographic scarp along a linear drainage on the west side of the ridge, and a linear drainage on the eastern side of the bedrock ridge	Low altitude aerial observations revealed that the topographic scarp is approximately 10-20m in height and likely an erosional feature related to solifluction. The scarp has a limited extent and is not expressed in any other bedrock segment or Quaternary deposit along Feature 8.	IIa
R9	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	29	5.75	A northwest trending photo-lineament that is mapped over Wisconsin age till (Qd3), alluvial fan (Qaf), and moraine (Qm3) deposits. The feature is coincident with numerous glacial related features. At one location near the center of its mapped trace, the lineament is overprinted with a Quaternary age alluvial fan. No trace of the lineament was observed within the alluvial fan deposit.	The lineament is created by an alignment of non-tectonic glacial features: a linear moraine, solifluction features, and glacial striations in bedrock and along the valley margin.	IIa
R10	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	26	10.5	The lineament is mostly composed of linear drainages, linear moraines, and breaks in slope. The breaks in slope in the north and south display an opposite sense of displacement (down to east) than the middle slope (down to west). Geomorphic features indicative of oblique or strike-slip faulting were not observed. Alluvial deposits within of the intersecting glacial valley (southern portion of the trace) and the glaciated plain (mid to northern segment of the trace) show no clear evidence of linear expression.	The opposing sense of apparent vertical displacement along the trace of the fault and lack of geomorphic indicators for strike-slip faulting is an argument against this feature having a tectonic origin. The mapped trace appears to depict a linear alignment of unrelated non-tectonics features.	IIa
R11	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	32	3.25	Observations made during low altitude aerial inspection showed that the mapped trace of this lineament is coincident with an alignment of moraine crests and linear erosion features. The lineament was not observed in any of the intersecting Quaternary deposits	This lineament represents the alignment of glacial features.	IIa
R12	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	34	1.25	The western and central segments of this lineament are coincident with linear drainages (erosion features). In its eastern extent, the mapped trace of the lineament is coincident with the linear flank of a rock glacier over an older rock glacier.	This lineament represents both erosional and glacial features.	IIa
R13	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	37	0.25	A north-northwest trending fault mapped in Basalt, Rhyolite, and Agglomerate (Tvfa) bedrock and terminates at Quaternary age rock glacier (Qcg) and Quaternary landslide (Qct) deposits. Dike swarms (Tgr-d) are mapped across the project path of this feature, unbroken. Observations from low altitude aerial inspection showed no expression of faulting within Quaternary deposits	Lacking evidence of Quaternary age deformation, this feature is not considered to be a Quaternary structure.	IIa

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R14	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	38	1	A north-northwest trending photo-lineament mapped in Basalt, Rhyolite, and Agglomerate (Tvfa) bedrock and Quaternary age landslide (Qct) and rock glacier (Qcg) deposits. This feature is along strike with, and it appears to be mapped as a possible northern extension of the Feature 13 fault. This lineament is formed by a linear drainage within a rock glacier in a narrow, south facing, cirque and an aligned saddle. Low altitude aerial inspection observed no evidence for faulting along this linear alignment	Field observations indicate that this feature is a linear drainage and is erosional in origin.	IIa
R15	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	39	1.5	A north-northwest trending fault mapped in Basalt, Rhyolite, and Agglomerate (Tvfa) bedrock and Quaternary glacial till (Qd) deposits. Low altitude aerial inspection observed the fault in bedrock outcrops on the mountain slopes and through a saddle. No expression of the fault or fault related deformation was observed in Quaternary (Qd) deposits in the valley floor or in an overlying rock glacier.	Lacking evidence of Quaternary age deformation, this feature is not considered to be an Quaternary structure.	IIa
R16	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	42	0.75	A northwest trending fault juxtaposing Tertiary Quartz Monzonite (Tqm) against Cretaceous Kahiltna Terrane Argillite, Sandstone, and Siltstone (KJs) bedrock and over Quaternary landslide (Qct) and till (Qd) deposits. This fault is along strike with, and north of, the Feature 15 fault. The two features are separated by a glacial valley. Low altitude aerial inspection observed evidence of faulting in bedrock at a ridgeline saddle near the center of the lineament, confirming the presence of the fault along the mapped trace. The Quaternary deposits (Qct, Qd) on the floor of the glacial valley and lower flanking slopes were observed, and no linear expression or evidence of tectonic deformation was observed.	Lacking evidence of Quaternary age deformation, this feature is not considered to be a Quaternary structure.	IIa
R17	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	42	2.25	A northeast trending photo-lineament mapped in Kahiltna Terrane Argillite, Sandstone, and Siltstone (KJs) bedrock and across Quaternary landslide (Qct) and unlabeled (till and/or moraine?) quaternary deposits. The mapped trace of the lineament crosses the till and moraine(?) deposits; however no clear through-going linear expression was observed during low altitude aerial inspection.	The mapped trace is coincident with, and most likely defining aligned and subtle slope inflections and linear drainage channels within the Quaternary deposits. The field observations found no evidence to support a tectonic origin for this feature.	IIa
R18	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	42	0.5	A northwest trending photo-lineament mapped in Kahiltna Terrane argillite, sandstone, and siltstone (KJs) bedrock and Wisconsin age till (Qd3), and unlabeled (till and moraine?) deposits. The mapped trace of the lineament is coincident with a topographic break-in-slope (apparent down-to-northeast) in bedrock. This lineament is parallel/sub-parallel, and along strike to the northwest, to a (down-to-northeast) normal fault mapped by Reger et al (1990). The two features are separated by a northeast trending glaciated valley. Low altitude aerial inspection observed an apparent fault exposure, in bedrock, at a topographic break-in-slope along the ridgeline. Quaternary deposits between Features 18 and 20 were inspected and found to be undeformed and lacking any linear expression.	Evidence indicates that this lineament is likely a continuation of the bedrock fault trace mapped to the southeast. However, lacking evidence of Quaternary age deformation, this feature is not considered to be an active structure.	IIa

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
R19	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	43	1	A northeast tending photo-lineament mapped in unlabeled. Quaternary (till and moraine?) deposits. Low altitude aerial inspection showed that the mapped linear trace correlates with a vegetated linear drainage. The lineament is made more prominent by the color contract between the vegetation and the surrounding rocky ground surface.	Observed to be an erosional feature this lineament is likely non-tectonic in origin and not considered further.	IIa
R20	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	41	1	A northwest striking photo-lineament mapped across orthogneiss and migmatite (TKgm) bedrock and Quaternary age undifferentiated colluvium (Qc) deposits. Low altitude aerial inspection confirmed that the mapped linear trace correlates with a linear drainage and has expression only in bedrock. No linear expression was observed in Quaternary deposits along the projected path of the feature.	Observed to be an erosional feature this lineament is not considered further.	IIa
R21	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	38	2.25	A northwest trending photo-lineament mapped over quartz monzonite (Tqm) bedrock and morainal deposits of Late Wisconsin age (Qm3). Low altitude aerial inspection showed that this lineament is composed of a collection of aligned feature. The northern and central segments of this feature are a bedrock ridge crest leading to a linear drainage. The southern extent, in Quaternary deposits, was observed to be the crest of a debris flow levee which bounds the linear drainage	This lineament represents a collection of aligned, non-tectonic features and is not considered further.	IIa
R22	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	45	0.75	An east-northeast trending photo-lineament mapped within a deposit of colluviated till of Illinoian age. Low altitude aerial inspection observed no clearly defined linear expression to correlate with the mapped lineament.	It is likely that the mapped trace represents a color contrast created by glacial till along the crest of a low-relief ridge separating two drainages. Likely non-tectonic in origin this feature is not considered further.	IIa
R23	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	46	3.75	An east-northeast trending photo lineament mapped across paragneiss (TKpgn) bedrock and morainal deposits of late Wisconsin age (Qm3), and till of Illinoian age (Qd2. Low altitude aerial inspection observed that the mapped trace of the lineament correlates with topographic scarps and linear solifluction features. Along strike, the topographic scarps were observed to express an opposing sense of vertical displacement (down-to-northwest and down-to-southeast). Geomorphic expression indicative of strike-slip or oblique faulting was not observed. No linear expression or scarps were observed within the intersecting Quaternary deposits.	The geomorphic expression of this lineament is composed of an unlikely combination of features to support a through-going tectonic structure with vertical displacement, and it lacks geomorphic expression to support strike-slip faulting. This lineament appears to be a collection of coincidentally aligned linear features and caused by solifluction and erosion.	IIa
R24	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	44	4	A northwest trending photo-lineament mapped in paragneiss (TKpng) bedrock for most of its length except for the northern extent where it is mapped within Quaternary age talus (Qct) deposits in an east-facing cirque. Low altitude aerial inspection of the lineament revealed that in bedrock the mapped trace consists of an alignment of variably-scaled, linear swales. In the Quaternary deposits the lineament corresponds to a linear drainage. Scarps and vertical displacement were not observed in the cirque floor described by Reger et al. (1990) and no evidence of tectonic origin was noted for this feature.	This lineament represents a collection of aligned non-tectonic features. The linear swales appear to be glacial in origin, and other segments of this lineament are formed by a linear drainage (erosional feature).	IIa

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)	Lineament Summary Observations	Lineament Summary Interpretations	Lineament Category
R25	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	43	1.25	An angled northwest trending photo-lineament. The lineament is mapped over paragneiss (TKpgn) bedrock and late Wisconsin age till (Qd3). Low altitude aerial inspection revealed that the mapped trace is coincident with a shallow linear drainage that is highlighted by an apparent vegetation color contrast.	Being an erosional feature, these field observations indicate that this feature is likely non-tectonic in origin.	IIa
R26	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	41	3.25	An east-to-west trending photo lineament mapped over bedrock for its entire trace except for the far western end. At this location it is mapped over a Quaternary age talus deposits before it is terminated against a bedrock knob in the center of the cirque. Visual inspection of the lineament revealed no clear linear trace through the talus deposits.	Within the cirque the only along-strike linear trend is attributed to a linear drainage incised into bedrock. The mapped trace appears to represent an erosional feature and is not considered further.	IIa
R27	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	40	2	An east-to-west trending photo-lineament mapped over paragneiss (TKpgn) bedrock in its middle portion and Quaternary talus (Qct) deposits on its eastern and western extents. Within bedrock, no continuous linear features were observed that correspond with the mapped trace of Feature 27. Within Qct, the only observed linear expressions were related to linear drainages.	The only linear expression observed in the vicinity of the mapped trace was a linear drainage (erosional feature) and non-tectonic in origin. This feature is not considered further.	IIa
R28	Y	Reger 1990, Geologic Map of the Healy A-3 Quadrangle, Alaska. Alaska Division of Geological and Geophysical Surveys, Public Data File 90-1 sheet 1 of 2	39	2.5	A north-northwest trending photo-lineament mapped over orthogneiss and migmatite (TKgm) bedrock and Quaternary age colluviated till (Qdc3). During low altitude aerial inspection the feature was observed to be characterized by a shallow liner trough oriented at an oblique angle to linear solufluction features and moraines, possibly indicating that this feature is related to bedrock structure. However, it has no expression in overlying Quaternary deposits or within adjacent Quaternary till deposit to the southeast.	Lacking evidence of Quaternary deformation, this feature is not considered to be an active structure.	IIa

Notes: *Y = yes, N = no.

†Distance value represents the approximate distance to the portion of the lineament group nearest to the dam.

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