ATTACHMENT 3: LINEAMENT MAPPING AND ANALYSIS

SUSITNA-WATANA HYDRO

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NTP 11
Technical Memorandum No. 8
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Lineament Mapping and Analysis for the Susitna-Watana Dam Site

AEA11-022

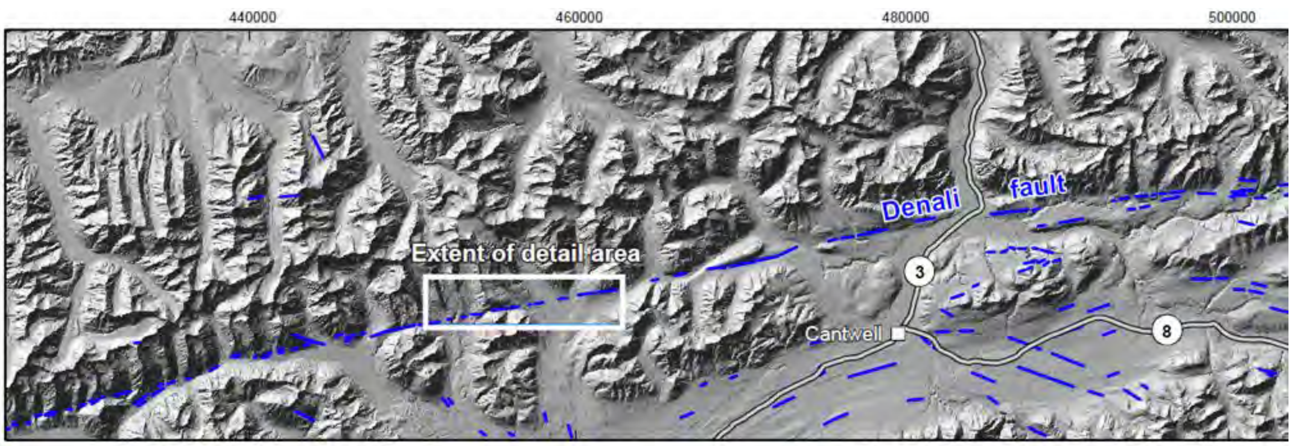

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TABLE OF CONTENTS

List of Tables

List of Figures and Plates

List of Appendices

Explanation of Abbreviations

AEA	Alaska Energy Authority
AEIC	Alaska Earthquake Information Center
DEM	Digital elevation model
FCL	Fugro Consultants, Inc.
FERC	Federal Energy Regulatory Commission
GPS	Global positioning system
INSAR	Interferometric synthetic aperture radar
ka	kiloannum (thousand years)
LiDAR	Light detection and ranging
MWH	MWH Americas, Inc.
NFFTB	Northern Foothills Fold and Thrust Belt
PSHA	Probabilistic seismic hazard analysis
RTS	Reservoir-triggered seismicity
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).

1.0 EXECUTIVE SUMMARY

The proposed Susitna-Watana Dam is a hydroelectric power development project being planned by the Alaska Energy Authority (AEA). This Technical Memorandum (TM-8) prepared by Fugro Consultants, Inc. (FCL) presents part of the continued seismic evaluations (Notice to Proceed [NTP] #11) developed assist MWH Americas (MWH) in the completion of engineering feasibility studies, including derive the size and capacity of the major structures, develop the design to sufficient detail for verification of project development cost estimates, and define the Project components and operation, in support of preliminary designs and submittal of the Federal Energy Regulatory Commission (FERC) License Application.

Based on the results of a previous preliminary seismic hazard assessment (FCL, 2012), additional seismic and geologic studies were identified for the project and license application support. These additional studies include desktop lineament mapping and evaluation, and limited field geologic reconnaissance. The purpose of the lineament mapping and evaluation is two-fold: (1) to identify potential seismic sources (i.e., crustal faults) that could appreciably contribute to the seismic hazard at the proposed dam site; and (2) to assess the potential for surface fault rupture at the proposed dam site area. An outcome of this study is identification and prioritization of potentially fault-related features of engineering significance that would require additional analysis in the 2013 field season.

FCL's lineament task used recently-acquired, detailed, topographic imagery data (i.e., INSAR and LiDAR) to examine the landscape for evidence of potential lineaments, faults, or geomorphologic features suggestive of late Quaternary faulting that may be relevant to the project. Existing geologic maps were compiled from published sources, however, the maps are a variety of scales and level of detail. Consequently, there is some inconsistency in the intensity, approach, and spatial coverage of fault or lineament mapping in the region, and mapping is sparse to incomplete compared to other regions along tectonic plate boundaries. This study therefore relies heavily on supplementation of existing mapping with analyses of high-resolution, INSAR- and LiDAR-derived topographic imagery data to identify potential fault-related features and landforms that may be indicative of faulting. The lineament mapping was conducted within approximately a 100 km (~62 mi) radius of the proposed site, including potential dam-proximal and reservoir areas for surface fault rupture assessment. Limited field reconnaissance fly-overs were performed to inspect and verify parts of the desktop-based lineament mapping.

Criteria were established to provide a basis for delineating lineament groups (that is, aggregates of individual lineaments) that seem to have geomorphic expression associated with tectonic processes and apparent lateral extent. A second set of 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. 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, and other features for which the lineament mapping provided little geologic or geomorphic evidence as potential Quaternary faults. This technical memorandum provides documentation of the geologic evidence and lines of reasoning for evaluation of each lineament group.

The mapping identified 32 lineament groups that meet the factors and criteria established to define them for inclusion in the project map. The evaluation also identified four areas containing features of potential tectonic significance to the project. These four distant spatially-defined areas are near the Broxson Gulch fault, the Broad Pass fault, the eastern Castle Mountain fault, and faults near the southwestern part of the mapping area. Application of screening criteria resulted in a reduction of the number of lineament groups to 22 lineament groups and three lineament areas which merit consideration for further study and evaluation. These resulting lineaments are compared to those defined by the WCC studies, although the WCC (1980, 1982) studies evaluated the combined Watana and Devil's Canyon dam project. Additional geologic data and analyses are needed to further evaluate the 22 lineament groups with respect to tectonic association or hazard (i.e., fault-related), and, if so, develop geologic data to provide a more complete characterization in terms of potential seismic hazard to the proposed Susitna-Watana Dam.

In addition to the regional lineament mapping, more-detailed mapping was performed within a few kilometers of the proposed Watana Dam site. The more-detailed mapping reveals an absence of obvious tectonic geomorphologic features that would be associated with past surface fault rupture events. It is noted that hypothetical slip-rates for faults in the dam site vicinity are likely small and the age of Quaternary surficial deposits is likely geologically young. Lineaments that are near, but not necessarily traversing the site footprint, are mapped primarily along roughly northwest trends. Although some further evaluation of features along Watana Creek is recommended, lineament groups with northeast strikes, which would correspond to previously mapped alignments of the Talkeetna thrust fault and Susitna feature are largely absent in the LiDAR-based lineament mapping nearest the proposed Susitna-Watana Dam site. Future proposed site geologic mapping and data collection anticipated to occur in the summer of 2013 will help assess the potential presence of faults in the dam site area.

The observations and analyses from the lineament mapping and reconnaissance described in this report confirm specific features warranting further evaluation, and facilitate and define the locations and general scope of the further characterization and evaluations of lineament groups and potentially relevant features to the project. A multi-phase framework for further evaluation of the lineaments is outlined. The goal of the future evaluations ultimately is to provide preliminary and final seismic source characterization inputs for the deterministic and probabilistic seismic hazard evaluations.

2.0 INTRODUCTION

The proposed Susitna-Watana Dam is a hydroelectric power development project planned to be constructed on the upper Susitna River under the auspices of the Alaska Energy Authority (AEA). The proposed dam would be constructed near about River Mile 184 on the Susitna River, north of the Talkeetna Mountains near the Fog Lake area. Current concepts envision a dam approximately 600-ft high, impounding a reservoir with a maximum water surface elevation at about 2,000 ft. At this elevation, the dam would impound a reservoir of approximately 5,000,000 acre-ft.

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 Federal Energy Regulatory Commission (FERC).

Under subcontract to MWH, Fugro Consultants, Inc. (FCL) prepared an initial seismic hazard assessment (FCL, 2012) based on desktop review of prior studies and recent literature. That effort included development of a regional seismic source model from which deterministic and probabilistic ground motion estimates were derived in support of continued seismic analyses for the proposed dam design and safety considerations. This TM-8 memorandum builds upon the initial geologic and seismic studies completed for MWH under NTP #6 in support of conceptual dam design and safety studies.

Based on the results of the initial seismic hazard assessment, additional seismic and geologic studies were identified for the project and license application support. This draft technical memorandum presents part of the continued seismic evaluations (Notice to Proceed [NTP] #11) associated with those studies, specifically desktop lineament mapping and evaluation. The following sections describe the lineament mapping and analyses, as well as technical conclusions and recommendations for potential 2013 geologic evaluation activities.

2.1 Scope of Work

The scope of work for this investigation is defined under Task Order T10500637-37876-OM dated May 14, 2012 (NTP #11). In general, the scope of services under this task order includes completion of a lineament mapping study with field reconnaissance for the proposed Susitna-Watana Dam. Specific technical activities within the scope of work include literature review and research, compilation of fault map data, mapping and analysis of lineaments for further evaluation of potentially significant seismic sources or lineament features that could potentially represent surface fault rupture hazards, field reconnaissance observations, and identifying and developing recommendations for lineament features that warrant additional field geologic characterization in 2013. Other activities specified in the task order include technical support for reservoir triggered seismicity analyses, long-term earthquake monitoring system, and work planning studies in support of project licensing; these activities are not described in this technical memorandum, and will be reported separately.

2.2 Lineament Mapping Objectives

The objective of FCL's lineament mapping task was to use recently-acquired, detailed, topographic data (i.e., INSAR (Figure 2-1) and LiDAR (Figure 2-2) to re-examine the landscape for evidence of potential lineaments, faults, or geomorphic features suggestive of Quaternary faulting. These data form a basis for evaluating potential seismic sources previously not accounted for in the initial PSHA, and to assess the potential for fault rupture through the proposed dam footprint. This work included review of the previous WCC studies (WCC, 1980; WCC, 1982) as well as recent literature, and provides updated mapping and interpretations on the presence or absence of potentially fault-related lineament features. Recent, detailed, digital terrain models were constructed from the INSAR and LiDAR data acquired well after the WCC study. Limited field reconnaissance including low-altitude fly-overs were performed to inspect and verify features identified by the desktop-based lineament mapping. Detailed structural or geologic mapping of the local dam site vicinity and broader region was not conducted during this lineament mapping effort. Such mapping of the dam site, including synthesis of existing geotechnical, geological, and geophysical data, is beyond the scope of this lineament mapping effort but is planned in upcoming work phases.

The lineament mapping will be used to: (1) document presence or absence of potential seismogenic sources within the broader site region (some previously not accounted for) and specifically in the near-site and reservoir area (e.g., within ~30 km[1] [19 mi]); (2) assess potential updates or alternative scenarios to the 2012 seismic source model (FCL, 2012); (3) document the presence or absence of lineaments near the proposed dam site foundation area for site-specific surface rupture evaluations; (4) provide additional geologic data to characterize potential bedrock faulting and fracturing in the reservoir area for use in analyses of reservoir-triggered seismicity analysis; and (5) develop a candidate list of features that may potentially require more thorough field investigation.

2.2.1 Field Reconnaissance

Limited field reconnaissance was performed to ground truth the desktop mapping and inspect potentially significant lineament or geomorphic features identified by the mapping. The reconnaissance

[1] A combined 30-km radius was defined to encompass a radius around the proposed dam site as well as the deeper portions of the anticipated reservoir extent (Figure 2-2). An initial 30 km radius was defined using the proposed dam site as a center point and a second 30 km radius was defined for the reservoir, using the confluence of the Kosina Creek and Susitna River as a center point. These two circles were then merged to define the combined radius.

occurred during September 5 through 9, 2012, and involved low-altitude helicopter flyovers of the site area and much of the 100 km (~62 mi) site radius area targeted to visually review features that were identified during the lineament mapping (Figure 2-3). The objective of the reconnaissance was to confirm, refute, or develop degrees of confidence in the interpretation of lineament features as tectonic or non-tectonic in origin, with limited and brief on-ground observations. Selection of routes for the flyovers were dictated and restricted by weather conditions, which included periods of low clouds and rain during the reconnaissance period. The field reconnaissance was conducted by senior FCL geologists (D. Ostenaa, J. Pearce). The field reconnaissance observations were documented by notes, photographs, and GPS.

2.3 Previous Lineament Studies

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 actual report to the Corps showing the lineament mapping with full methodological description (i.e., Gedney and Shapiro, 1975) is unavailable to this study at present time. Landsat imagery also was used to map lineaments in the upper Susitna Basin by Army Corps of Engineers Cold Regions Research and Engineering Laboratory (Gatto et al., 1980). The mapping recognized lineaments in the NE-SW and NNW-SSE directions, but none in the E-W directions.

Previous seismic hazard investigations for the proposed Watana site area 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). These efforts also consisted of detailed field investigations on a selected subset of lineaments. In the previous WCC studies, the term "recent" was generally applied to rupture of the ground surface within the past 100,000 years (100 ka).

The WCC (1980) seismic study first reviewed available literature and then interpreted remotely-sensed data to map lineaments that were compiled onto 1:250,000-scale base maps. From that effort, 216 lineament features were identified for reconnaissance from helicopters, fixed-wing aircraft, and by ground mapping at selected locations. For identification of potential seismic sources, length-distance screening criteria were developed to select only those faults and lineaments for further evaluation that were close enough to the site(s) and had sufficient length. The criteria thus established concentric zones around the sites in which faults or lineaments of a set minimum length would be further evaluated (WCC, 1980). At distances of less than 10 km (6 mi) all faults or lineaments with a length of 5 km (3 mi) or more were selected; at distances of 10 to 50 km (6 to 31 mi), all faults or lineaments with a length of 10 km or more were selected for further evaluation; at distances 50 to 150 km (31 to 93 mi), all faults or lineaments with a minimum length of 50 km (31 mi) were selected for further evaluation.

Of the 216 identified lineaments, 110 lineaments were classified as nonsignificant (e.g., non-tectonic). From the 106 remaining lineaments, all features less than 5 km (3 mi) in length were excluded (2 excluded under this criterion). Next, 58 lineaments were excluded because they were not expected to affect seismic design considerations based on estimated contribution to site ground accelerations. Thus, 46 lineament features were identified that could potentially affect seismic design considerations. Through separate analyses, WCC (1980) identified 22 lineaments that could have a potential for surface fault rupture through either sites; 20 of which were already considered as seismic sources. In total, 48 lineament features were designated as “candidate significant features” (WCC, 1980). The candidate significant features were evaluated individually using significance criteria as seismic sources and potential surface rupture hazards. From the significance 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 (Table 2-1, Figure 2-4) were the subject of detailed field studies in 1981-82; 4 for the Watana site, and 9 for the Devil’s Canyon site. As part of these studies, trenches were excavated at three locations, T1, T2, and S1, shown on Figure 2-4.

As shown in Table 2-1, the 13 lineaments were classified by WCC as tectonic or non-tectonic. None of the tectonic lineaments (faults) assessed in the 1982 study were judged to have “recent” displacement.

Table 2-1. Susitna Region 13 Significant Features (WCC, 1982)

Feature Name	WCC (1982) Classification (Abridged)	Length
Talkeetna thrust fault	Fault, not recently active	78 mi (125 km)
Susitna feature	Non-tectonic lineament	95 mi (153 km)
Watana lineament	Short, disconnected lineaments unrelated to youthful faulting	n.a.
Fins feature	Fault without recent displacement	2 mi (3.2 km)
KC5-5	Fault without recent displacement	12 mi (19 km)
KD5-2	Fault with no evidence to suggest recent displacement	0.8 mi (1.3 km)

KD5-3	Lineament, not a fault	51 mi (82 km)
KD5-9	Lineament controlled by rock jointing	2.5 mi (4 km)
Feature Name	**WCC (1982) Classification (Abridged)**	**Length**
KD5-12	A series of unrelated linear features related to a lithologic contact	14.5 mi (25 km)
KD5-42	A series of short lineaments which originated from glacial enhancement	3 mi (5 km)
KD5-43	Possible fault without recent displacement	1.5 mi (2.4 km)
KD5-44	A series of unrelated lineaments whose origin is related to the alignment of stream drainages	21 mi (34 km)
KD5-45	A range front modified by glacial processes	0.8 mi (1.3 km)

2.3.1 Previous Fault Mapping

Regional faults and lineaments documented by previous geologic maps were compiled for this lineament mapping effort. Synthesis with the previous fault map data occurred after this study's lineament mapping to avoid introducing bias into the lineament mapping. It is important to note that because of the large expanse of mostly inaccessible wilderness country, much of the previous geologic and lineament mapping relied heavily on aerial photographic interpretations and thus may contain some degree of uncertainty.

Key geologic publications reviewed for this lineament mapping included: Grantz (1953), Csejtey (1974), Csejtey et al. (1978), Kachadoorian and Moore (1979), Silberling et al. (1981), Smith (1981), Nokleberg et al. (1982, 1985), Williams and Galloway (1985), Smith et al. (1988), Nokleberg et al. (1989), Kline et al. (1990), Reger et al. (1990), Csejtey et al. (1992), Nokleberg et al. (1992, 1994), Wilson et al. (1998), Blodgett et al. (1999), Clautice et al. (2001), O'Neill et al. (2001), Wilson et al. (2009), and Koehler et al. (2012). Fault and lineament features from these various maps were spatially referenced in a GIS database to develop a composite fault and lineament map of the 100 km (~62 mi) site radius area (Figure 2-6). Because the previous maps were developed at a variety of scales, using various methods and level of detail, and for multiple purposes, there is some inconsistency in the intensity and coverage of fault or lineament mapping throughout the radius. The emphasis of most prior mapping in the region was directed to regional geologic framework and mineral resource evaluations, with relatively less emphasis to aspects of Quaternary geology and neotectonics. Furthermore, some areas simply have received little to no geologic or lineament mapping, notably in the Copper River basin and the distal southwestern part of the 100 km radius.

The State of Alaska Division of Geological and Geophysical Surveys (DGGS) recently has updated and released the Quaternary fault and fold database for Alaska (Koehler et al., 2012). This map compiles Alaskan faults and folds with known Quaternary displacement. With the exception of the Denali, Susitna Glacier, and Castle Mountain faults, no Quaternary faults or folds are mapped within the 100 km (~62 mi) site radius by DGGS (Figure 2-7). However, this does not preclude the possibility of unmapped Quaternary faults existing within the 100 km (~62 mi) site radius, and does not address the extent to which the reconnaissance level of most mapping in the region may contribute to the apparent absence of young faults.

2.3.2 Comparison of Plate Boundary Zone Fault Maps

Comparison of the published, readily-available Quaternary fault and fold data compilations for areas along the Pacific-North America Plate boundary zone in California, Washington, and Alaska provides a sense of the relatively limited understanding of Quaternary-active faults within the 100 km (~62 mi) Susitna-Watana site radius. For example, a map with a 100 km (~62 mi) radius centered on the eastern San Francisco Bay area shows a fairly thorough understanding of the region's tectonic structures, ranging from the easily-recognized major structures (i.e. slip rates > 1.0 mm/yr) to more subtle and difficult to recognize minor structures having slip rates < 1.0 mm/yr (i.e., the yellow- and purple-colored faults on Figure 2-8). This figure reinforces the concept that differences in relative motion across tectonic plates commonly is distributed across a broad zone along the plate margins, as opposed to being accommodated solely along a single fault. In the Seattle, Washington area, the understanding of the plate boundary zone's tectonic structures is challenged by youthful glacial deposits in the Puget Lowlands and extensive forest cover. However, modern remote sensing techniques, coupled with detailed field investigations, have begun to improve understanding and mapping of the more-subtle and difficult to recognize minor structures having slip rates < 1.0 mm/yr (Figure 2-9). Nonetheless, the Puget Lowlands remains an area conspicuously lacking of mapped Quaternary structures given its seismotectonic setting.

Compared to both the San Francisco Bay area and the Seattle area, the area of south-central Alaska around the proposed Susitna-Watana dam site has a comparative dearth of published and recognized Quaternary moderate or low slip rate faults (Figure 2-7). Specifically, the most recent DGGS Quaternary fault and fold database for Alaska (Koehler et al., 2012) indeed show the major tectonic structures with high slip rates (i.e., the Denali, and Castle Mountain faults) as well as the recently-recognized Susitna Glacier fault, but no low (< 1.0 mm/yr) slip rate faults are mapped for the area. This absence of Quaternary faults in the database does not mean that (1) no fault mapping exists for the area, or that (2) Quaternary faults do not exist within the 100 km (~62 mi) site radius. Rather, as described in Section 2.3.1, various scales of geologic mapping has been completed for portions of the region, but the state of the Quaternary fault knowledge and fault characterization remains immature in the general Talkeetna Mountains region. Compared to the well-studied San Francisco Bay area, south-central

Alaska's terrain is much more rugged and difficult to access, and is covered largely by youthful geologic deposits in which low slip rate faults would leave little, if any, evidence of surface displacements.

2.4 Regional Tectonics

South-central Alaska experiences rapid rates of tectonic deformation driven by the obliquely convergent northwestward motion of the Pacific plate relative to the North American plate. In southern and south-eastern Alaska, the convergent and oblique relative plate motion is accommodated by subduction of the Pacific Plate at the Alaska-Aleutian megathrust and dextral (right-lateral) transform faulting along the Queen Charlotte and Fairweather fault zones. The transition from subduction to transform tectonics is complicated by the Yakutat microplate which is colliding with southern Alaska along the eastern edge of the subducting slab. The collision of the Yakutat microplate is considered to have substantial influence on the deformation and counter-clockwise rotation in the interior of south-central Alaska (Haeussler, 2008). GPS velocity measurements show that the microplate is moving northwest at ~50 mm/yr (2.0 in/yr), a velocity that is similar in magnitude to the subducting Pacific plate. The similarity in motion vectors suggests substantial coupling between the two plates (Elliott et al., 2010).

Within south-central Alaska, 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. Major strain release occurs on northern and southern block transform boundaries (i.e., Denali and Castle Mountains bounding faults), as well as beneath the continental crust (subduction earthquakes), but mechanisms of stress accommodation/release are less well defined to the east, west, and central areas.

An evaluation of crustal stresses aids the understanding of faulting styles in areas of limited fault data. Crustal stress conditions also provide important information to help define tectonic structures that would be expected to be potentially active in the current stress field versus older structures related to a previous stress conditions. Ruppert (2008) generated Alaskan stress maps and stress tensor inversions derived from earthquake focal mechanisms. The crustal stress data in the site region, south of the Denali fault and north of the Castle Mountain fault, is heterogeneous and appears to rotate in orientation from west to east, but largely seems to be consistent with a transpressional tectonic setting favoring dominantly reverse and dextral strike-slip faulting.

2.5 Geologic Map Data

The distribution of regional Paleozoic and Mesozoic geologic formations define the accretion and suturing of major lithographic terranes to Alaska, with Paleozoic rock distributions limited to southeast of the Talkeetna thrust fault[2], and Cretaceous rocks chiefly present to the northwest of the Talkeetna thrust fault (Figure 2-10). Younger rocks and strata provide insights to the Cenozoic tectonic evolution of south central Alaska, and late Cenozoic deposits reflect repeated glacial advance and retreats with consequent glacial, glacio-fluvial, or lacustrine surficial and near-surface deposits.

Tertiary volcanic deposits, attributed to subduction of a plate spreading ridge beneath south central Alaska (Trop and Ridgeway, 2007) have intruded into and overlie the older rocks within the region, and are fairly extensive in their map distribution (Figure 2-11). The volcanic rocks are over 1,500-m thick, and the upper part of the sequence includes gently dipping flows interlayered with minor amount of subaerial tuff. Because rock age is fairly well constrained to Eocene to Paleocene (Csejty et al., 1978), the volcanics aid the evaluation of lineaments in the study area because they act as a long-term datum from which to evaluate faulting along part of the Talkeetna thrust fault or other faults. The volcanics are mapped as overlying a number of fault traces (Figure 2-11), and conceivably may be used to examine outcrops for potentially positive evidence of no Quaternary faulting if the volcanics are not displaced, as suggested by the mapping (Figure 2-10) and field investigations by Kachadoorian and Moore, (1979).

Quaternary deposits are recognized in existing geologic map data although at various levels of differentiation and scale based on map purpose. Smith et al. (1988) and Reger et al. (1990) both map similar extents of glacial deposits as Csejtey et al. (1978), but differentiate six chronologic till units. Surficial till near the Deadman Lake area appears to be differentiated by Reger et al. (1990) as map unit Qdt3 – a till of late Wisconsin age (about 11,800 to 25,000 yr BP). WCC (1980) also consider those deposits as late Wisconsin till, however, details of radiocarbon dating results across the studies may not necessarily support each other. In sum, recent Quaternary mapping has improved the detail of map units and unit differentiation, however chronologic uncertainty remains.

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[2] Most previous workers in the region have used the term "Talkeetna thrust" or "Talkeetna thrust fault" (e.g., Csejtey et al. (1978), WCC (1982), Nokleberg et al. (1985), O'Neill et al. (2001), etc.) . An exception is Glen et al. (2007) who use the term "Talkeetna Suture Zone", but their emphasis is on the broader, deep crustal structure that bounds the Wrangellia terrane and they identify discrete surface structures near and overlying the suture zone separately. In this report, we maintain usage of "Talkeetna thrust fault" to be consistent with bulk of the previous literature and maps from which we compiled mapped fault locations.

2.6 Quaternary Geology

Understanding the Quaternary geologic history in the south central Alaska 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 chronology form a basis to establish a geologic datum for evaluating tectonic (fault) activity during the late Quaternary.

The surficial deposits and landscape modifications created by glacial advances and retreats created many non-tectonic linear landforms in the study area. Such landforms include deeply incised linear gullies carved into upland ridges from sub-glacial processes[3], linear valley margins from ice flow scour, linear ice marginal deposits, drumlin fields, paleo-lake shorelines, and linearly oriented bogs and creeks. In addition, scour and erosion of bedrock by flowing ice has locally exposed regional joint sets, creating linear patterns visible at varying scales across the region. These linear landforms and features are present in various distributions throughout the 100 km (~62 mi) radius and locally complicate recognition of tectonically-derived landforms (See Data and Mapping Section below).

The occurrence of several thick ice sheets during Quaternary depressed the crust by increased load, and the retreat of the glaciers may promote vertical adjustments (i.e. rebound, unloading) in the crust due to isostatic response. The rate of crustal rebound can be relatively rapid (e.g., tens of mm/yr) after initial unloading (e.g., Larsen et al., 2005), but also continues at lesser rates over several thousands of years. The glacial loading and unloading produce changes in the stress field of the shallow crust that may result in differential uplift or isostatic faulting (NRC, 1999).

For this office-based seismic hazard lineament mapping, assessing late Quaternary faults via existing data and literature helps provide a framework for evaluating lineaments, and helps screen for evidence of surface fault rupture hazard. Synthesis and evaluation of existing Quaternary geologic mapping and related scientific publications are therefore crucial data for this assessment.

2.6.1 Surficial Geology

During the Pleistocene glacial expansions, snow accumulated on the mountains and into the heads of valleys where it compacted into ice and flowed down the valley as glaciers. Essentially the entire 100 km (~62 mi) radius was covered by Pleistocene glaciers at one point or another during the Quaternary (Wahrhaftig 1965; Hamilton, 1994; Kaufman and Manley, 2011) and thus subject to glacial stripping and peri-glacial processes of ground modification. During the late Wisconsin (~15-20 ka), glacial

[3] http://www.graenslandet.se/en/traces-of-the-ice-age/meltwater-ridges-meltwater-channels-or-glacial-grooves

extent was slightly restricted, the proposed dam site and immediate vicinity were covered by ice (Figure 2-12). Glacial erosion dominated the morphology of mountains and elevated areas, while lowlands were the locus for material deposited from the ice (till) and melting ice-water (glaciofluvial). In addition, these glacial advances commonly blocked drainage paths forming ice-dammed lakes of large to small dimensions (Figure 2-12). These lakes may have breached the damming ice and drained with potentially great vigor (e.g., Wiedmer et al., 2010).

Numerous ice fields and glacial lobes existed in the Talkeetna Mountains as well as the Chugach Mountains to the south (Williams and Ferrians, 1961). Mid to Late Wisconsin glacial advances in the northern Copper River basin and Talkeetna Mountains region directly east of the Susitna-Watana dam site are well documented by Williams and Galloway (1986). Glaciers sourcing in the central and eastern Alaska Range and the Chugach, Wrangell, and Talkeetna Mountains developed alpine glacial lobes that flowed down their respective valleys and extended onto the Copper River basin floor to various lengths. As glaciers filled the Copper River basin, they created an ice dam which formed at least two, and probably more, aerially extensive ice-dammed lakes (Nichols, *in* Carter et al., eds., 1989). The lake (i.e., Lake Ahtna) may have episodically drained at different elevations and times during the late Wisconsin (Williams and Galloway, 1986; Williams, *in* Carter et al., eds., 1989; Wiedmer et al., 2010). At their greatest extents, these glaciers coalesced and extended across the Susitna-Watana dam site area; as the glaciers receded, the dam site was inundated by glacial Lake Ahtna.

Evidence of at least two areally-extensive lake bodies during the Quaternary (Lake Ahtna and Lake Susitna) is manifested as paleo-shorelines and by lacustrine deposits (e.g., Figure 8). WCC (1982) identified thick lacustrine beds as owing to the formation of lakes by glacial ice damming in the vicinity of the proposed Susitna Reservoir. Subsequent geological research (Williams and Galloway, 1986; Carter et al., 1989; Hamilton, 1994; Weidmer et al., 2010) showed likely intermittent or semi-permanent connection of the lake basin in the Susitna Reservoir area with the more extensive Copper River Basin lake during the late Pleistocene and perhaps into the early Holocene (Lake Susitna, older; Lake Ahnta, younger). These ice-dammed paleolakes may have occupied several elevations through time identified by abandoned shorelines and potential geologic “spillways” near the northern Copper River Basin (Williams and Galloway, 1986). Based on radiocarbon dating, the last stands of the younger lake in the Copper River Basin, Lake Ahtna, may have drained by around as recently as 9,400±300 ka (Williams and Galloway, 1986).

Additional deposits that may be present within the study area’s near-surface sediments are volcanic tephra beds (Dixon et al., 1983). These deposits are thought to have originated from eruptions in the Tordrillo Mountains to the southwest of the Watana site (Riehle et al., 1990). Tephra beds of numerous vintages are found throughout Alaska, ranging from late Pleistocene to late Holocene (Westgate, 1975). 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, 1985). The tephra deposits and the tephrochoronology are very important to establishing site geologic chronology with respect to datable marker horizons and evaluation of lineament mapping.

2.6.2 Relevance to Lineament Mapping and Evaluation

The Quaternary geology influences the lineament mapping and evaluation in two primary ways: chronologically and geomorphologically. The glacially stripped landscape and presence of likely youthful surficial deposits provides few long-term (e.g., ~100 ka) datums to assess crustal deformation, and poses challenges for identifying potentially low slip-rate faults. Geomorphically, linear landforms formed by non-tectonic processes (e.g., ice) may mimic topographic expression of fault-related lineaments, somewhat obfuscating the seismic lineament assessment. There are multiple genetic origins for lineaments mapped during this study: glacial or fluvial erosion, geomorphologic (e.g. lake shorelines), as well as lithologic (e.g. jointing or structure).

Considering the complications introduced to lineament evaluation by Quaternary landscape features, there are several factors that may be used to evaluate the likelihood of a lineament as Quaternary tectonic origin. These factors, or general criteria, include (from weaker to stronger likelihood): solitary, short features; alignment within or along a group of features; orientation consistent with tectonic faulting style and regional stress orientations; spatial coincidence with previously mapped faults; slope position (e.g., base of slope or linear ridge crest vs. mid-slope); geomorphic domain boundaries. In addition, delineation of potentially relevant lineaments also considered features that lacked readily explainable geomorphic context.

3.0 DATA AND MAPPING APPROACH

Several advancements in the state of the science for mapping potentially tectonically-related lineaments have occurred within the last few decades. New insight has developed based on geologic reconnaissance and mapping following ground-rupturing earthquake events (e.g., Hitchcock et al., 1994; Lettis et al., 1999; Kelson et al., 2003; Kelson et al., 2005, and McCalpin, 2009) and the increasing availability of high resolution aerial and topographic data facilitates more accurate mapping and analysis. The concepts described in NUREG/CR-5503, “Techniques for Identifying Faults and Determining Their Origins” (Nuclear Regulatory Commission [NRC], 1999) include many of these insights and the approach for the lineament mapping generally follows techniques outlined in this document. Tectonic faults, which may or may not be seismogenic, include primary structures capable of producing earthquake (i.e., seismogenic faults), and secondary structures that are produced by earthquakes but are not themselves capable of generating an earthquake (i.e., nonseismogenic faults). Seismogenic faults of engineering significance are relevant to the estimation of strong vibratory motion for dam design. Both seismogenic and non-seismogenic faults may represent local surface displacement hazard to the dam foundation, if present.

Geomorphic evidence of fault activity includes features preserved on the landscape as a result of surface rupture. Characteristic types of landforms are associated with each major type of faulting (reverse, strike-slip, normal). These landforms range from centimeters to kilometers in scale, from small scarps and fissures that develop at the time of surface faulting to large-scale geomorphic landforms such as triangular faceted ridge spurs along mountain fronts that result from repeated activity over tens to hundreds of thousands of years (NRC, 1999). Usually, combinations of these features are present if a fault has experienced repeated late Quaternary rupture. Conversely, erosional patterns along old faults may produce landforms that mimic geomorphic evidence of surface fault rupture, such as linear drainages, and fault-line scarps. In addition, large scale and extensive glacial processes and features often are expressed by lineaments and can mimic the expression of tectonically-derived lineaments. Geomorphic evidence of ground-rupture (e.g., scarps) may be laterally discontinuous at large (detailed) scales such that, when aggregated and assessed at smaller (regional) scales may cumulate to a potential tectonic structure. Thus, in the stages of mapping lineaments for seismic hazard analysis, it is important to consider all forms and scales of geomorphic expression in the search for potential faults.

Detailed topographic elevation data (i.e., INSAR) were made available in July 2012. These data provide a detailed and high quality model of the ground surface for the 100 km (~62 mi) radius around the proposed site, from which to observe and interpret geomorphic or tectonic features on the landscape (see Figure 2-1 and Section 3.2 below). In the proposed dam site and reservoir area, mapping of lineaments and geomorphic features was based on LiDAR data (Figure 2-2). The desktop lineament mapping also reviewed available existing geologic mapping including published fault maps (see Section

2.3.1 above). The combination of regional and small scale images and detailed large scale image analysis therefore provides the best approach to identify and evaluate potential tectonic structures.

3.1 Geospatial Data

The principle data sets utilized during the lineament mapping consisted of several high-resolution topographic and aerial imagery datasets (Table 3-1). Of the available data, the INSAR and LiDAR (Figures 2-1 and 2-2) were the most valuable due to their high resolution and broad coverage of areas of interest. INSAR (Interferometric Synthetic Aperture Radar) is a radar technique that uses two or more synthetic aperture radar (SAR) images to generate digital maps of surface elevation, using differences in the phase of the waves returning to the satellite or airplane. LiDAR (Light Detection And Ranging) is an optical remote sensing technology that measures certain properties of a target, including the distance to a target, by illuminating the target with light, usually using pulses from a laser carried by an airplane or helicopter. 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.

In addition to the elevation data, two imagery datasets covered the study area: 1) ortho-imagery (1 ft) collected as part of the Matanuska-Susitna Borough LiDAR collection project, and 2) Landsat scenes (30 m) (Table 3-1). 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 reconnaissance. However, all lineament mapping (discussed below) was conducted on base maps constructed from the high resolution elevation data.

Table 3-1. Principal Data Sets Utilized during the Lineament Mapping

Data	Cell Size	Year collected	Source
INSAR elevation data (bare earth)	5 m	2010	Data collected by Intermap (50%) and Fugro EarthData. Inc. (FEDI) (50%)*
Ortho-rectified Radar Image (ORI)	0.625 m for Intermap 2.5 m for FEDI	2010	Data collected by Intermap (50%) and Fugro EarthData. Inc. (FEDI) (50%)*
MatSu LiDAR elevation data (bare earth)	1 m	2011	Matanuska-Susitna Borough*†
MatSu aerial imagery	0.3 m	2010	Matanuska-Susitna Borough*†
Landsat satellite imagery	30 m	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/

3.2 Mapping Approach

This study analyzed the high-resolution, INSAR- and LiDAR-derived topographic data to identify potential fault-related features and landforms indicative of Quaternary-active faults within an approximately 100 km (~62 mi) radius of the dam site (Figures 2-1 and 2-2). Given the remote, rugged, and sometime heavily vegetated or forested nature of much of Alaska, the INSAR and LiDAR data allow an efficient recognition of potentially fault-related features and landforms in areas where access would be challenging and time consuming, if not impossible. Given the potential for subtle features to be obscured by vegetation and thus to be difficult to recognize on aerial photos or sometimes even during ground reconnaissance, these data enable observation and characterization of potentially active fault strands at a high level of detail and precision (e.g., Sherrod et al., 2004; McCalpin, 2009; Brossy et al., 2012 and references within all three).

The approach consisted of evaluating the geomorphology to identify lineaments such as linear slope breaks, faceted hillslopes and linear range fronts, deflected streams, aligned saddles, and linear valleys. In order to visualize the geomorphology in detail, digital elevation models (DEMs) of the landscape were created from the INSAR and LiDAR data. The resulting DEMs were then used to create a variety of hillshade, slope (i.e., first derivative of topography), and slope of slope (i.e., second derivative) maps. DEMs symbolized with color elevation ramps facilitated easy visualization of the range in elevation values across both local and regional scales. Along with locally available high-resolution aerial imagery, these data were all imported into GIS, and through various layering arrangements and levels of transparency, these data provided accurate and intuitive visualizations of the landforms. For example, the dramatic relief of the rugged and highly dissected alpine areas is readily apparent when a semi-transparent elevation color ramp is overlaid upon a hillshade base. However, the hillshade effect in areas of high relief naturally generates long shadows that can obscure portions of steep slopes. In these areas, the subtle geomorphic features often associated with active tectonics, such as low-angle topographic scarps or linear sag ponds, are often highlighted more effectively when the hillshade is replaced by a slope map base.

3.2.1 Resolvability of Features

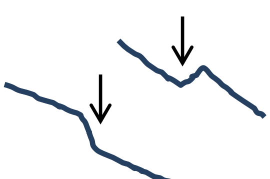
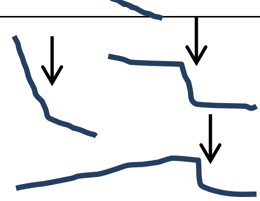
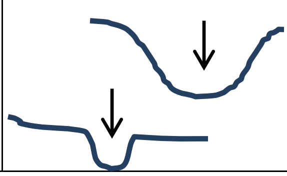
Both the LiDAR and the INSAR data produce detailed models of the landscape. Of the two, the LiDAR data is the most detailed because of its smaller cell size. However, obtaining LiDAR coverage for the entire area of interest would be cost-prohibitive. INSAR data are a more appropriate data set and effective means by which to assess the geomorphology and potential fault-related lineaments of such a large area at a reconnaissance scale. For comparison, standard DEM models available for much of the lower 48 states are mainly at 30-m (~100-ft) cell sizes while the INSAR data used for this study has a 5-ft (~1.5 m) cell size (Table 3-1), which results in a significantly more detailed depiction of the landscape.

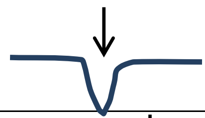
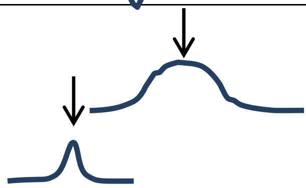
The Denali fault provides an excellent example of the resolution of the INSAR and the geologist's ability to recognize tectonically-derived features in the landscape (Figure 3-1). Even the smaller topographic lineaments in the region that are a result of surface faulting are readily visible in the INSAR data at reconnaissance scale. For example, 200-meter-long (~600-ft-long) scarps along the Denali fault are readily apparent at 1:40,000 scale (Figure 3-1b and 3-1c). Zooming out to a regional view of the Denali fault provides an example of how high slip-rate faults could be identified via the reconnaissance lineament mapping. At this scale, the trace of the Denali fault is readily apparent in the landscape as a series of closely-spaced, aligned or en-echelon short lineaments (Figure 3-1a). When viewed at this regional level, these short lineaments aggregate to define the overall trace of the fault.

3.2.2 Lineament Categories

To facilitate efficient lineament mapping across such a large radius (approximately 31,400 km^2 [~12,100 mi^2]) of diverse terrain, potential fault-related geomorphological features were grouped into five categories based on their basic and most fundamental topographic expression (Table 3-2). Mapped lineaments were attributed with one of these categories at the time of digitization. Several related, but non-topographic categories were used in some cases (Table 3-2). Lineaments were mapped using ESRI's ArcGIS software (version 10.2) in a heads-up digitizing environment where various combinations of all the available digital geologic and topographic data and imagery could be readily viewed and interpreted.

Table 3-2. Attributes of Mapped Lineaments

Attribute	Cross Section Morphology*	Description	Examples
1		Linear break-in-slope bisecting a planar surface	Uphill- or downhill-facing scarps, lateral moraines or kame deposits along lateral margins of valley glaciers
2		Abrupt changes in slope adjacent to otherwise relatively horizontal (and planar) surfaces	Linear range fronts, faceted ridges, terrace risers, steep downstream faces of rouche mountonees
3		Linear U-shaped trough	Glacial valleys, ice-scoured flutes, flood-scoured flutes

Attribute	Cross Section Morphology*	Description	Examples
4		Linear V-shaped trough	Active stream channels
5		Linear ridges	Drumlins, water-scoured terrain, eskers
6 (also 77)	n/a	A series of aligned features	Could include attributes #1-5 above and/or aligned saddles, tonal lineaments, etc.
66	n/a	Data artifacts	Linear seams between data sets collected on different dates
88	n/a	A series of aligned features, which are too small to individually map at the given scale	Could include features with attributes #1-5 above and/or aligned saddles, tonal lineaments, etc.
99	n/a	A line which encloses a broad expanse of features all having the same orientation	An area of jointing or of glacial striae all having the same, parallel orientation
10	n/a	Anthropogenic lineaments	Roads, rail roads, power lines and other linear clearings, etc.
Notes: *Arrow points to location of the mapped feature.			

Example areas that demonstrate how the lineaments were recognized on the bare-earth hillshade, and how the attributes were applied to the geomorphic features mapped, are presented in Figures 3-2 and 3-3 at 1:40,000 scale. (These figures also demonstrate the level of landscape detail provided by the INSAR data.) The INSAR data makes clear the locally persistent and intricate linear patterns created in the landscape by bedrock fabric (Figure 3-2). In this case, numerous lineaments are defined and attributed according to their morphologic expression in the landscape, without regard to their genesis. Lineament attribution requires some judgment; multiple attributes may apply to a single lineament but only the attribute corresponding for the apparently most-dominant morphology is used. In the area shown on Figure 3-2, the lineaments are mostly expressed as a variety of linear breaks-in-slope (attribute #2, Table 3-2), V- and U-shaped linear troughs and valleys (attributes #3 and 4, Table 3-2), and linear fronts (attribute #2), all at multiple scales. When viewed regionally, the genesis of the lineaments is interpreted to be largely due to the bedrock fabric. This fabric potentially results from multiple processes not directly related to neotectonics, including the strain applied to volcanic and plutonic rock masses during or after their emplacement, differential composition and/or cooling, isostatic response of loading and unloading by ice, as well as differential weathering. However, lineaments derived from tectonic activity may exist within such a complex arrangement of lineaments.

In other areas, mapped lineaments may consist of numerous elongate, linear ridges and swales (attributes #5 and #3; Table 3-2), regardless of whether the area is composed of bedrock or alluvium (Figure 3-3). Lineaments exhibiting these morphologies are commonly a result of Quaternary glacial processes. Figure 3-3 shows where two ice streams converged: one ice stream flowed southward from the upper left corner of the figure, and one flowed southwestward from the upper right. Located in the top center of the figure, in between the lineaments of the two ice streams, lies an area containing several U-shaped linear drainages (attribute #3) that are interpreted to result from local bedrock fabric. Numerous linear fronts (attribute #2) that trend parallel to the elongate linear ridges (attributes #5) also exist. These features lie along a common trend and are distinctly sharp in their expression and could be explained as linear terrace risers resulting from stream erosion, or as possibly tectonically-derived scarps. Thus, the lineament attribute assigned does not imply a certain genetic origin; that is for the geologist to assess based on geologic evaluation of the lineament(s) in question.

Identification of any tectonically-derived lineaments or Quaternary faults in areas of complex bedrock- or ice-scour–related lineaments is indeed challenging. The INSAR data shows that many more features are present than those mapped, but this effort focused on mapping and characterizing through-going and lengthy, potentially tectonically-derived lineaments. The approach to this task is presented below in Section 3.2.3.

3.2.3 100-km Radius Mapping

DEMs with 5 m (~16 ft) cell size were created from the INSAR data. A variety of hillshades, elevation color ramps, and slope maps were then created from the DEMs. The geomorphology within the 100 km (~62 mi) radius of the dam site, but south of the Denali fault, was reviewed at a variety of scales as detailed as 1:40,000-scale for potential fault-related lineaments. Digitization of lineaments was performed at 1:40,000-scale, regardless of if the lineament was identified at a smaller scale. The area north of the Denali fault was not reviewed for potential fault-related lineaments because sensitivity PSHA studies documented in FCL (2012) show that potential seismic sources north of the Denali fault are not dominant contributors to the seismic hazard at the proposed Susitna-Watana site, and any further evaluations of future seismic source models can be completed based on existing data available for this area.

3.2.4 Mapping of Proposed Dam Site Area

Several different base maps with 1 m (~3.2 ft) cell size were created from the LiDAR data for the area of the dam site (Figure 2-2). These maps included hillshades with low and high sun angles and maps with sun from the northwest, northeast, and southeast, as well as various slope maps. This large variety of maps facilitated mapping in both the deep and shadow-prone Susitna River canyon as well as the low-relief uplands along the river. Mapping of potential fault-related lineaments was completed at scales as detailed 1:10,000 scale for the LiDAR coverage within the proposed dam site (Figure 2-2). The high-resolution color imagery that was collected concurrently with the LiDAR provided an accurate and detailed perspective on features near the proposed dam site.

3.2.5 Criteria for Selection of Lineaments Requiring Further Analysis

The above sections describe the approach for mapping of individual lineaments across the 100 km (~62 mi) radius and near the dam site, and assigning morphologic attributes to the individual lineaments. Multiple acceptance criteria were established to serve as a basis for delineating potentially tectonically-relevant lineament groups (Table 3-3). The lineament groups are shown on Plate 1 and also on more-detailed strip maps (Appendix A Figures A0–A27). Larger areas requiring a broader view of the compiled data and interpreted lineaments are presented as plates (Appendix A Plates A1–A4). In general, the lineament groups consist of areas of lineaments having consistently similar orientations that when aggregated together as a group, have a relatively appreciable length and which trend across terrain. Several criteria were established to serve as a relatively inclusive basis for delineating lineament groups within the study area. These criteria are described below (Table 3-3), and are presented in generally decreasing degree of confidence in lineament delineation as a potential crustal feature.

Table 3-3. Criteria for Delineating Lineament Groups

Criterion	Reasoning
Lineaments that are expressed in Quaternary deposits, that collectively aggregate to greater than about 6 miles (10 km) 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.

Criterion	Reasoning
Lineaments with possible tectonic geomorphology 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 geomorphology that are not spatially associated with previously mapped faults/lineaments.	Suggestive, but not conclusive, of neotectonism.
Lineaments that aggregate to greater than 10 km 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 from the proposed site and reservoir, and are greater than 20 km in aggregated length.	Seismogenic features within 30 km 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 3-4). The semi-objective criteria include length and distance restrictions, and also geologic process restrictions. The screening process thus requires an examination of the identified lineament groups to assess the possible genesis of the features. The screening step eliminates lineaments that show strong evidence of being non-tectonic in origin, or those that likely would not appreciably contribute to the seismic hazard at the proposed dam site.

Table 3-4. Desktop Evaluation Exclusion Criteria

Criterion	Reasoning
Lineament groups that are greater than 100 km distance from the proposed dam site, excepting potential extensions of the Castle Mountain fault	Lineaments over 100 km distant would have no contribution in hazard calculations. Potential extensions of the Castle Mountain fault may contribute to hazard calculations.
Lineament groups that are greater than 70 km distance from the proposed site and less than 40 km 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 initial (2011) PSHA.
Lineament groups that are greater than 30 km from the proposed dam site and less than 20 km in length are excluded from further analysis, where the group cannot be linked to an adjacent group	Based on the results of the initial (2011) PSHA, it is likely that these lineament groups (if seismic sources) will not appreciably contribute to the hazard calculations.

Criterion	Reasoning
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 3-5) was applied to the remaining lineament groups, based on geological examination of the data compiled on the lineament group strip map (see Section 4.1.1 below). This process served to identify potentially significant lineament groups that would need additional data and evaluation as part of the year 2013 studies. The evaluation provides a framework to develop approaches for future efforts.

Table 3-5. 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.
Lineament groups that transect or cut across different geologic units proceed to further analysis	Lineaments that are traceable across different geologic units implies 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.

4.0 MAPPING RESULTS

The lineament results are presented by the primary levels of mapping: regional 100 km (~62 mi), mapping using INSAR base data (Figure 4-1 and Plate 1), and dam and reservoir proximal mapping using LiDAR base data (Figure 4-2).

4.1 Regional INSAR-Based Mapping

Figure 4-1 depicts in summary form the individual lineaments mapped at regional scale (Section 3.4) from the INSAR data. Each of the mapped lineaments is attributed in GIS according to the categories shown in Table 3-2. This attribution framework is used in conjunction with other geologic and tectonic data (Sections 2 and 3.5) to evaluate the potential tectonic significance of the mapped lineaments. Because the lineaments were generally mapped at relatively detailed view scales, and individual lineaments are relatively short, subsequent evaluation has focused on defining groupings of individually-aligned lineaments as a basis for identifying potentially relevant landscape features.

The 100 km radius mapping has identified 32 lineaments (as groups or aggregates of mapped lineaments) that meet the factors and considerations which suggest they may have some potential to be tectonic features and thus merit consideration for further evaluation (Table 4-1; Plate 1). Four broader areas containing features of potential tectonic significance area also are identified (see Appendix A, Figure A-0). The lineaments arbitrarily are numbered for reference purposes; numbers are used to avoid potential confusion with geographic names that may not be unique in the area. The analyses and evaluation of the lineaments provides an initial characterization of their genesis, with documentation of the geologic evidence and lines of reasoning for evaluation of each lineament or lineament group.

The 32 lineament groups broadly fall into two categories: those that are coincident with previously mapped faults or lineaments (21 lineament groups), and those that are not (11 lineament groups). The approximate group lengths and distances from the proposed Watana dam site are listed in Table 4-1. The four larger study areas are not listed in Table 4-1 because of the map complexity, however each of the four areas are associated with numerous previously mapped faults.

The lineament mapping (Figure 4-1, Plate 1) depicts lineaments of relatively short to relatively long length features, depending on the scale and expression of those features on the landscape. Relatively longer lineaments are mapped in the smoother landscape areas to the west-southwest of the proposed dam site where bedrock (Figure 2-10) is exposed near the ground surface.

Table 4-1. Summary of Lineament Groups

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)
12a	Y	Spatially proximal to a thrust fault mapped by Turner and Smith (1974), Belkman et al. (1975), and Kachadoorian and Moore, (1979)	14	12
6	Y	Talkeetna thrust fault of Csejtey et al. (1978); WCC, (1982); and Wilson et al. (2009)	14	17
12b	Y	Unnamed fault of Clautice, (1990)	16	11
26	N	--	16	13
4	Y	Unnamed fault of Wilson et al. (2009)	23	11
25	N	--	23	32
17a	Y	Unnamed lineament of Wilson et al. (2009)	24	11
22	N	--	27	17
3b	N	--	27	19
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
17b	Y	Unnamed lineament of Wilson et al. (2009)	30	20
9	Y	Coincidence with feature KD5-44 of WCC (1982); Partial coincidence with an unnamed lineament and an unnamed fault of Wilson et al. (2009)	31	24
8	Y	Coincidence with feature KC5-5 of WCC (1982); Partial coincidence with an unnamed fault of Wilson et al. (2009)	38	26
3a	N	--	40	12
21a	N	--	40	12

Group Number	Previously Mapped? *	Source of Previous Mapping	Approximate Distance to Dam Site† (km)	Approximate Length of Group (km)
11	Y	Coincidence with an unnamed lineament and an unnamed fault of Wilson et al. (2009)	40	18
5	Y	Partial coincidence with an unnamed lineament of Wilson et al. (2009)	40	23
21b	N	--	42	12
15	Y	Coincidence with unnamed fault of Wilson et al. (2009)	43	6
17c	Y	Unnamed fault of Wilson et al. (2009)	45	8
2	N	--	46	12
1	N	--	51	20
18	Y	Partial coincidence with two unnamed faults of Wilson et al. (1998)	52	10
19	Y	Partial coincidence with unnamed fault of Clautice (1990)	54	44
16	Y	Partial coincidence with an unnamed lineament of Wilson et al. (2009)	60	19
23	N	--	62	17
14	Y	Coincidence with unnamed fault of Wilson et al. (2009)	62	18
27	Y	Coincidence with Sonona Creek fault of Williams and Galloway (1986)	62	50
13	Y	Coincidence with unnamed fault of Wilson et al. (2009)	67	15
10	N	--	70	27
20	Y	Partial coincidence with unnamed normal fault of Wilson et al. (2009)	94	14
24	Y	Partial coincidence with lineament of Wilson et al. (2009)	120	14

Notes: *Y = yes, N = no.
†Distance value represents the approximate distance to the portion of the lineament group nearest to the dam.

As noted in Section 3, lineament length is, in part, a function of mapping and data scale. Mapping at more-detailed scale, with higher resolution imagery, will typically lead to identification of shorter features, which must be aggregated into groups for broader evaluation. Mapping by this study included identification of new, shorter features at more-detailed scales along previously mapped WCC lineaments, but recognized relatively little or no expression of these aligned, smaller scale features in the landscape (based on the INSAR data) which might be considered suggestive of potentially high rates of late Quaternary slip (Figure 4-1; Figure 4-2; Plate 1).

4.1.1 Discussion of Individual Lineament Groups

The following section discusses each of the individual lineament groups and larger areas identified via analysis of the INSAR data. The individual lineament groups are shown in their regional context on Plate 1, along with the compiled faults. The groups and larger areas are depicted in detail on a series of strip maps and plates on which geologic and geomorphic data are compiled and evaluated (Appendix A). Lineament groups 1 through 27 are shown on Appendix A Figures A0 through A27[4]. The larger areas showing the Broad Pass fault, Clearwater Mountains, northeastern Castle Mountain fault, and the Talkeetna River-Susitna River confluence are shown on Plates A1, A2, A3, and A4, respectively. Detailed mapping on the LiDAR in the area of the proposed dam site is shown on Plate A5. The strip maps and plates facilitate discussion and evaluation of the available data with respect to the features' relevance to the seismic hazard evaluation for the proposed Susitna-Watana dam site and potential needed further study. The application of the criteria presented above in Section 3.2.5 and evaluation of the lineament groups and larger areas is summarized in Table 4-2.

Lineament Group 1: Observations and Evaluation

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 mi) north of the proposed Watana dam site (Appendix A, Figures A0 and A1-1). Individual mapped lineament features range from approximately 200 m to 4 km (~650 ft to 2 mi), with an aggregate length of approximately 20 km (~12 mi). Discrete lineaments that make up the aggregate group occur in the Cretaceous Khalitna flysch sequence (Wilson et al., 1998). Mapped Quaternary surficial deposits of undetermined age show no apparent expression of the lineament, and the Jack River bisecting the lineament shows no apparent deflection across the projected lineament trend (Figure A1-1). Glacial valley orientations are

[4] Note that for ease of reference, Appendix A figure numbers correspond to lineament group numbers. For example, Figure A1 shows the extent of lineament group 1. Also, the explanation of symbols and geologic map units on Figure A1-2 is valid for Figures A1 through A27.

Table 4-2. Matrix of lineament groups and applied criteria

	Lineament groups and larger areas																														
	1	2	3a & b	4	5	6	7	8	9	10	11	12a & b	13	14	15	16	17a,b,c	18	19	20	21a & b	22	23	24	25	26	27	Broad Pass	Clearwater Mtns	Castle Mountain	Talkeetna-Susitna River Confluence
Criteria for delineating lineament groups (Table 3-3)																															
Lineaments that are expressed in Quaternary deposits, that collectively aggregate to greater than about 6 miles (10 km) in length.	x	x	x		x?	x	x			x	x	x					x	x	x		x	x	x	x	x	x	x	x		x	x
Lineaments that appear to represent potential extensions or continuations of known Quaternary faults.																				x								x	x	x	
Lineaments with possible tectonic geomorphology that are spatially associated with previously mapped faults/lineaments				x	x	x	x	x	x		x	x	x	x	x	x	x	x	x?	x				x			x	x		x	
Lineaments with possible tectonic geomorphology that are not spatially associated with previously mapped faults/lineaments	x	x	x							x											x	x	x			x			x		
Lineaments that aggregate to greater than 10 km length	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x[1]	x	x	x	x	x	x	x	x	x	x			x	
Lineaments that are within 30 km from the proposed site and reservoir, and are greater than 20 km in aggregated length.			x									x							x		x[1]	x			x						
Desktop evaluation exclusion criteria (Table 3-4)																															
Lineament groups that are greater than 100-km distance from the proposed dam site, excepting potential extensions of the Castle Mountain fault																								x							
Lineament groups that are greater than 70-km distance from the proposed site and less than 40-km aggregate length and with no apparent association to previously mapped structures										x										CMF ext.?[2]											x
Lineament groups that are greater than 30-km from the proposed dam site and less than 20-km in length are excluded, where the group cannot be linked to an adjacent group	x?				x?			x?	x?		x		x	x	x	x		x		CMF ext.?[2]			x?								
Lineament groups whose individual lineament features are dominantly erosional and/or depositional features with no apparent association with previously mapped faults or lineaments	x?																					x?	x?		x						x
Lineament groups with inconsistent expression of kinematics along strike	x?			x?						x?		x?																			
Criteria for desktop geologic evaluation of lineament groups (Table 3-5)																															
Lineaments within groups that appear to have expression in Quaternary units or Quaternary landforms proceed to further analysis	x	x	x		x?	x	x	x				x					x		x		x	x	x			x	x	x	x		
Lineament groups that transect or cut across different geologic units proceed to further analysis		x	x		x	x	x	x	x			x					x		x	x	x	x				x	x	x		x	
Lineaments within groups that may be tested for positive evidence of inactivity proceed to further analysis		x (Q)	x (Q)	x (T)	x (Q)	x (Q, T)	x (Q)	x (T)	x? (Q)			x (Q)					x (Q, T)		x (Q?)	x (Q?)	x (Q)	x?	x (Q)			x (Q)	x (Q)				
Lineament groups that demonstrate relative consistency of geomorphic expression and anticipated structural kinematics along strike proceed to further analysis					x?	x?		x	x			x?					x		x	x?	x	x?				x	x				
Lineament groups that are explainable in the context of the tectonic model proceed to further analysis		x	x	x	x?	x	x	x	x			x					x		x	x?	x?	x?				x	x		x	x	
Additional analysis needed?	x	x	x		x	x	x	x	x			x					x		x	x	x	x	x			x	x	x	x	x	

Note: The presence of an question mark (?) indicates the presence of potentially contradictory evidence and less certainty in the analysis. The letters Q and T are used to designate the presence of Quaternary- and Tertiary-age desposits that may be used to test for activity.

[1]If groups considered linked (i.e., sub-groups A and B form a single, through-going structure), then the criteria apply.

[2]Group 20 meets these criteria but is not excluded on the basis that it could be a possible extension of the Castle Mountain fault.

sub-orthogonal to the lineament suggesting that Quaternary glacial processes had little influence on the formation of the lineament. No previously mapped faults or lineament features coincide with the group (Figure A1-1), although the feature has a similar trend to the relatively proximal Denali fault.

The occurrence of the lineament features within one bedrock unit (Cretaceous flysch) suggests, but does not demonstrate, that the observed features may be a topographic expression of internal rock structure as opposed to a through-going crustal tectonic structure. Additionally, the lineaments of group 1 do not align across the drainage at larger (more detailed) map scales, suggesting the lineament group may represent two shorter sets of unrelated features. However, there appears to be sufficient geologic and geomorphic observations to suggest that the lineaments within group 1 could represent crustal features, based on strength of lineament expression.

Lineament Group 2: Observations and Evaluation

An east-northeast trending lineament group defined by a series of aligned, linear drainages, slope-breaks, and V-notched saddles (Figure A2) is located approximately 46 km (~29 mi) north-northwest of the proposed Susitna-Watana dam site (Figure A0). Individual features range from a few hundred meters to approximately 2 km (<985 ft to ~1 mi), with an aggregate length of approximately 12 km (~7 mi). Specific lineaments that compose the aggregate group have a clear expression in both the Cretaceous Khalitna flysch sequence, and Tertiary volcanic rocks (Wilson et al., 1998; Figure A2). Mapped Quaternary surficial sediments, several unnamed drainages, and an alluvial fan deposit show no apparent deflection or deformation where overlying the projected trace of the lineament group (within the resolution of the 5-m-cell size DEM) (Figure A2). 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. No previously mapped geologic faults or lineament features coincide with the group 2 lineament, although the group 2 feature has a similar trend to the relatively proximal Denali fault.

Discrete lineaments within group 2 occur primarily in Tertiary volcanic rocks, 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). The limited and ambiguous expression of lineament features beyond the Tertiary volcanic rocks suggests that the observed trend may represent internal bedrock structure, as opposed to a through-going crustal structure. However, because the lineament is expressed in two different geologic map units, a tectonic origin cannot be precluded based on the available data.

Lineament Groups 3a & 3b: Observations and Evaluation

Lineament group 3a is an east-west-trending group consisting of a series of linear to sub-linear, aligned drainages, approximately 40 km (~25 mi) northwest of the proposed Watana dam site (Figure A3a). Individual features range from a few hundred meters to approximately 2 kilometers (~1 mi), with an aggregate length of approximately 12 km (~7 mi). Discrete lineaments that make up the group are well expressed within the Khalitna flysch, as well as multiple mapped Tertiary volcanic units (Wilson et al., 1998). Mapped Quaternary surficial deposits show limited apparent expressions of lineaments along the observed lineament trend, but geomorphic landforms do not show any apparent deformation within the resolution of the data (Figure A3a). No previously mapped fault or lineament features align or are coincident with the observed lineament (Figure A3a). The expression of the lineament at oblique to high-angles to local and regional ice-flow patterns suggests that Quaternary glacial processes likely had little role in creating these features.

Lineament group 3b is an east-west trending lineament defined by a series of aligned, linear to sub-linear drainages, slope-breaks, and steep V-shaped notched canyons, approximately 27 km (~17 mi) north-northwest of the proposed Susitna-Watana dam site (Figure A3b). Subtle side-hill benches were observed during low-altitude helicopter-based reconnaissance of the lineament in Fall 2012. Individual mapped features range in length from approximately 300 meters to 3 km (~985 ft to 2 mi), with a group length of approximately 19 km (~12 mi). The individual mapped lineaments within group 3b traverse Tertiary intrusive and volcanic rocks, as well as Cretaceous rocks (Wilson et al., 1998) (Figure A3b). The expression of individual features within variable bedrock lithology suggests the observed trend may represent a crustal feature as opposed to structure within the bedrock units. No previously mapped fault or lineament features align with the group 3b lineament. The occurrence of the lineament at an oblique trend to regional ice-flow direction and the alignment of steep, V-notched canyons, suggests that glacial ice likely had little role in creating the observed trend. Apparent expressions of lineaments in Quaternary deposits that are not aligned with ice flow directions indicate the possibility that the mapped lineaments may represent a crustal fault. Regional stress data suggest both lineament groups, given their orientation, have the potential to accommodate deformation as east-west trending, right-lateral, strike-slip system.

Based on the overall similar trends of both 3a and 3b groups, the relatively close spatial correlation between group 3a and 3b, and the expression of lineaments in multiple bedrock lithologies suggests that lineament group 3a and 3b may conceivably be linked to represent a single, longer crustal feature and additional study is warranted (Table 4-2).

Lineament Group 4: Observations and Evaluation

Lineament group 4 consists of east-northeast trending lineaments defined by an arcuate break in slope with apparent southeast-side-up sense of motion, approximately 23 km (~14 mi) northwest of the proposed Watana dam site. Individual features defining this lineament range in length from approximately 200 m to 4.5 km (~650 ft to 3 mi), with an aggregate length of approximately 11 km (~7 mi) (Figure A4). The group 4 lineament coincides with a previously mapped unnamed thrust fault (Wilson et al., 2009). Previous work (Csejtey et al., 1978) mapped a stratigraphic offset along the arcuate slope-break, juxtaposing older Triassic metavolcanic rocks on the northwest against Cretaceous (argillite) sedimentary rocks along the southeast, with a northwest-dipping fault symbol. Kachadoorian and Moore (1979) notes Tertiary deposits overlying the fault show no apparent evidence of deformation; to the east, the thrust fault is overlain by unfaulted Tertiary volcanic sediments, and to the west the fault is terminated by an intrusion of Tertiary granodiorite (Kachadoorian and Moore, 1979). Wilson et al. (2009) show the fault as dipping to the southeast, which is relatively more consistent with the apparent topographic expression of the faulting (Figure A4).

Group 4 is spatially coincident with a previously-mapped thrust fault that juxtaposes older Triassic units over younger Cretaceous units, likely accounting for the prominent arcuate slope-break. Reportedly unfaulted Tertiary volcanic deposits that overlie the fault to the east in conjunction with the termination of the fault to the west by Tertiary granodiorites suggest the group 4 lineament features, while permissibly a fault, may represent a structure from prior stress regimes. However, there is opposing morphology along the strike of the lineament, suggesting inconsistent expression of potential fault kinematics. The apparent absence of any expressions of lineaments across the mapped bedrock units as well as in the striated glacial terrain to the west provide further support to suggest this feature as an older crustal structure. The approximate length of the lineament group is just over the delineation length criteria of 10 km (Table 4-2). The cumulative geologic and geomorphic observations suggest that the lineaments within group 4 likely do not represent a Quaternary neotectonic crustal feature, and this group is removed from additional evaluation (Table 4-2).

Lineament Group 5: Observations and Evaluation

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 mi) west-northwest of the proposed Watana dam site, near Chulitna Pass. Individual features defining this lineament range in length from approximately 350 m to 1.5 km (~1,150 ft to 1 mi), with an aggregate length of approximately 23 km (~14 mi) (Figures A5-1 and A5-2). Discrete lineaments that make up the aggregate group are expressed within both Cretaceous sedimentary rocks and Tertiary granodiorites (Wilson et al., 2009). Several lineament features are apparent in mapped Quaternary glacial sediments (Figures A5-1 and A5-2). Three unnamed drainages cross the eastern extent of the lineament group with no apparent deflection in their longitudinal traces. The eastern extent of the lineament group also coincides with a previously mapped, unnamed lineament feature (Wilson et al., 2009), and shows a general coincidence with regional ice-flow directions. Coincidence with the regional ice-flow indicators suggests that Quaternary glacial processes may have played a role in the formation of the individual lineaments. Regional stress data allows for the potential reactivation of this lineament group as an east-northeast strike-slip fault.

The projection of the lineament across variable terrain and lithologies suggests the observed trend may represent a crustal feature as opposed to internal rock structure. However, expressions of lineaments in Quaternary glacial deposits, although limited, indicate the possibility that the observed features may represent either a crustal tectonic structure or the results subglacial melt water erosional processes. Additional analysis is warranted (Table 4-2).

Lineament Group 6: Observations and Evaluation

The northeast-trending linear drainage of Watana Creek is a prominent landscape feature (Plate 1); this and smaller lineaments along Watana Creek are grouped as Lineament 6 (Figure A6; Table 4-1). The lineaments primarily define a northeast-trending, linear to sub-linear drainage, approximately 14 km (~9 mi) east of the proposed Susitna-Watana dam site. Individual features mapped via the INSAR-derived DEM range in length from 1 to 9 km (<1 to ~6 mi), with an aggregate length of approximately 17 km (~11 mi). Individual features mapped via the LiDAR-derived DEM are much shorter, typically <1 km (<1 mi) in length. The lineament group lies spatially close to the previously-mapped (as concealed and/or inferred trace) Talkeetna thrust fault (Table 4-1) (Csejtey et al., 1978; Kachadoorian and Moore, 1979; WCC, 1982; Wilson et al., 2009). Csejtey et al. (1978) also map northeast-trending, southeast-dipping, thrust faults in the hills directly east of the inferred location of the Talkeetna thrust fault. Smith et al. (1988) actually shows the trace of the Talkeetna thrust fault splaying from its traditional valley location, and climbing into the low western foothills where it juxtaposes Mesozoic and Triassic rocks. Smith et al.'s (1988) trace of the fault is, in places, depicted as concealed under Quaternary sediment. Thus, there is disagreement in the literature about the position and character of the Talkeetna thrust fault near and northeast of lineament group 6.

The mapped lineaments mostly occur in Tertiary sedimentary rocks; several small features are subtly apparent in Quaternary sediments to the northeast (Figure A6). A series of prominent slope breaks (with attributes of "1") are readily apparent in the LiDAR data near the center of the lineament group on the north bank of Watana Creek. These features could represent internal structure (i.e., bedding) within the Tertiary sedimentary rocks or have another genesis, including tectonism. The observation of sheared and deformed Tertiary sedimentary outcrops in the Watana Creek drainage (Kachadoorian and Moore, 1979; WCC, 1982) is indicative of late Tertiary faulting, possibly along these features. Kachadoorian and Moore (1979) does note tilted and possibly faulted Tertiary sediments along Watana Creek, but suggests activity was not "recent" 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. Regional stress data allows for the potential reactivation of this lineament as a northeast-oriented thrust fault.

The absence of significant numbers of mapped lineaments along the Talkeetna thrust fault south of the Susitna River appears to be consistent with prior observations, including trenching and mapping, of undeformed Tertiary volcanics overlying the part of the southwestern extents of the Talkeetna thrust fault (Figures 2-9 and 2-10; WCC, 1982). However, the Tertiary volcanics have limited spatial extent across the features and may not necessarily apply to all parts of the >75 mile (~120 km) feature length. Additionally, past field observations along the Watana Creek drainage attest to some apparent deformation of Tertiary sedimentary rocks, this current evaluation has not identified other surface landforms or features from the elevation data which would suggest Quaternary tectonic activity along this trend. Field observations by Kachadoorian and Moore (1979) document no evidence of scarps or active faulting along the inferred trace of the fault along Watana Creek. Csejtey et al. (1978) identifies the fault as a feature of Cretaceous compression, and does not note any evidence of the fault in surficial sediments. The limited regional crustal stress data (e.g., Ruppert et al., 2008) appears to suggest that northeast-striking reverse faults near the proposed dam site area may be favorably oriented for reactivation with respect to horizontal stresses.

Lineament Group 7: Observations and Evaluation

Lineament group 7 is a northeast-oriented lineament group defined by an aligned series of linear to sub-linear drainages and slope-breaks (Figure A7), approximately 28 km (~17 mi) east of the proposed Watana dam site (Figure A0 and Plate 1). Individual features defining the lineament range in length from 1 to 3 km (~3,000 ft to 2 mi), with an aggregate length of approximately 17 km (~11 mi). Mapped lineaments occur in Cretaceous (Nikolai) greenstone, Jurassic metamorphic and plutonic rocks, and Paleozoic volcanic rocks (Wilson et al., 1998; Wilson et al., 2009). A previously mapped, unnamed shear zone shown by Wilson et al. (2009) coincides with the trend of the lineament group, but has no mapped stratigraphic offsets. Additionally, the lineament group coincides with a previously mapped thrust fault (Turner and Smith, 1974; Belkman et al., 1975; Kline et al., 1990). Csejtey et al. (1978) depict a northeast-trending anticline axis relatively coincident with the group 7 lineament. Glacial ice-flow indicators occur at a high angle to the lineament trend, and suggest that Quaternary glacial processes likely had little influence on the formation of the feature. Regional stress data allows for the potential reactivation of this lineament as a northeast-oriented thrust fault.

The expression of individual features across variable bedrock lithology suggests the mapped lineament may represent a crustal feature as opposed to other causative processes such as internal structure within the rock units or depositional or erosional action. In addition, the lineament group coincides with previously mapped faults (Kachadoorian and Moore, 1979; Clautice, 1990), supporting the presence of a bedrock fault. However, Kachadoorian and Moore (1979) found little field evidence to characterize the feature, yet the fault is mapped as northwest-dipping thrust fault that traverses southerly across the Susitna River and projects toward lineament group 12. The lineament features identified in Quaternary deposits on the western portion of group 7 also project towards lineament group 12, potentially allowing the groups to connect to represent a longer crustal feature. No fault is mapped by Csejtey et al. (1978) near lineament group 7.

Lineament Group 8: Observations and Evaluation

Lineament 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, approximately 38 km (~24 miles) west of the proposed dam site. Individual geomorphic features in this lineament group range in length from approximately 400 m to 3 km (~1,310 ft to 2 mi), with an aggregate length of approximately 26 km (~16 mi). In two locations, on 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). The orthogonal orientation of the lineaments to the regional ice-flow direction suggests that the features likely do not result from ice-flow or scour. The lineament group coincides with a north-trending promontory around which the Susitna River makes a prominent bend in course (Figure A8). The southern extent of lineament group corresponds to unnamed, inferred fault mapped by Wilson et al. (2009) that juxtaposes Tertiary undivided volcanic rocks (unit Tvu) against Paleocene granite (unit Tpgr) and granodiorite (unit Tgd) against Kahlitna flysh (unit KJs) (Figure A8). WCC feature KD5-44 coincides with the lineament group 8 (Table 4-1 and Figure 2-4). 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).

Exposed bedrock (map units Tgd, Tvu, and KJs) in the area surrounding the lineament group 8 shows surface weathering patterns most likely related to rock joint sets or discontinuities (Figure A8), rather than a neotectonic structure. However, the length and consistency of individual lineaments together as a group across several different bedrock lithologies suggests the observed trend of lineament group 8 may represent a crustal feature, as opposed to internal structure (i.e., bedding or jointing) within the bedrock units. In addition, the lineament group coincides with previously mapped fault features (Figure A8), further suggesting that it represents a bedrock fault from previous stress regimes. Sparse regional stress data and conceptual stress models indicate the lineament may have a favorable orientation to reactivate as sinistral strike-slip fault.

WCC's evaluation of the lineaments in the area of group 8 (i.e., their feature KD5-44) consisted of desktop analysis, along with aerial and ground reconnaissance, and targeted field mapping. Via aerial reconnaissance, WCC geologists observed an oxidized mafic dike on the northern canyon wall of the

Susitna River that projects across the observed lineament trend. Poor exposure led to some ambiguity in the relations between the dike and the linear drainage that defines the lineament at that location, but WCC did interpret that the dike is not truncated by the linear drainage (WCC, 1982). If the dike were indeed a through-going structure that projected undeformed across the linear drainage, it would provide evidence that the drainage is not a result of tectonic deformation post-dating emplacement of the dike.

WCC reviewed previously conducted studies of the nearby Susitna River channel. Review of seismic refraction studies conducted by Shannon and Wilson in 1978 for the USACE (USACE, 1979), suggested that a bedrock step with 300 to 330 ft (~91 to 100 m) of southwest side up-northeast side down relief underlies the prominent bend in the Susitna River (WCC, 1982). Review of the INSAR-derived DEM in areas beyond the Susitna River generally shows that other, smaller, northeast-facing topographic breaks are scattered along the alignment of lineaments in group 8 (Figure A8). WCC acknowledged that the interpreted bedrock step could be a fault scarp but did not observe any evidence of surface faulting located along strike to the northwest and southeast of the bedrock step to suggest the feature was part of a through-going fault. Consequently, WCC (1982) concluded the feature to be an anomaly without clear explanation but whose genesis was likely not tectonic.

WCC's Interim Report (WCC, 1980) described zones of light-colored, fractured, and highly weathered rock in Cheechako Creek whose origin could relate to faulting, although WCC (1982) concluded that the zones were not part of a through-going fault after mapping conducted by Acres (Bruen, 1981) did not find that the zones were part of a through-going fault system. Similar, if not the same, fracture zones were also observed by FCL geologists during low-altitude aerial reconnaissance completed in September 2012.

WCC also evaluated the presence of potentially overlying rock units for evidence of displacement along the lineament. Specifically, WCC (1982) described that unfaulted Tertiary intrusive bedrock is exposed adjacent to the along-strike projection of their feature KD5-44. They observed no evidence of fault displacement of the Tertiary bedrock along the trend of the lineament feature, as exposed in the banks and channel of a tributary to Cheechako Creek. However, south of this location, more recently-compiled geologic mapping depicts a fault running along the alignment of the southern half of Feature KD5-44 that juxtaposes units KJs against Tpgr, Tvu against Tpgr, and unit Tgd against KJs (Wilson et al., 2009) (Figure A8). Considering that WCC (1982) did not find evidence of faulting nearby, this potential fault contact merits field examination. WCC (1982) also interpreted that a shallow linear depression identified in early investigations (i.e., WCC, 1980) along feature KD5-44 was related to glacio-fluvial processes and was a drainage channel cut into a terrace.

Based on the evidence excerpted above, WCC concluded that the features in the area of lineament group 8 (their Feature KD5-44) were not related to active faults but were rather "a series of unrelated lineaments whose origin is related to the alignment of stream drainages." (WCC, 1982, p. 4-63).

However, based on review of the geologic mapping and coincidence with previously mapped fault features, lineaments within group 8 may represent a potential crustal structure requiring additional evaluation in 2013 (Table 4-2).

Lineament Group 9: Observations and Evaluation

Lineament group 9 consists of north-northwest oriented features expressed principally as a prominent V-shaped linear drainage greater than 5 km (~3 mi) in length, along with smaller, linear to sub-linear aligned drainages and aligned knobs (Figures A9-1 and A9-2) approximately 31 km (~19 mi) west of the proposed dam site (Figure A0). Individual features in this lineament group range in length from approximately 400 m to 5 km (~120 ft to 3 mi), with an aggregate length of approximately 24 km (~15 mi). The orthogonal orientation of the lineament group to the regional ice-flow direction suggests that the feature likely does not result from ice-flow or scour (Figure A9-1). A sharp bend in the Susitna River exists where the lineament group projects across the river (Figure A9-1). The lineament group coincides with WCC fault KC5-5 (Table 2-1 and Figure 2-4). 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.

Individual lineaments are expressed in several geologic units: KJs, Tpgr, and at the contact between units KJs and Tpgr (Wilson et al., 2009). The northern extent of lineament group projects toward an apparently undeformed contact between KJs and Tpgr, while the southern portion of the lineament group corresponds to an inferred fault mapped by Wilson et al. (2009) that juxtaposes Tpgr against KJs (Figure A9-2). 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 along the northern extent of the lineament group, because the mapped the contact between KJs and Tpgr is apparently undeformed 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). 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).

Segment 2 is the V-shaped linear drainage >5 km (~3 mi) 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 field reconnaissance.

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 unit KJs (Figure A9-2), suggesting an apparent discrepancy in the understanding of the geologic units. 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 reconnaissance 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).

Segment 4 consists of an alignment of northeast-facing linear bedrock scarps, some of which coincide with the location of several springs. These topographic escarpments are readily apparent in the INSAR data along the southernmost portion of the lineament group (Figure A9-2). 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). After evaluating all four segments, 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; p. 4-44).

The geologic mapping and the similar orientation of lineaments in group 9 to that of lineaments of group 8 suggests that group 9 features may result from the same underlying bedrock structure and therefore represent a potential crustal structure. WCC's (1982) interpretation that several of the individual lineaments within the larger group are fault controlled suggests the presence of a potential crustal structure. In addition to cutting across several different geologic units, portions of lineament group 9 coincide with previously mapped faults, further suggesting that group 9 represents a bedrock fault. Sparse regional stress data and conceptual stress models indicate the lineament group may have a favorable orientation to reactivate as a left-slip fault. Lineaments within group 9 may represent a potential crustal structure that should have additional evaluation in 2013 as a potential seismogenic source.

Lineament Group 10: Observations and Evaluation

Lineament group 10 is an overall east-west trending lineament defined by a series of aligned V- and U-shaped troughs and slope-breaks, approximately 70 km (~44 mi) west-southwest of the proposed Watana dam site. Individual features defining this lineament range in length from approximately 100 m to 3.5 km (~330 ft to 2 mi), with an aggregate length of approximately 27 km (~17 mi) (Figures A10-1 and A10-2). Limited geologic mapping at the eastern extent of the observed trend (Wilson et al., 2009) shows chiefly east-west lineaments expressed in Tertiary granodiorites, and, to a lesser degree, Cretaceous sedimentary rocks. Northeast-oriented fabric in Cretaceous rocks is attributed to glacial ice-flow directions. The eastern extent of the lineament group is proximal to a previously mapped, unnamed lineament feature (Wilson et al., 2009) (Figure A10-2). West of the Chulitna River, the lineament group consists of a series of northwest-trending, downhill facing slope-breaks in the unmapped, but probable Quaternary surficial sediments (Figure A10-1). The individual lineament trend is sub-orthogonal to the down-valley direction of ice and water flow, and is likely unrelated to Quaternary glacial or glacio-fluvial processes. Regional stress data allow for the potential reactivation of this feature as an east-west oriented strike-slip fault.

Lineament features in group 10 occur within variable bedrock lithologies as well as across probable Quaternary deposits. The lineaments expressed in Quaternary deposits are somewhat notable, however. The kinematic sense of motion implied by lineaments observed in the Quaternary deposits to the west compared the lineaments in bedrock units to the east are inconsistent along strike. Topographic features observed in the bedrock to the east suggest south-side up motion (Figure A10-2), whereas features observed in the Quaternary deposits to the west indicate north-side up motion (Figure A10-1). Although more geologic study could be done to better understand the genesis of the group 10 lineaments, the lineament group is over 70 km (~44 mi) from the proposed dam site and less than 40 km long (Table 3-4), and likely would not appreciably contribute to the hazard calculations. It is therefore not evaluated further by this study (Table 4-2).

Lineament Group 11: Observations and Evaluation

A west-northwest trending lineament expressed as a prominent V-shaped drainage on the west and a series of smaller, linear to sub-linear, narrow depressions and aligned, discontinuous slope breaks on the east in relatively low-standing topography underlain by unmapped Quaternary deposits, based on the presence of ponds and creeks (Figure A11). The lineament group is approximately 40 km (~25 mi) west of the proposed Watana dam site. Individual features defining this lineament range in length from approximately 250 m to 7.5 km (~820 ft to 4.7 mi), with an aggregate length of approximately 18 km (~11 mi). The lineament group is entirely in sedimentary rocks of the Cretaceous Khalinta flysch sequence (Wilson et al., 2009), and coincides with two queried faults and a lineament previously mapped by Wilson et al. (2009) (Figure A11). No fault or lineament is identified in this area by Csejtey et al. (1978). Lineament group 11 projects at an oblique angle towards the southern extent of lineament 8, where Wilson et al. (2009) shows lineament 11 terminating against, and not displacing, Wilson et al.'s (2009) inferred fault that is coincident with lineament 8 (Figure A11).

Lineaments within group 11 occur entirely within sedimentary rocks of the Cretaceous Khalinta flysch sequence, and are expressed as erosional features in the landscape, with no apparent features or extension in Quaternary deposits towards the east or west (Figure A11). Additionally, the north-northwest trending lineament group 8 truncates the west-northwest end of lineament group 11. The cumulative geologic and geomorphic observations suggest surficial processes are likely exploiting existing topographic position and/or local weaknesses in the underlying bedrock to create the lineament. Because of the limited lateral continuity and because surficial processes (erosion or deposition) likely acted to construct the landscape feature, this lineament is not evaluated further. Also, this lineament group meets the exclusionary criteria (Table 3-4) because it is greater than 30 km from the proposed site and is less than 20 km in length.

Lineament Groups 12a & 12b: Observations and Evaluation

Lineament group 12a is an east-northeast trending lineament group expressed as a series of side-hill benches, approximately 14 km (~9 mi) southeast of the proposed Watana dam site. Individual features defining this lineament range in length from approximately 140 m to 1 km (~460 ft to 0.6 mi), with an aggregate length of approximately 12 km (~7 mi). Field reconnaissance of the lineament documented a pronounced mid-slope bench with an apparent sheared rock contact dipping northwest into the hillside. Discrete lineaments within the aggregate group occur primarily in mapped Paleozoic assemblages (the Slana Spur volcaniclastic rocks; Wilson et al., 2009), but there are slight scarps in possible Quaternary colluvial or solifuction sediments.

Lineament 12a traverses part of the southeastern-facing Paleozoic volcanic hills in the Fog Creek area, southeast of the proposed dam site (Plate 1, Table 4-1, Figure 2-10). The lineament is expressed as discontinuous northeast-trending side-hill benches (Figure A12a) and exhibits a pronounced mid-slope bench that appeared to be a sheared rock contact dipping into the hillside (i.e. northwest dipping) during the field reconnaissance. A tributary creek flowing nearly orthogonal across the lineament shows plan form changes (single thread channel to braided to single thread) that may be suggestive of gradient changes. To the northeast, the expression of the lineament decreases in the landscape as it projects towards Lineament 12b, however Lineament 12b has a more easterly strike as compared to 12a. Nonetheless, there are a number of faults mapped in the Paleozoic volcanics near and adjacent to 12b (Clautice, 1990), indicating that there are internal structure within the volcanics. Similar to the Talkeetna thrust fault, the regional stress model allows for preferred re-activation of these northeast-oriented structures as thrust faults.

Lineament group 12b is an east-northeast trending lineament defined by two linear to sub-linear drainages, a break in slope near the base of the hill between the two linear drainages (Figure A12b). Lineament group 12b is approximately 16 km (~10 mi) southeast of the proposed Watana dam site. Individual features defining this lineament range in length from approximately 170 m to 3 km (~560 ft to 2 mi), with an aggregate length of 11 km (~7 mi). Expressions of the lineaments within the aggregate trend occur in Paleozoic Slana Spur volcaniclastic rocks (Wilson et al., 2009). Previous mapping by Clautice (1990) indicates an unnamed, kinematically-undefined fault coincident with the lineament, as well as multiple adjacent faults to the south of lineament group 12b.

Both lineament groups 12a and 12b are roughly coincident with a previously mapped thrust fault (Turner and Smith, 1974; Belkman et al., 1975; Kachadoorian and Moore, 1979). Csejtey et al. (1978) do not map a fault near lineament groups 12a and 12b. Additionally, the trend of lineament groups 12a and 12b runs orthogonal to proximal glacial valleys, suggesting that Quaternary glacial process likely had little influence on the formation of the feature. Regional stress data suggest both lineaments, given their orientation, have the potential to reactivate as east-northeast trending strike-slip to oblique-reverse faults.

Individual features in groups 12a and 12b occur in Paleozoic assemblages, and aerial reconnaissance indicated evidence of possible bedrock shearing, and possible adjustments in creek morphology across the lineament trend that may be suggestive of localized gradient changes. Largely similar trends of lineament groups 12a and 12b, in conjunction with their spatial proximity along strike, and their association with a previously mapped structure, suggest they could potentially represent a longer crustal feature. Additionally, lineament features identified in Quaternary deposits east of group 7 and west of group 12b suggest the two groups may represent a longer continuous crustal feature. Given the relatively close distance to the proposed site, a likely fault exposed in the bedrock, and potential scarps in Quaternary alluvium, the observations suggest lineament groups 12a and 12b may need further study to clarify the lineament origin and seismogenic potential.

Lineament Group 13: Observations and Evaluation

Lineament group 13 is a north-northwest trending lineament defined by a pronounced linear drainage approximately 67 km (~42 mi) southwest of the proposed Watana dam site. Individual features defining this lineament range in length from approximately 400 m to 2.5 km (1,310 ft to 1.5 mi), with an aggregate length of approximately 15 km (~9 mi) (Figure A13). Aerial reconnaissance of lineament groups 8 and 9, which occur in similar rocks, suggests the surface expression of features in this group may partially result from underlying bedrock structure (e.g., joint sets). A previously mapped, unnamed fault (Wilson et al., 2009) coincides with the lineament group 13 trend, and depicts a faulted contact relationship between the Cretaceous sediments and Tertiary granodiorite in the northwestern extent of the lineament (Figure A13). Drainages at the northwest and southeast ends of the lineament show no apparent deflection along the observed trend. No scarps or deformation are observed in the Quaternary deposits flanking the lateral ends of the lineament group, although this does not demonstrate the absence of a fault. The orientation of the lineament sub-orthogonal to the regional ice-flow direction suggests the features did not result from Quaternary glacial processes. Regional stress data allows for the potential reactivation of this lineament as a north-northwest oriented strike-slip fault.

Lineament features that make up group 13 occur in heavily-jointed bedrock, and likely represent erosional features or enhancements where fluvial/surficial processes have exploited existing weakness in the underlying rock (Figure A13). Additionally, the observed trends have no apparent expression in the drainages to the north and south of the primary trend, nor expression in Quaternary sediments flanking the lineament, supporting the interpretation of the lineament group 13 as an erosional feature. Because of these observations, coupled with the lineament group lying greater than 40 km distance from the proposed dam site and being less than 20 km in aggregate length (Table 3-4), this lineament is discounted from further evaluation as a potential seismic source significant to the proposed dam (Table 4-2).

Lineament Group 14: Observations and Evaluation

Lineament group 14 consists of a north-northwest trending set of aligned slope-breaks, linear drainages and v-notches, approximately 62 km (~38 mi) southwest of the proposed Watana dam site. Individual features comprising this lineament range in length from approximately 300 m to 2.5 km (~985 ft to 1.5 mi), with an aggregate length of approximately 18 km (~11 mi) (Figure A14). Aerial reconnaissance of lineament groups 8 and 9, which occur in similar geologic units, suggests observed structure in this group may partially result from underlying bedrock structure (e.g. jointing). A previously mapped, unnamed fault (Wilson et al., 2009) coincides with parts of the lineament trend (Figure A14). Although adjacent to lineament group 13, and with a similar trend, available geologic mapping does not depict a fault contact between the Cretaceous sediments and the Tertiary granodiorites. The queried fault shown by Wilson et al. (2009) transects geologic units without apparent throw (Figure A14). There are several additional lineaments in the area that trend oblique (westerly) to lineament group 14 and do not align well or aggregated with the group. These lineaments may be related to ice-scour. Furthermore, the orientation of lineament group 14 is sub-orthogonal to the regional ice-flow indicators, suggesting that Quaternary glacial process may have had little role in creating lineament group 14. Regional stress data allow for the potential reactivation of this feature as a north-northwest trending strike-slip fault.

Lineament features within lineament group 14 occur in jointed bedrock, and likely represent erosional features where fluvial processes exploited existing weakness in the underlying rock. The observed trends have no apparent expression in the drainages to the north and south of the primary trend supporting the interpretation of the lineament group as an erosional feature. The lineament group is greater than 30 km from the site and less than 20 km in aggregate length, thus meeting lineament exclusion criteria (Table 3-4), it is removed from further evaluation.

Lineament Group 15: Observations and Evaluation

Lineament group 15 is a northwest-trending lineament manifested primarily by three geomorphic features: two aligned and pronounced V-shaped linear drainages and an aligned broad saddle (Figure A15), occurring approximately 43 km (~27 mi) southwest of the proposed Watana dam site. Individual features defining this lineament range in length from approximately 500 m to 1.5 km (~1,640 ft to 1 mi), with an aggregate length of 6 km (~4 mi). Discrete lineaments that comprise the aggregate group occur within Triassic metavolcanic and sedimentary rocks, but are not mapped in the Tertiary volcanic rocks that abut the southeastern lineament extent (Wilson et al., 2009) (Figure A15). This lineament is subparallel to other regional mapped faults and partly coincides with a queried fault mapped by Wilson et al. (2009). Regional ice-flow indicators are sub-orthogonal to the orientation of the lineament, and suggest that Quaternary glacial processes had little role in the formation of the feature. The oblique orientation of the lineament to the least compressive stress suggests that feature has the potential to reactivate as a strike-slip fault.

Individual lineaments that make up group 15 are expressed as relatively short and discontinuous erosional features in the bedrock landscape. The northwestern projection of lineament 15 terminates into a mapped fault. The southeastern extent of the lineament is not expressed in the Tertiary volcanic rocks and is thus inferred as not disrupting the volcanics. This condition, in addition to the few and short collection of lineaments (less than 20 km aggregate [~12 mi]), located at a considerable distance from the proposed dam site (~43 km [~27 mi]), suggest it would not be an appreciable seismic source to the proposed dam site and the lineament is removed from further evaluation.

Lineament Group 16: Observations and Evaluation

Lineament group 16 is a west-northwest trending lineament group defined by a number of aligned, linear to sub-linear drainages (Figure A16), approximately 60 km (~37 mi) southwest of the proposed Watana dam site (Figure A0). Individual features defining this lineament range in length from approximately 2 km to 6 km (~1 mi to 4 mi), with an aggregate length of approximately 19 km (~12 mi) (Figure A16). The lineaments comprising lineament group 16 cross the mapped regional lineaments of both the Susitna feature (the eastern green line in Figure A16) and the Talkeetna thrust fault (WCC, 1982) (the western green line and orange lines in Figure A16) at a high angle. WCC trench location T2 (Figures 2-4, 2-10, and A16) was located along the mapped trace of the Talkeetna thrust fault about 1 km southeast of one of the features comprising lineament group 16. Individual lineaments that comprise the aggregate group occur across Tertiary granodiorite and volcanic rocks, Cretaceous flysch, and Permian volcaniclastic rocks, (Wilson et al., 2009) (Figure A16). Previous mapping indicates a partial coincidence with an unnamed lineament (Wilson et al., 2009). The nearly orthogonal orientation of the lineament to regional ice-flow indicators suggest that Quaternary glacial processes played little role in the formation of the feature. Regional stress data allow for the reactivation of this lineament as a northwest trending strike-slip fault.

Expression of the lineament group across variable bedrock lithologies suggests a possible crustal feature, as opposed to structure within the bedrock. However, individual features comprising the lineament group are expressed as erosional features in the bedrock landscape, suggestive of a possible inactive structure exploited by fluvial processes. The cross-cutting relationship of these features, to the Susitna feature and the Talkeetna thrust fault in this area provides confirmation of the WCC (1982) conclusions for a lack of late Tertiary or Quaternary displacement in this area. In addition, group 16 represents a short group of lineaments (~19 km [~12 mi]) at a significant distance from the proposed dam site (~60 km [~37 mi]), meeting the exclusionary criteria (Table 3-4) that suggest it would not appreciably contribute to the hazard calculations for the proposed dam site. This lineament is removed from further evaluation (Table 4-2).

Groups 17a, 17b, & 17c: Observations and Evaluation

Lineament group 17a is a north-northwest trending lineament, approximately 24 km (~15 mi) west of the proposed Watana dam site (Figure A0). This lineament group is expressed as a high-angle change in the orientation of the Susitna River from approximately west-northwest to north-northwest (Plate 1). This orientation is along trend with a north-flowing linear to sub-linear tributary drainage located to the south (Figure A17a and Plate 1). A number of shorter, proximal lineaments, defined by linear slope-breaks have similar orientations to the Susitna River segment and the tributary drainage. Individual features defining this lineament range in length from approximately 1.3 km to 4 km (~0.8 mi to 2.4 mi), with an aggregate length of 11 km (~7 mi) (Figure A17a). Discrete lineaments that comprise the observed trend occur in mapped Tertiary granites and Quaternary sediments (Wilson et al., 2009), although lineament’s expression in mapped Quaternary sediments is weak to non-existent. Within mapped Quaternary sediments the lineament is expressed as a shallow, linear depression. Expression of the lineament across different lithology suggests a possible feature unrelated to structure within the bedrock. Previous mapping indicates an unnamed lineament (Wilson et al., 2009) is coincident with the observed lineament group trend however; it is not depicted on earlier maps by Csejtey et al. (1978).

Lineament group 17b is a north-northwest trending lineament group, approximately 36 km (~22 mi) southwest of the proposed Watana dam site (Figure A0), defined primarily by an east-facing bedrock ridge aligned with linear to sub-linear drainages to the northwest and southeast (Figure A17b). Several short, discontinuous features, largely defined by slope-breaks, with similar orientations occur proximal to the primary trend. Individual features defining this lineament range in length from approximately 250 m to 4 km (~820 ft to 2 mi), with an aggregate length of 20 km (~12 mi). Expression of lineament traces occur primarily in Paleozoic Slana Spur volcaniclastic rocks (Wilson et al., 2009), with lesser traces expressed in Jurassic metamorphic rocks and Tertiary volcanic rocks (Wilson et al, 2009). The occurrence of features across variable bedrock lithology, including Tertiary volcanics, suggests a possible crustal feature, as opposed to jointing or other structure within the bedrock. The observed trend coincides with a previously mapped, unnamed, lineament (Wilson et al., 2009). Evidence of glacial control is slightly ambiguous along this trend, but potential glacial striae exist at the foot of the the east-facing bedrock escarpment, suggesting some ice scour and erosion may have occurred to accentuate the linear valley. However, prominent lateral moraines and other glacial landforms largely are absent along this lineament trend.

Lineament group 17c is a north-northwest trending lineament group, defined by an aligned set of notches, V-shaped saddles, and linear to sub-linear drainages. This group is approximately 45 km (~28 mi) south-southwest of the proposed Watana dam site, and is the southernmost extent of lineament 17a, 17b, and 17c (Figures A0 and A17c, Plate 1). Individual features defining this lineament range in length from approximately 900 m to 4 km (~2,950 ft to 2 mi), with an aggregate length of 8 km (~5 mi). Individual lineaments along the observed trend occur in Tertiary volcanic rocks (Csejtey et al., 1978; Wilson et al., 2009). Whereas Csejtey et al. (1978) does not depict faults or lineaments along group 17c, other mapping indicates two unnamed faults, each about 4 km (~2 mi) in length, coincident with mapped features in the lineament group (Wilson et al., 2009) (Figure A17c). Sparse regional stress data and conceptual stress models indicate the lineament may have a favorable orientation to reactivate as left-slip fault.

These three lineament groups, 17a, 17b, and 17c, align along a similar north-northwest trend, suggesting the lineaments may be structurally related. The specific relationships between the individual groups, if any, is not yet well understood. Quaternary erosional and depositional processes may have obscured or removed geomorphic features between the groups of lineaments, reducing the expression of a longer feature. Alternatively, 17a, 17b, and 17c may be independent of one another. The topographic and geomorphic position of lineament groups 17a and 17c support a non-depositional model for genesis; the orthogonal orientation of the groups to the regional ice-flow direction suggests that the features likely did not result from ice-flow or scour. The persistence of all three lineament groups across multiple bedrock units (including Tertiary volcanics), as well as coincidence with a previously mapped fault, suggest the combined lineament group may represent a crustal feature, and a possible fault(s). Considering the total length of groups 17a, 17b, and 17c (~40 km [~25 mi]) and their closest approach distance to the proposed dam site (~30 km [~19 mi]), these lineament groups will be investigated further for an assessment of faulting and seismogenic potential.

Lineament Group 18: Observations and Evaluation

Lineament group 18 is a northeast-trending lineament group defined by aligned, linear drainages and slope breaks, approximately 52 km south-southwest of the proposed Watana dam site (Plate 1 and Figure A0). Individual features defining this lineament range in length from approximately 500 m to 3.5 km (~1,640 ft to 2.1 km), with an aggregate length of 10 km (~6 mi) (Figure A18). Expressions of discrete lineaments occur in Triassic metavolcanic and sedimentary rocks and Tertiary volcanic rocks (Wilson et al., 2009), with limited expression as drainage channels in Quaternary deposits (Figure A18). Lineament group 18 is partially coincident with an unnamed, southeast-dipping, thrust fault with Jurassic rocks in the hangingwall and Paleozoic rocks in the footwall (Csejtey et al., 1978). Previous geological maps extend this unnamed fault more southwesterly than lineament group 18 extends; this study found an absence of geomorphic or topographic features along this extended projection within the resolution of the data. The northeastern and southwestern portions of the lineament are expressed as linear valleys within a region exhibiting strong evidence of previously widespread valley glaciers. Quaternary glacial processes may have had a role in the formation of the lineament. This lineament group meets the exclusion criteria (Table 3-4), and is discounted from further evaluation.

Lineament Group 19: Observations and Evaluation

Lineament group 19 is a semi-arcuate, northeast-trending group of linear features that is nearly 44 km (~27 mi) long, located approximately 54 km (~34 mi) southeast of the proposed Watana dam site (Plate 1 and Figure A0). This feature is defined by a series of aligned linear range-fronts, slope breaks, linear valleys, and a few aligned saddles (Figures A19-1, A19-2, and A19-3). Existing geologic mapping (Wilson et al., 2009; Csejtey et al., (1978) suggests that, this lineament group may represent a bedrock contact between various Jurassic age bedrock units (mostly Trondhjemite [map unit Jtr] vs a Migmatite border zone of granodiorite [map unit Jpmu]). A northeast-trending glacial valley lies directly adjacent and sub-parallel to this lineament group (Figures A19-1 and A19-2). Lateral moraines within this valley locally form non-tectonic side-hill benches. Despite the glacial explanation of some lineaments, the aligned and abrupt northeast-facing slopes along the northern portion of the range front (Figure A19-3) and the continuation of the linear range fronts and other lineaments across several obliquely-oriented valleys (Figure A19-2 and A19-3) implies that this feature is relatively continuous and extensive. Low-altitude aerial field reconnaissance in 2012 along this lineament confirmed the observed northeast-facing slope breaks and topographic escarpments in Quaternary deposits along parts of the lineament trend north of Black River, but rock exposures were not readily apparent. 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 through A19-3). However, it is uncertain if a correlation can be made between the two features because of differences in scale at which the fault was mapped, and the horizontal distance offsetting the two. Near the middle of the lineament group, the wide Goose Creek Valley crosses the lineament group at a nearly perpendicular orientation (Figure A19-3). A preliminary topographic profile of the floor of Goose Creek Valley as it crosses the lineament group appears to exhibit drops and gradient changes that could represent tectonic deformation or simply differential erodability of the contrasting bedrock types mapped in the area. Based on the aggregate length of the individual features within group 19, its association with a previously mapped inferred fault, the presence of lineaments expressed within Quaternary deposits, as well as several abrupt slope changes along the length of the lineament group, further study of this lineament group is warranted (Table 4-2).

Lineament Group 20: Observations and Evaluation

Lineament group 20 is a northeast-trending lineament group defined by a series of sub-linear, aligned drainages, and v-notch canyons (Figure A20), approximately 94 km (~58 mi) southeast of the proposed Watana dam site (Plate 1 and Figure A0). Individual features range from a few hundred meters to approximately 1.7 km (<1,000 ft to ~1 mi) in length, with an aggregate length of 14 km (~9 mi). The features in this lineament coincide with a mapped, unnamed fault with apparent vertical throw (Csejtey et al., 1978; Wilson et al., 1998) that lies along the northeastern projection of the Castle Mountain fault (Plate 1 and Figure A0). Stratigraphic offsets are mapped along this arcuate fault trace which juxtapose Jurassic-age sedimentary rocks against one another (Jn against Jtc) as well as Jurassic sedimentary rock units against Tertiary sedimentary units (Jtk against Ttw) (Figure A20). Several drainages cut across the mapped fault at oblique or near-oblique angles and show no apparent signs of gradient deflection or planform deviation within the resolution of the data.

The expression of features in lineament group 20 across multiple bedrock units suggests the lineament group more likely represents a crustal structure as opposed to internal bedrock jointing. Lineament group 20 has a similar trend to the Castle Mountain fault, and the group is spatially proximal to the projected strike of the Castle Mountain fault. Although the overall modest length of the feature group (less than 40 km [~25 mi]) and its significant distance from the proposed dam site (greater than 70 km [~43 mi]), group 20 represents a possible northeastern extension of the Quaternary-active Castle Mountain fault, which is a major structural boundary fault that contributes to the seismic hazard. Lineament group 20 is considered for further study to assess potential structural linkages of the group to the Castle Mountain fault (Table 4-2), which could potentially extend the length of the existing modeled seismic source and reduce the distance of the seismic source to the dam site.

Groups 21a & 21b: Observations and Evaluation

Lineament group 21a is a northwest-trending group of lineaments expressed as abrupt changes in slope adjacent to otherwise flat surfaces, with downhill-facing slope breaks (Figure A21a), approximately 41 km (~25 mi) northeast of the proposed Watana dam site (Plate 1). Individual features defining this lineament group range in length from approximately 300 m to 2 km (~985 ft to 1 mi), with an aggregate length of 12 km (~7 mi). Individual lineaments on the projected trend occur variously in Quaternary deposits, Tertiary granodiorite, and Cretaceous flysch (Csejtey et al., 1992; Wilson et al. 2009) (Figure A21a). No previously mapped fault or lineament feature coincides with the projected trend of the lineament group. The lineament group 21a is near the confluence of three drainages that join Brushkana Creek. The ice direction emanating from the drainage located to the west would be of similar orientation as lineament group 21a. Conversely, the ice direction from Brushkana Creek would be northerly, as indicated by the lateral moraines and esker-like features near the center of the lineament group (Figure A21a). Glacial or periglacial processes may have had a role in constructing the lineament, the degree to which is somewhat unclear at this time. Regional stress data allow for the potential reactivation of this feature as a northwest trending strike-slip fault.

Lineament group 21b also is a northwest trending group of lineaments expressed as a series of linear slope breaks and aligned linear drainages (Figure A21b), approximately 43 km (~27 mi) north-northeast of the proposed Watana dam site. Individual features defining this lineament group range in length from approximately 300 m to 1.3 km (~985 ft to 0.8 mi), with an aggregate length of approximately 12 km (7 mi). Lineament group 21a is separated from group 21b by about 5 km (~3 mi). Discrete lineaments along lineament group 21b occur in mapped Quaternary deposits and Cretaceous flysch, and to a lesser extent, Cretaceous granite (Csejtey et al., 1992; Wilson et al., 2009). Lineaments in mapped Quaternary sediments have relatively strong expression as linear drainages, and in one case, a downhill-facing break-in-slope. No previously mapped fault or lineament feature coincides with the projected trend of the lineament group 21b. Regional stress data allow for the potential reactivation of this feature as a northwest-trending strike-slip fault.

Lineament groups 21a and 21b align along similar trends, suggesting they may collectively represent a crustal feature in contrast to bedrock-related jointing patterns, although at larger scales (i.e. more detail), features associated with groups 21a and 21b do not align as closely as suggested from a regional view. The long break in slope at the eastern extent of lineament 21b (shown in Quaternary sediment on Figure A21b) is somewhat spatially coincident with a bedding strike and dip symbol shown on Csejtey et al. (1992) mapping. It is possible that this long (> 1 km) lineament may be an expression of bedding planes within the Late Jurassic – Early Cretaceous flysch rocks. However, the 1:250,000-scale of Csejtey et al. (1992) likely introduces some scale limitations and apparent inaccuracies when depicted at 1:60,000-scale. However, the expression of features across multiple, different bedrock units, and expression in Quaternary deposits, suggests the lineament groups more likely represent a crustal structure as opposed to internal bedrock jointing and additional analysis in 2013 is warranted (Table 4-2).

Lineament Group 22: Observations and Evaluation

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 mi) northwest of the proposed Watana dam site (Plate 1, Figure A0). Individual features defining the lineament group range in length from approximately 300 m to 1 km (~985 ft to 0.6 mi), with an aggregate length of approximately 17 km (~11 mi). Lineaments of the group occur within Cretaceous granitic rocks, Mesozoic metamorphics (phyllite, schist, and amphibolite), Tertiary granitic rocks (Oligocene to Paleocene), and to a lesser extent, mapped Quaternary deposits (Csejtey et al., 1992; Wilson et al, 1998). No previously mapped fault or lineament feature coincides with or lies near the projected trend of the lineament group. Features along the western extent of the lineament group coincide with previously mapped Quaternary glacial extents, while features to the east occur orthogonally to mapped glacial extents (Reger, 1990). The geomorphic features that make up the lineaments on the southeast side of Deadman Creek are weakly expressed compared to the lineaments on the west side of the creek (Figure A22) Regional stress data allow for the potential reactivation of this feature as a northwest trending strike-slip fault.

Manifestations of lineament features occur largely as erosional features in the landscape, such as incised drainages. However, the occurrence of features across different rock units, as well as apparent expression in Quaternary deposits, suggests a possible crustal feature as opposed to structure within the bedrock. In addition, the length of the lineament group and its proximity to the proposed dam site suggest it may make an appreciable contribution to the hazard calculations, and thus it is considered for further study.

Lineament Group 23: Observations and Evaluation

Lineament group 23 is an arcuate group of roughly east-west trending lineaments defined by a series of aligned slope-breaks (Figure A23), approximately 62 km (~39 mi) southeast of the proposed Watana dam site (Plate 1). Individual features within the lineament group range in length from approximately 70 m to 3 km (~210 ft to 2 mi), with an aggregate length of approximately 17 km (~11 mi). Features along the lineament trend occur entirely within mapped Quaternary deposits, and do not coincide with any previously mapped faults or lineaments (Wilson et al., 2009). The northwest extent of the lineament group is partly spatially coincident with published glacial lake extents in the Copper Basin (Kaufmann et al., 2011), suggesting Quaternary glacial processes may have influenced the formation of this feature. The topography along the lineament group is positive relief (Figure A23), suggesting constructional geomorphic processes may have played a role in the formation. Regional stress data allow for the potential reactivation of this feature as a west-northwest trending strike-slip fault.

The morphology of lineament group 23 does appear similar to a terminal moraine complex. Regardless of its genesis, the feature's relatively subtle expression could derive from being obscured by glacial lake deposits. Although the lineament group is mapped as greater than 30 km (~18 mi) from the site, the overall length (~22 km [~14 km]) suggests that were it a fault, it may have an appreciable contribution to hazard calculations. Additionally, the features making up lineament group 23 occur entirely in Quaternary deposits and should be evaluated further to assess the potential neo-tectonic origin.

Lineament Group 24: Observations and Evaluation

Lineament group 24 is northeast-trending lineament group defined by a series of aligned slope-breaks and linear troughs (Figure A24) approximately 120 km (~75 mi) southwest of the proposed Watana dam site (Plate 1 and Figure A0). Individual features defining the lineament group range in length from 140 m to 800 m (~460 ft to 2,625 ft), with an aggregate length of approximately 15 km (~9 mi). The aligned features coincide with a previously mapped lineament (Wilson et al., 2009), and occur entirely in Quaternary fluvial and glacial deposits of the Chulitna River Valley (Figure A24). The projected trend of the lineament group occurs at an oblique angle to the modern braid plain and regional glacial trends, suggesting those processes likely had a limited role in the formation of the mapped lineaments. Regional stress data allow for the reactivation of the group of features as a northeast trending strike-slip fault.

The lineament expression and orientation in Quaternary fluvial and glacial deposits suggests that erosional or depositional processes may not have been responsible for the origin of the lineament, but does not necessarily preclude this as a genesis. The relatively lengthy extent of the lineament group suggests that a random alignment of features is a relatively unlikely explanation. However, the large distance of the features from the proposed dam site (~120 km [~75 mi]), as well as an apparent lack of feature continuity to the southwest and northeast, suggest the lineament group will not appreciably affect the seismic hazard at the proposed site, and the lineament group thus is not considered any further by this study (Table 4-2).

Lineament Group 25: Observations and Evaluation

Lineament group 25 is oriented west-northwest, and chiefly consists of linear to sublinear aligned drainages and glacial valleys, approximately 23 km (~14 mi) south of the proposed Watana dam site (Plate 1 and Figure A0). Individual features defining this lineament range in length from approximately 300 m to 4 km (~985 ft to 2.5 mi), with an aggregate length of approximately 32 km (~20 mi) (Figure A25-1 and A25-2). Previous mapping does not identify the lineament, and no readily identifiable structures were apparent during low-altitude reconnaissance, although alluvial cover along the valley floor may be obscuring relevent features. The lineament lies mostly in Paleozoic rocks (Csejtey et al., 1978) but the eastern termination of lineament lies in Jurassic granodiorite and quartz monzonite (map unit Jqm) (Wilson et al., 2009) after the lineament crosses an obliquely-oriented high-angle reverse fault (Csejtey et al., 1978). Similar to the lineaments discussed above, structures with this oblique orientation to compressive stresses would suggest a potentially favorable attitude for strike-slip faulting based on sparse regional stress data.

At smaller (less-detailed) scales the alignment of mapped features in group 25 indicates an apparent lineament trend. However, the individual lineaments consist chiefly of somewhat aligned erosional valleys or drainage features in the landscape, and do not correlate to any previously mapped lineaments or faults. It is judged that the lineament group is the results of erosion and depositional processes, and it is likely that lineament group 25 does not represent a crustal feature. Lineament group 25 is not considered any further by this study (Table 4-2).

Lineament Group 26: Observations and Evaluation

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), approximately 2 km (~1 mi) west of the proposed Watana dam site (Plates 1 and A5). Individual features defining this lineament group range in length from approximately 40 m to 1 km (~130 ft to 0.6 mi), with an aggregate length of 13 km (8 mi). North of the Susitna River the lineament group is defined by a series of linear drainage segments; south of the river the lineament group manifests as multiple aligned U-shaped troughs and a short west-facing slope-break (Figure A26). The lineament group does not coincide with any previously mapped faults. Expressions of individual features occur variously in Tertiary granitic and gneissic rocks, as well as mapped Quaternary surface deposits (Wilson et al., 2009). The projected trend of the lineament group runs orthogonal to regional ice-flow features, suggesting that Quaternary glacial processes likely had little influence on the formation of this aggregate feature.

Individual lineaments making up group 26 manifest largely as erosional features in the landscape. Expressions of the lineament group north of the Susitna River occur as linear to sub-linear drainage segments. Further, mapped lineament features at the confluence of Tsusena Creek and Susitna River coincide with apparent terrace risers cut into fluvial sediments. Linear slope-breaks mapped within the braid plain may represent paleo-margins of Tsusena Creek or the Susitna River. Features south of the Susitna River do not largely manifest as discrete landforms in the landscape, but rather as broad, approximately aligned landforms. A single discrete slope-break occurs south of the river which apparently cuts a west-southwest regional ice-scour feature, and is subsequently cut by an ice-scour feature immediately to the northwest. The unnamed drainage defining the lineament north of the river exhibits a deflection from northeast trending, to northwest trending, and back to a north-northeast trend. Although this deflection is suspicious, neither Tsusena Creek, nor the Susitna River exhibit deflections along the projected trend of the lineament group. Cumulative geologic and geomorphic observations suggest the mapped lineament group likely represents a coincident alignment of erosional features and not necessarily a crustal feature. However, based on its proximity to the proposed dam site and its aggregate length of 16 km (~10 mi), additional study of lineament group 26 in 2013 is warranted.

Lineament Group 27: Observations and Evaluation

Lineament group 27 is a northeast-trending lineament defined by an aligned series of lakes and subtle topographical troughs/swales that project towards a large and linear U-shaped valley (Figures A27-1 through A27-3), approximately 80 km (~50 mi) southeast of the proposed Watana dam site (Plate 1 and Figure A0). Individual features appear to be no longer than 1 km (~0.6 mi), and in aggregate add to approximately 50 km (~31 mi). This feature is expressed in mapped Quaternary sediments within the Copper River Basin and partially coincides with the mapped Sonona Creek fault (Wilson et al, 2009). Features observed in the western extent of the lineament group coincide with interpreted glacial features along the Oshetna River, suggesting that glacial processes may have influenced the creation of some of the mapped lineaments. However, the lineament group's orientation does align with an apparent regional structural grain in the landscape, based on the orientation of possible Castle Mountain Fault extensions, and lineament group 19.

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) and coincide with the mapped Sonona Creek fault. Previous maps only depict the Sonona Creek fault for a short distance; there are no traces of the fault mapped in the western portion of the lineament group. The northeast-trending glacial valley in this area may obscure any tectonically-derived lineaments. This effort mapped few geomorphic lineaments in this area. The presence of lineaments in Quaternary deposits that coincide with a mapped fault, albeit at considerable distance from the proposed, recommend this lineament group be studied further (Table 4-2).

Broad Pass Fault Area: Observations and Evaluation

The Broad Pass fault is a northeast trending thrust fault previously mapped by Csejtey (1961), approximately 56 km (~35 mi) northwest of the proposed Watana dam site, within the Chulitna River Valley (Plate A1). Mapping by Csejtey (1961) also indicates that the Broad Pass fault projects towards the Denali fault to the northwest, and infers a link between the two systems, but does not detail the kinematic nature of the inferred link. Mapped traces of the Broad Pass fault are defined largely by stratigraphic separation of bedrock units exposed along the middle, and east fork of the Chulitna River. Clautice et al. (2001) indicate that offset bedrock units along the middle and east fork of the Chulitna River, include Triassic rocks juxtaposed against Cretaceous and Tertiary rocks, as well as Cretaceous rocks juxtaposed against Tertiary rocks (Plate A1). Although Clautice et al. (2001) show Tertiary rocks in fault contact with both Cretaceous and Triassic rocks, Csejtey (1961) has also mapped Tertiary granodiorites overlying a strand of the fault farther north, proximal to the Denali fault.

A strong fabric of northwest-trending glacial features characterizes the geomorphology in the Chulitna Valley, with numerous landforms such as drumlins, and glacial striae occuring throughout the valley. The parallel orientation of the glacial features to the mapped trend of the fault hinders the evaluation of identifying potential evidence of Quaternary activity along the fault. Data available for this study does not provide sufficient resolution to differentiate glacial geomorphic features from potential evidence of Quaternary fault activity within the Chulitna Valley. Regional stress data allow for the potential reactivation of the Broad Pass fault as a northeast trending thrust feature.

Published maps indicate multiple mapped locations of bedrock offset on the Broad Pass fault along the Chulitna River, overlain in almost all cases by Quaternary glacial sediments. Detailed field studies of the evidence of fault activity along the Broad Pass fault are needed to evaluate the continuity and constrain the age of the Quaternary glacial deposits overlying locations with faulted bedrock. Additionally, mapping by Csejtey (1961) infers a link between the Broad Pass fault, and the Quaternary active Denali fault system, suggesting that the Broad Pass fault may have also experienced Quaternary activity, which further recommends the fault for additional study.

Clearwater Mountains: Observations and Evaluation

The Clearwater Mountains consist of an area of notably high-relief, elevated, youthful and rugged terrain in an area otherwise dominated by low-lying and subdued terrain (Plate A2). The apparent youthfulness of the terrain leads to the question of its genesis and whether the dramatic relief could be related to recently or currently active uplift. In particular, 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. In addition, the western extent of the purportedly Quaternary-active (Nokleberg et al., 1994) Broxson Gulch fault lies within the Clearwater Mountains, potentially providing a 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 A2 displays the area surrounding the Clearwater Mountains.

The geomorphology directly south of the Clearwater Mountains is heavily influenced by the presence of a terminal moraine complex. The lowest elevations are dominated by undulating kame-and-kettle topography and most of the area lies at elevations that could have been inundated by several different glacial lakes. However, prominent and laterally extensive shorelines or wave-cut benches are not readily apparent (Plate A2), although periglacial processes could have modified and obscured the original landforms. The south-sloping alluvial fans present at the southern foot of the Clearwater Mountains show no apparent topographic scarps (Plate A2). The most conspicuous potentially tectonically-derived features are numerous south- and southwest-facing linear fronts, faceted (i.e., truncated) ridgelines, and linear uphill- and down-hill facing topographic breaks which are present along the south-facing slopes at the foot of the mountains (Plate A2).

WCC (1982) conducted field reconnaissance within the Windy Creek Valley of the Clearwater Mountains. In the lower Windy Creek Valley, WCC observed that Quaternary glacial sediments overlie the trace of the Talkeetna-Broxson Gulch thrust fault. Here, the fault dips northward and is defined by the contrast between the metasedimentary rocks of the Maclaren terrane and the volcanic rocks of the Wrangellia terrane (WCC, 1982). The dip direction is inferred from the presence of overturned drag folds exposed in Windy Creek.

Several publications depict the Broxson Gulch fault trending westward from the Denali fault into the Clearwater Mountains, but the literature is ambiguous on the neotectonism. Nokleberg et al. (1985) describe that the Broxson Gulch fault has had a long and complex history of movement, but that it has experienced strike-slip and thrust movement as recently as the late Tertiary, as evidenced by “inclusion of middle Tertiary sedimentary and volcanic rocks in the thrust and by onlap of the thrust by Quaternary glacial deposits.” (p. 1264). The phrase *onlap of the thrust by Quaternary glacial deposits* suggests that Quaternary deposits overlie the fault and are undeformed. However, later publications suggest that the fault does deform Quaternary deposits: “[s]outh-vergent movement [on the Broxson Gulch fault] is indicated by (Nokleberg and others, 1982, 1985, 1989a, and 1992b) (1) juxtaposition of older bedrock of the Wrangellia terrane over Tertiary sedimentary and volcanic rocks, and over Wisconsin glacial deposits along various north-dipping branches of the fault….” (Nokleberg et al., 1994, p. 354). Review of the mapping cited above as evidence of both deformed and un-deformed Quaternary glacial deposits (Nokelberg et al., 1982 and 1992), is inconclusive as to the nature and locations of any faulted or un-faulted Quaternary glacial deposits because: (1) the contact relations of the bedrock units are complex in this area, (2) the reconnaissance scale (1:250,000) precludes the authors from showing substantive detail, and (3) the image quality of the electronic copies readily available is poor.

Based on review of the INSAR data in the area of the potential junction of the Broxson Gulch fault and the Talkeetna thrust faults, only a few mapped lineaments potentially coincide with previously mapped faults (Plate A2). Furthermore, the Talkeetna thrust fault is not readily apparent in the Quaternary glacial and fluvial deposits of neither the Susitna River valley nor the Windy Creek valley (Plate A2). Individual mapped lineaments range from 200 m (60 ft) to 1000 m (300 ft) in length and only a few aggregate into apparent groups that lie along consistent trends. One such group of lineaments is an approximately 16- km-long, approximately east-west oriented aggregation of lineaments that may coincide with the mapped Black Creek fault (Plate A2). In addition, several linear saddles located between the South Fork Pass Creek and the Windy Creek Valleys also roughly coincide with locations of faults mapped by Smith (1981), Silberling at al. (1981), and Csejtey et al. (1992) (Plate A2). The potential junction of the Broxson Gulch fault and Talkeetna thrust faults lies approximately 83 km (52 mi) northeast of the proposed dam site.

Several different iterations of geologic mapping exist for the area of the southern Clearwater Mountains. 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). These maps all cover at least a portion of the area and all show a buried fault running the length of the Windy Creek Valley that corresponds to the Talkeetna thrust fault. However, the maps do differ in the level of detailed mapping of the high-elevation glaciated terrain to the north, south, and east of the Windy Creek Valley.

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 A2). 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 data reviewed for this effort, the possibility that the Clearwater Mountains are the result of Quaternary uplift along a blind thrust fault is difficult to fully evaluate. For example, the geomorphology directly south of the Clearwater Mountains is heavily influenced by the presence of a terminal moraine complex which results in altered stream gradients and patterns that could otherwise be a result of broad uplift. Furthermore, no aggregations of individual lineaments or tilted tectonic markers (such as shorelines or terraces) that could be definitively linked to a tectonic origin were readily apparent in the area south of the mountains. However, numerous south-facing linear fronts, faceted (truncated) ridgelines, and linear uphill- and down-hill facing topographic breaks, which are geomorphic features commonly associated with active faults, are present. More detailed study is warranted.

Based on review of the INSAR data, the trace of the Broxson Gulch fault is not readily apparent in Quaternary deposits of the Pass Creek area. However, Nokleberg et al. (1994) describe the fault as having a long and complex history that most recently includes the thrusting of Wrangellia terrane (Paleozoic to Triassic age, i.e., no younger than about 200 million years old) rocks over Quaternary glacial deposits. The fault could represent a similar feature to the Susitna Glacier fault and provide a mechanism to transfer slip from the Denali fault to the southwest. This potential Quaternary activity and potential linkages to the Denali fault and Talkeetna thrust fault, suggest that Broxson Gulch-Black Creek-Talkeetna thrust fault intersection area contains crustal features worthy of additional study.

Castle Mountain Fault Splay Extension: Observations and Evaluation

The Castle Mountain fault is a Quaternary seismogenic structure, as well as a major structural boundary with the potential to contribute to the ground shaking at the proposed dam site. 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 A3). 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 A3). Lineament features aligned with the Castle Mountain fault could potentially increase the overall rupture length of the fault, and thus increase the potential contribution of the fault to the ground motion estimations at the proposed site.

Lineaments within the northeast trending group are defined by a series of side-hill benches, uphill-facing slope-breaks, and linear, v- and U-shaped troughs, approximately 100 km (~62 mi) southeast of the proposed Watana dam site (Plate A3). Individual features within the group range in length from approximately 70 m to 2.5 km (~230 ft to 1.5 mi) , with an aggregate length of approximately 21 km (~13 mi). A previously mapped fault (Csejtey et al., 1978) coincides with the lineament group. Observed lineament features occur in multiple bedrock lithologies, including: a Cretaceous quartz monzonite, and the Jurassic Talkeetna, Chinitna, Tuxedni, and Naknek formations.

Bubb Creek, Little Nelchina River, and Tyone Creek show apparent course deflections that coincide with the potential projected extension of the Castle Mountain fault. All three waterways show a progressive change in their courses from east-flowing as they approach the lineament, to southeast-flowing just before crossing the projected lineament trend, and back to east-flowing after crossing the projected trend (Plate A3). The change in the course of each waterway from southeastward to eastward coincides with the lineament features evident in the surrounding terrain, as well as previously mapped features by Csejtey et al. (1978), but no lineament features are apparent in the Quaternary deposits associated with the three waterways. Although Tyone Creek exhibits a change in course similar to both Little Nelchina River and Bubb Creek to the southwest, there are no apparent lineament features in the bedrock terrain on either side of the Tyone Creek that coincide with the projected trend of the lineament group.

Individual lineaments occur within multiple bedrock units, spatially correlate with mapped splays of the Castle Mountain fault, and project along a similar trend. The proximal spatial correlation and similar trend of the lineament group to the Castle Mountain fault suggest that the lineament group could potentially rupture 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 mi) to the northeast of the current mapped extent of the fault as shown in Koehler et al. (2012).

North-South Features near Talkeetna River-Susitna River Confluence: Observations and Evaluation

A number of north-south trending, unnamed, normal faults are identified in previous mapping by Wilson et al. (1998; 2009), approximately 85 km (~53 mi) southwest of the proposed Watana dam site (Plate A4). Individual faults that comprise the north-south suite of normal faults range in length from approximately 3 to 30 km (~2 to 19 mi), with an aggregate length of 43 km (~27 mi). Wilson et al. (1998, 2009) indicate one location of possible bedrock offset at the southern end of the longest mapped normal fault (~30 km [~19 mi]) in an east-west trending drainage (Plate A4). The apparent bedrock offset places younger Cretaceous granodiorites to the east, against older Cretaceous gabbroic rocks to the west. North and south of the apparent bedrock offset, the inferred fault trace generally coincides with a series of sinuous, north-south-trending features, cut in multiple locations by east-west-trending drainages. Other normal faults mapped within the suite coincide with similar sinuous, north-south-trending features. The sinuous, north-south trending features may represent an abandoned drainage network. Excepting the previously mentioned north-south-trending features, the normal faults have little to no apparent expression in Quaternary deposits. Additionally, the mapped normal faults generally coincide with the orientation of regional ice-flow indicators, suggesting Quaternary glacial processes may have influenced or created the expression of the features.

The identification of one location of apparent bedrock offset (Wilson et al., 1998; Wilson et al., 2009) indicates that at least one of the north-south trending faults may represent a crustal structure. However, with the exception of the mapped offset, the observed features have little to no apparent expression in the surrounding Quaternary sediments, or in Tertiary granodiorite outcrops further north. Expressions of the mapped faults in Quaternary sediments consist almost entirely of erosional features (i.e., terrace risers cut into glacial outwash plains) suggestive of an abandoned, north-south-trending drainage network. The geologic and geomorphic evidence suggests that the suite of north-south-trending faults may possibly represent a crustal structure developed from previous stress regimes but there is no readily apparent geomorphic expression of the faults.

The north-south trending normal faults of the Talkeetna River-Susitna River confluence area are not considered for further study on the basis of their large distance (i.e., >70 km [>40 mi]) to the proposed dam site and their poor expression in the surrounding Quaternary sediments and Tertiary granodiorite outcrops (Table 4-2).

4.2 LiDAR-Based Mapping

Lineament mapping in the proposed reservoir area based on the presently available LiDAR elevation data is shown on Figure 4-2 and Plate A6. Compared to the reconnaissance mapping on the INSAR-derived DEMs the increased number and diversity of lineaments mapped at this more-detailed scale reflects the multi-genetic origin of landscape lineaments and the increased ability to recognize small geomorphic features. For example, multiple lineaments on the north and south side of Susitna River are oriented west-southwest; these features likely are created by non-tectonic processes based on their length, frequency of occurrence, consistent attitudes, and geomorphic settings. It is likely that the features were developed by ice flow, and perhaps subsequently blanketed by some limited thickness of fine-grained glacio-lacustrine deposits. Other lineaments mapped in locations of high-standing terrain, particularly in the north-central and southeast portions of Plate A6, show a more diverse set of orientations likely related to bedrock fabric and drainage networks.

Lineaments located on the north side of the Susitna River along the projection of the Talkeetna thrust fault are presented on Plate A6 and Figure A6 and discussed in Section 4.1.1 above. Of particular significance for fault evaluations, are the absence of any lineaments evident in the LiDAR that are parallel to or along the projection of the Talkeetna thrust fault in the area south of the Susitna River and near Fog Lakes (Figure 4-2 and Plate A6).

Early site investigations identified a zone of fractured and highly disturbed rock[5], with a prominent exposure in the cliffs along the north side of the Susitna River directly upstream of, but not traversing, the dam site (Acres, 1981). The structure, termed the "Fins" feature, also known as GF 1 in Acres (1981, 1982) and Harza-Ebasco (1984), , strikes northwest-southeast between the Susitna River and Tsusena Creek and dips 70 to 75 degrees to the northeast (WCC, 1982).

A set of north-northwest trending lineaments are mapped north of the proposed dam site, and do not intersect the proposed footprint. These lineaments are mapped near the location of the Fins feature of WCC (1982), but appear to have a more westerly strike as compared to the Fins feature. These lineaments are somewhat restricted in their distribution, being mapped chiefly between the proposed

[5] Previous studies for the Watana dam site identified several significant geologic features which consist of broad areas of shears, fracture zones, alteration zones, and/or combinations of these features. These areas (or individual structures) considered significant to warrant detailed discussion were identified by letters GF 1 through GF 8 and discussed individually by Acres (1981). One of these areas, initially mapped by the Army Corps of Engineers (1979) and further studied by Acres (1981, 1982), was called "The Fins" (GF 1). The GF 1 through GF terminology was also used in Harza-Ebasco (1984).

dam site and Tsuena Creek (Figure 4-2). The Fins feature 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 borings 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." Borrow area and geotechnical evaluations in the Harza-Ebasco studies depict a sequence of Quaternary glacial deposits which would overlie the extensions of the northwest striking feature and which appear to be unfaulted. However, further field evaluation of the structure would be necessary to verify the conclusions of WCC (1982) and Harza-Ebasco (1984).

Other lineaments in the LiDAR map area follow a northwest trend, and to a lesser amount, west-northwest trends (Figure 4-2 and Plate A6). A series of northwest trending lineaments extending from the south side of the river to the north side are mapped approximately 1.5 mi downstream of the proposed dam site (Figure 4-2 and Plate A6). This lineament set, lineament group 26 (Figure A26), is west of the "Fins" lineament of WCC (1982), and does not appear to be coincident with that feature. Although no strong expression of Quaternary faulting was observed during the reconnaissance, it is difficult to ascribe a glacial origin to this lineament set based on its orientation and position on the landscape although erosional processes are plausible a explanation of genesis.

Multiple shorter lineaments are mapped throughout the LiDAR map area; a number of them likely are related to gully development along the top of the river valley bluffs based on the similarity of gully morphology and gully frequency. Based on helicopter reconnaissance, a number of lineaments on the flanks of the river valley appear to be related to caribou trails on the landscape; others may have been remnants of past seismic refraction lines. Locally, some of these features are subparallel to river bluffs and may represent local slope movement or trails along the bluff edge. At the eastern part of the LiDAR map area (Figure 4-2), a north-south–trending lineament set is mapped both on the south and north side of the Susitna River bluffs. The lineament is not readily apparent outside of the LiDAR extent within in the Quaternary glaciolacustrine deposits on the north side of the River.

4.3 Discussion of the Thirteen "Significant" Features of WCC (1980, 1982)

Of the 13 significant lineaments investigated by WCC (1980), this study found three of the WCC lineaments coincide either proximally, in part, or in whole (FCL lineaments 6, 8, 9; Table 4-1) with newly mapped lineaments. The following section reviews previous interpretations of the 13 "significant" features identified by WCC (1980, 1982) and discusses the interpretations and reasoning made during the current study based on review of the INSAR and additional data to provide a rationale for why certain lineaments proposed in WCC are not adopted by this study.

Susitna Feature

The Susitna feature was described by Gedney (1976) as a topographic lineament observed on LANDSAT imagery (WCC, 1980). Previously, Turner and Smith (1974) inferred the presence of a Susitna feature as a fault based on thermal geochronology data that suggested a difference in rock cooling rates in plutonic units on either side of the Sustina Glacier, and which was interpreted as a manifestation of Cenozoic fault throw. Turner and Smith (1974) place an inferred trace of the Susitna feature along the present day Susitna Glacier. This is the location where the 2002 surface rupture occurred along the Susitna Glacier fault, that ruptured just above the base of the mountains and curved northward beneath the glacier and propagated to the Denali fault. Based on this information, it is likely that the varying geochronologic data are more attributable to fault throw along the Susitna Glacier fault, rather than the Susitna feature. The Susitna Glacier fault, as it is mapped, truncates the northern inferred trace of the postulated Susitna feature. In addition, Csejtey et al. (1978) report an absence of physical field evidence for the postulated Susitna feature. WCC (1982) evaluated geomorphic features along the lineament including a trench excavation across a prominent scarp (at location S1 on Figures 2-4 and 2-10) and concluded that the scarp is not related to faulting but rather is of glacial origin. Therefore, based on the absence of geomorphic expression found by this study as well as previous studies, coupled with the new knowledge of the Susitna Glacier fault where the Susitna feature was first postulated, the Susitna feature is not considered further as a significant lineament or fault-related feature in the vicinity of the proposed Watana Dam site.

Watana Lineament

According to WCC (1980), 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 SLAR imagery. WCC (1980) describe that, at the scale of the imagery, the lineament corresponds to a series of somewhat linear sections of the Susitna River between approximately the confluences of Tsusena Creek on the west and Jay Creek on the east. However, Gedney (1975) states that “the occurrence of lineaments in an east-west direction is practically nil, and this makes it seem unlikely that the course of the Susitna River is fault controlled.” During the WCC (1980) investigation, “virtually no evidence of a major through-going lineament was observed.” (p. 8-24). Additionally, WCC 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. Furthermore, the Watana feature is not recognized in mapping by Lahr and Kachadoorian (1975), Csejtey et al. (1978), Kachadoorian and Moore (1979), Williams and Galloway (1985), or Wilson et al. (1998).

Mapping by Clautice (1990) depicts an 11-km-long fault that juxtaposes Jurassic rocks against pre-Permian volcanics terminating approximately 37 km (23 mi) east of the site. The feature was drawn on the north side of Susitna River in a steep topographic depression, crossing the river near about river mile

234, and continuing along the south side of the river for about 8 km (5 mi). The trend of this fault is N65W, and it projects approximately 7 km north of the proposed site based on its depicted orientation. Clautice (1990) depicts this fault as a splay of a mostly-concealed (i.e. inferred) fault trace he dubs the West Fork fault.

This study found an absence of geomorphologic expression along the proposed Watana lineament, consistent with 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 river were inspected during low-altitude reconnaissance and judged to be from caribou tracks at the heads of steep gullies. At this time, direct or indirect geologic evidence of a crustal structure (i.e., fault) along this postulated lineament is absent.

Fins Feature

The "Fins" feature, also known as geologic feature 1 (GF 1) of Acres (1981, 1982) and Harza-Ebasco (1984), is discussed above in Section 4.2.

Talkeetna Thrust Fault

The Talkeetna thrust fault is discussed above as part of lineament group 6 in Section 4.1.1.

Feature KC5-5

Feature KC5-5 coincides with lineament group 9, which is discussed above in Section 4.1.1.

Feature KD5-2

WCC lineament KD5-2 is not considered a seismic source for this study because it is less than 10 km long and greater than 30 km from the dam site. It is therefore not considered further.

Feature KD5-3

WCC lineament KD5-3 was attributed to Landsat imagery interpretation by Gedney and Shapiro (1975) and geologic studies by Kachadoorian and Moore (1979). This lineament extends from the valley of Portage Creek southerly though the Susitna River valley. Both valleys' morphology appears to be a result of non-tectonic processes; depositional and erosional landforms are aligned in the down-valley direction parallel to local glacial ice flow directions. Field reconnaissance by WCC (1982) found no evidence of a fault along this lineament whose origin was attributed to glacial-related processes (WCC, 1982). Geologic mapping available to this study do not recognize a lineament or fault along the Portage

Creek valley. Based on an absence of geomorphic and geologic evidence to support that the lineament is a fault, this current study does not recognize WCC lineament KD5-3 as a seismic source.

Feature KD5-9

WCC lineament KD5-9 is not considered a credible seismic source for this study because it is less than 10 km long and greater than 30 km from the dam site. It is therefore not considered further.

Feature KD5-12

No geomorphic evidence of expression of WCC lineament KD5-12 was recognized by this study's landscape analysis. Field reconnaissance by WCC (1980) found an absence of evidence of a fault or structural control along this lineament where it crosses the Susitna River, and later reconnaissance by WCC (1982) found additional evidence that the lineament was not fault-related. There is no evidence to provide a basis for consideration of WCC lineament KD5-12 as a seismic source and it is not considered further.

Feature KD5-42

WCC lineament KD5-42 is not considered a seismic source for this study because it is less than 10 km long and greater than 30 km from the dam site. It is therefore not considered further.

Feature KD5-43

WCC lineament KD5-43 is not considered a seismic source for this study because it is less than 10 km long and greater than 30 km from the dam site. It is therefore not considered further.

Feature KD5-44

Feature KD5-44 coincides with lineament group 8, which is discussed above in Section 4.4.1.

Feature KD5-45

No geomorphic evidence of expression of WCC lineament KD5-45 was recognized by this study's landscape analysis. Field reconnaissance by WCC (1980) found an absence of evidence of a fault or structural control along this lineament where it crosses the Susitna River. Following further reconnaissance, WCC (1982) judged the lineament originated from glacial processes, and lacked morphologic features representative of fault genesis. Therefore WCC lineament KD5-45 is not considered further.

5.0 SUMMARY

The purpose of the lineament mapping and evaluation is two-fold: (1) to identify potential seismic sources (i.e., crustal faults) that could appreciably contribute to the seismic hazard at the proposed dam site and thus affect dam design; and (2) to identify faults and assess the potential for surface fault rupture at the proposed dam site area. An outcome of this study is identification and prioritization of potentially fault-related features of engineering significance that would require additional analysis in the year 2013 field season.

The approach included reviewing the results of the WCC studies (WCC, 1980; WCC, 1982), as well as other maps, reports, and literature, and using recently-acquired, detailed topographic imagery data (i.e., INSAR and LiDAR) to re-examine the landscape for evidence of geomorphic features suggestive of Quaternary faulting that may affect the seismic hazard to the proposed dam site. This lineament mapping forms a basis for recognizing and evaluating potential seismic sources previously not accounted for in the initial PSHA (i.e., FCL, 2012), and to document the presence or absence of lineaments near the proposed dam site area for site-specific surface fault rupture evaluations. Based on results of initial PSHA evaluations, the study region is limited to areas south of the Denali fault within about 100 km (~62 mi) radius of the Watana dam site.

Following the identification and mapping of potential fault-related lineaments throughout the study region, the lineaments' relevance to the seismic hazard investigation of the Watana dam site was evaluated through a series of inclusive criteria (Section 3.5 and Table 3-3). These criteria served as a basis for delineating potentially tectonically-relevant lineament groups which consist of areas of lineaments having consistently similar orientations that when aggregated together as a group, have a relatively appreciable length and which trend across terrain in a similar manner to a potential through-going tectonic fault. From these criteria, 32 lineament groups and four areas of lineaments were identified for further evaluation (Table 4-2).

Following aggregation of the individual lineaments, the lineament groups and larger areas were screened using exclusionary criteria (Table 3-4) to focus further efforts on features most significant to the Watana dam site seismic hazard evaluations. These criteria included length and distance measures along with evaluations from geological and geomorphological data compiled on 1:60,000-scale strip maps (Section 4.1.1). The screening process thus required a desktop examination of the identified lineament groups to assess the possible genesis of the features. The screening process removed lineaments that demonstrated strong evidence of being non-tectonic in origin, or those that likely would not appreciably contribute to the seismic hazard at the proposed dam site. Through this evaluation, the initial 32 lineament groups and four areas were reduced to 22 lineament groups and three areas (Table 4-2). Three of the 22 lineament groups are spatially proximal with the previously-mapped 13 significant lineaments identified for the combined Watana and Devil Canyon projects presented in WCC

(1982). However, the current mapping did not identify a lineament group consistent with the previously mapped Susitna feature or along WCC's (1982) Watana lineament within the study region.

The 22 lineament groups and features within the three larger study areas remaining from the evaluation and screening phases all have some attributes that are potentially indicative of association with Quaternary faulting and/or significance to the Watana dam site seismic hazard investigation (Table 4-2). If warranted by further evaluations, the 22 lineament groups would be candidates for consideration as new features in the regional seismic source characterization. Conversely, not all 22 lineament groups necessarily would be candidates as new features, depending on the further evaluations. The distant study areas consist of the Broad Pass, Clearwater Mountains (i.e. Broxson Gulch), and eastern-most Castle Mountain fault areas. These areas represent extensions of previously known or suggested Quaternary faults and are not presently considered in the preliminary Watana seismic source model (FCL, 2012). The additional evaluations described below will provide data on which seismic source characterizations of these features can be based.

5.1 Future Evaluations

While the desktop lineament mapping has identified potential candidate features and areas, information crucial to evaluation of the lineaments will need to be collected in the field to assess the origin and significance of these lineament groups. The observations and interpretations from the initial mapping and reconnaissance described in this report will facilitate and solidify the further characterization and evaluations of lineament groups and potentially relevant features to the project. A framework for further evaluation of the mapped lineaments to provide preliminary and final seismic source characterization inputs for the deterministic and probabilistic seismic hazard evaluations is outlined below.

Five potential activity phases are identified to further evaluate the lineaments as possible refinements to the preliminary seismic hazard model (FCL, 2012): (1) limited additional desktop analysis, (2) field reconnaissance, (3) detailed site mapping and geomorphic evaluation, (4) site specific and subsurface investigations, and (5) seismic source characterization and integration with the PSHA source model. It is anticipated that not all lineament groups and features will require additional or significant effort on each step. For example, it is expected that only some sites might ultimately be considered as candidates for site-specific or subsurface investigations.

The objective of the limited desktop analysis Phase 1 activities is to further compile and synthesize the data for the 22 lineament groups and three larger areas that will need field reconnaissance. These activities, including preparation of site-specific field maps, are important for conducting efficient data collection and documentation in the field.

Specific additional field reconnaissance for Phase 2 activities on the 22 potentially tectonically-relevant lineament groups and potentially tectonically-relevant features within the three larger areas would be conducted to verify existing mapping and geologic relationships, field check geologic exposures and information, and to gather initial stratigraphic and geomorphic data. The anticipated level of reconnaissance effort required to gather field data during 2013 reconnaissance varies for each lineament based on the data evaluation. Additional field studies in summer 2013 would be based on the results of the initial field reconnaissance.

5.1.1 Objectives and Selection of Features for Future Detailed Field Studies (Phases 3 through 5)

The results from the Phase 2 reconnaissance investigations described in preceding the section are expected to identify sites for further field studies including surficial geologic mapping, developing stratigraphic relationships, age-dating, and potential subsurface or geophysical investigations. From these sites an initial "shortlist" of potential field sites would be screened for issues related to field access, permits, and other logistics that might impact future study plans. In addition, the results of the reconnaissance investigations would be evaluated for potential impact on seismic source characterizations and site faulting evaluations to consider whether further data would modify conclusions or significantly reduce uncertainty.

The detailed site mapping (Phase 3) would develop local geologic and geomorphic mapping for site-specific fault activity evaluations. This phase could include: detailed mapping and data collection for geomorphic site evaluation, mapping and sample collection for age dating at key stratigraphic sites to establish local and regional chronologies, and site-specific evaluation of the potential for trenching, test pits, or other subsurface investigation methods.

At selected locations, based on the detailed mapping results, subsurface investigations such as geophysical lines, test pits, or paleoseismic trenching would be conducted (Phase 4). These data would provide site-specific information for the final evaluations of specific lineaments and features. Interpretation of the data from these investigations would be used to update prior documentation and evaluation for seismic source characterization.

Phase 5 of evaluation will integrate all results with the PSHA and ground motion source model. The data from the desktop and field phases would be integrated into an updated regional tectonic model. Along with additional regional and local data from ongoing seismic monitoring in the region, these data would be used to develop updated seismic source characterizations for seismic sources in the Watana site region and to support local surface faulting evaluations for site geohazards and triggered seismicity evaluations.

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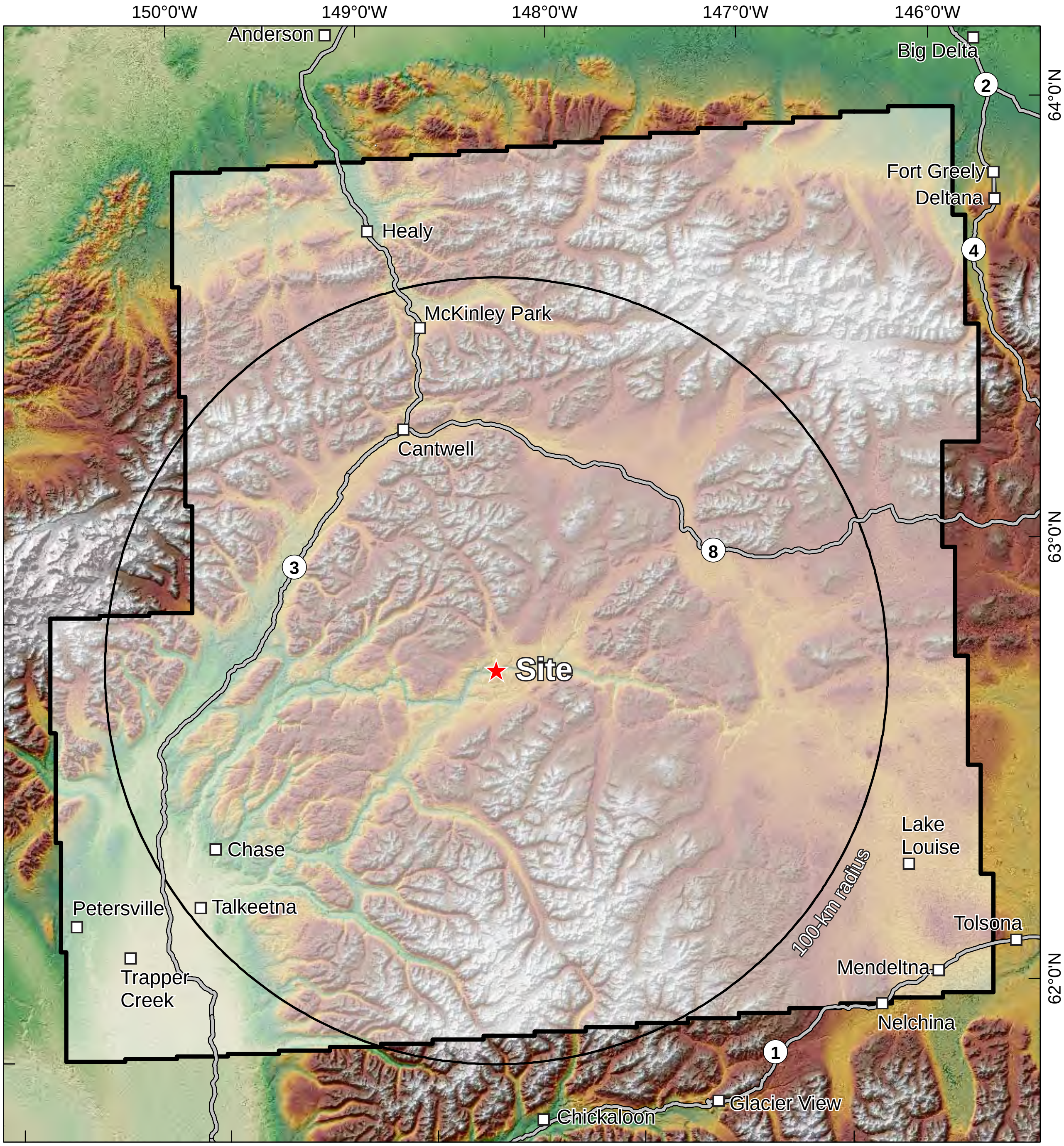
Wilson, F.H., Dover, J.H., Bradley, D.C., Weber, F.R., Bundtzen, T.K., and Haeussler, P.J., (1998), Geologic map of central (interior) Alaska: U.S. Geological Survey Open-File Report 98-0133-B, 63 p., 3 sheets.

Wilson, F. H., Hults, C.P., Schmoll, H.R., Haeussler, P.J., Schmidt, J.M., Yehle, L.A. and Labay K.A., (2009), Preliminary Geologic Map of the Cook Inlet Region, Alaska U.S. Geological Survey Open-File Report 2009-1108, 54 p., 2 sheets.

Woodward-Clyde Consultants (WCC), (1980), Interim Report on Seismic Studies for Susitna Hydroelectric Project. Prepared for Acres American Inc.

Woodward-Clyde Consultants (WCC), (1982), Subtasks 4.09 through 4.15, Final Report on Seismic Studies for Susitna Hydroelectric Project.



Base data from ASTER Global Digital Elevation Model

N

0 20 mi

0 40 km

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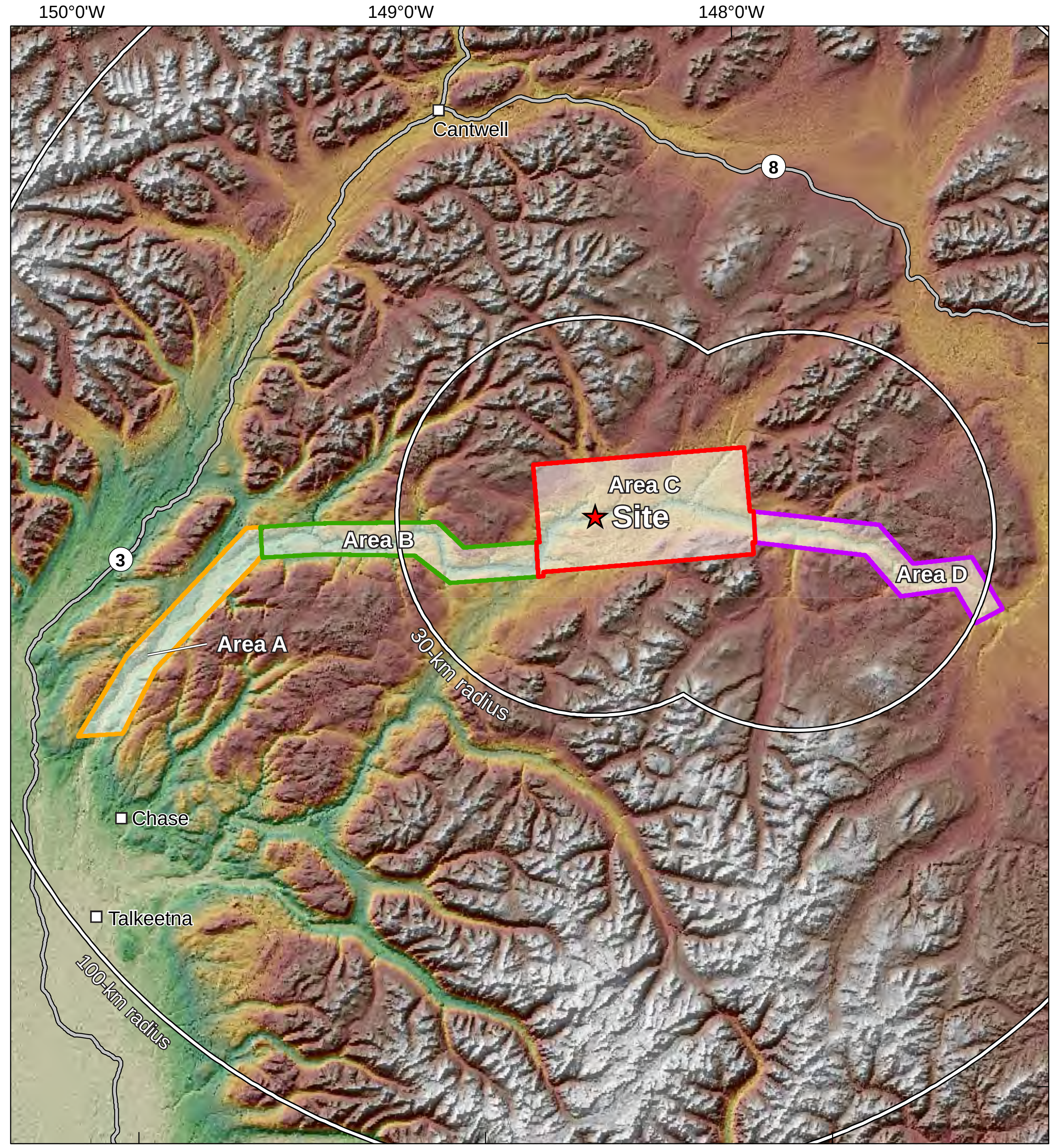
SUSITNA-WATANA HYDROELECTRIC PROJECT

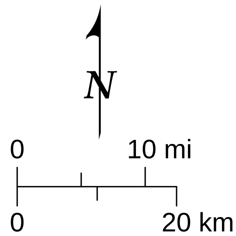
EXTENT OF INSAR DATA

02/04/13

FIGURE 2-1



Base data from ASTER Global Digital Elevation Model



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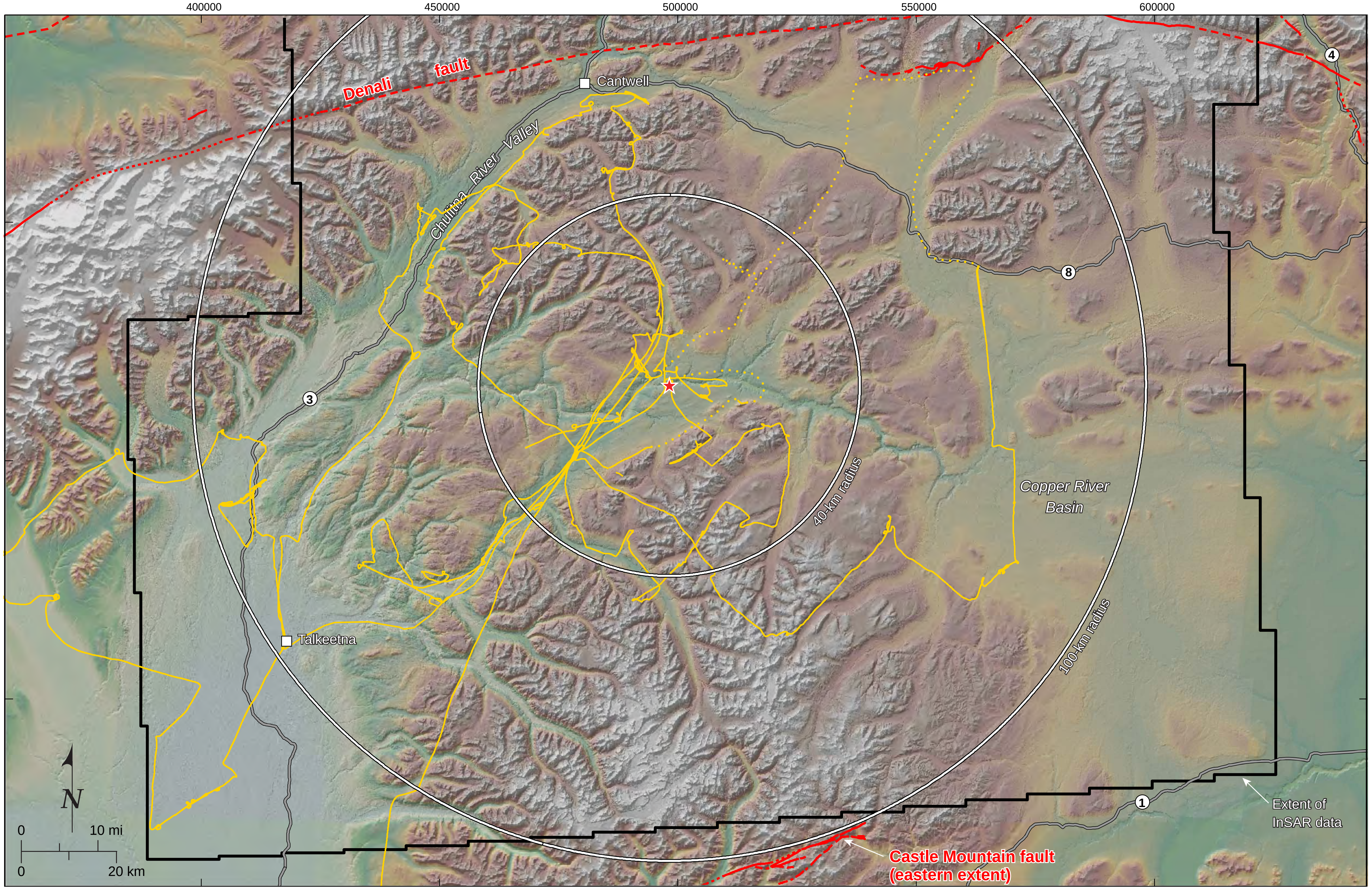
EXTENT OF LIDAR DATA

02/04/13

FIGURE 2-2



Explanation

- Quaternary fault, solid where well constrained, long dash where moderately constrained, short dash where inferred (Koehler et al., 2012)
- Proposed Watana site
- GPS track, dotted where estimated (September 2012 reconnaissance)

Coordinates on NAD83 UTM 6 North.
Elevation from IFSAR data and USGS SRTM data.

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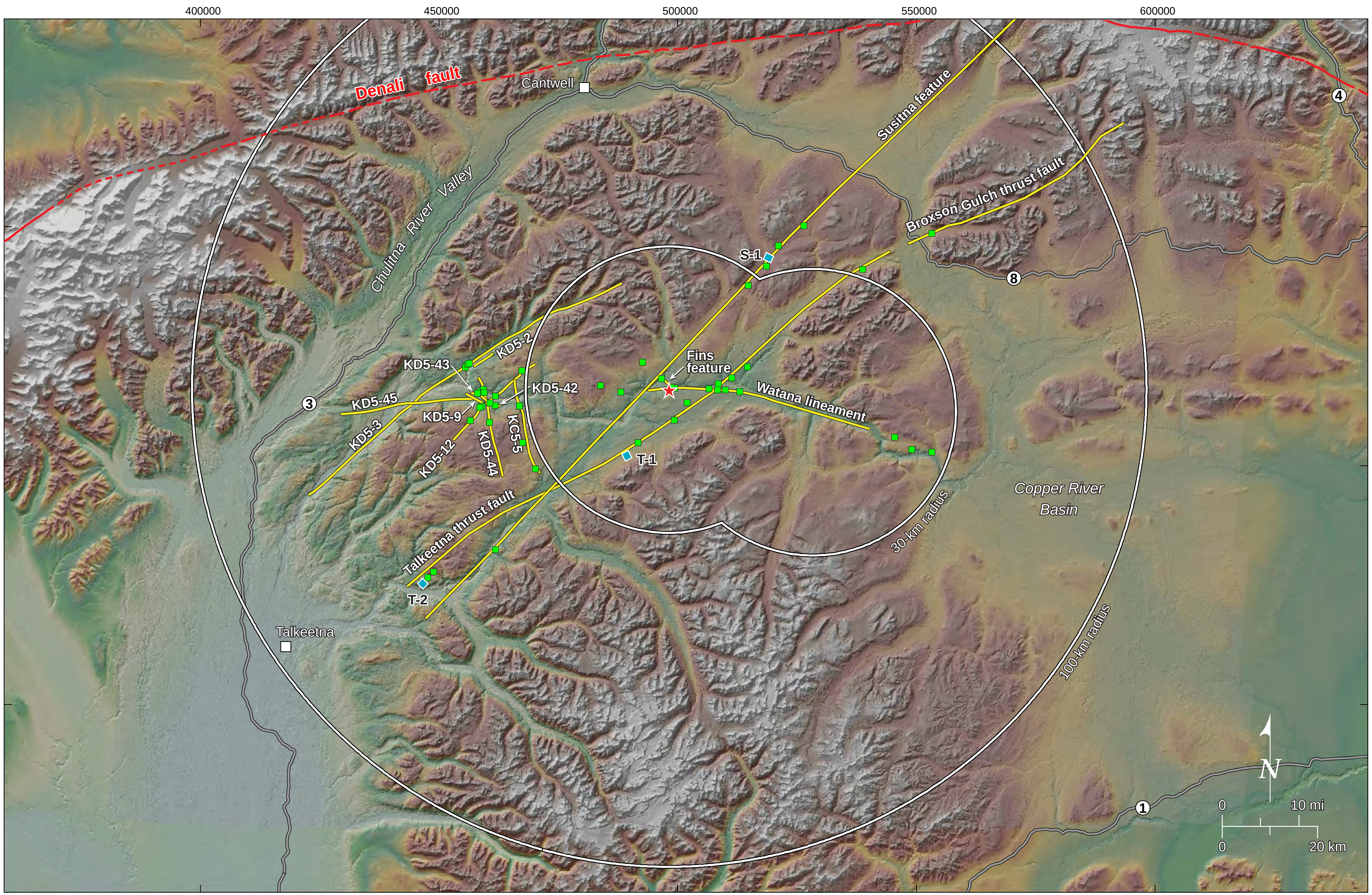
SUSITNA-WATANA HYDROELECTRIC PROJECT
SEPTEMBER 2012
FIELD RECONNAISSANCE GPS TRACKS

FIGURE
FIGURE 2-3



Explanation

S-1 Trench location from WCC (1982)

WCC (1982) ground inspection location

Significant feature (WCC, 1982)

Proposed Watana site

Coordinates on NAD83 UTM 6 North.
Elevation from IFSAR data and USGS SRTM data.

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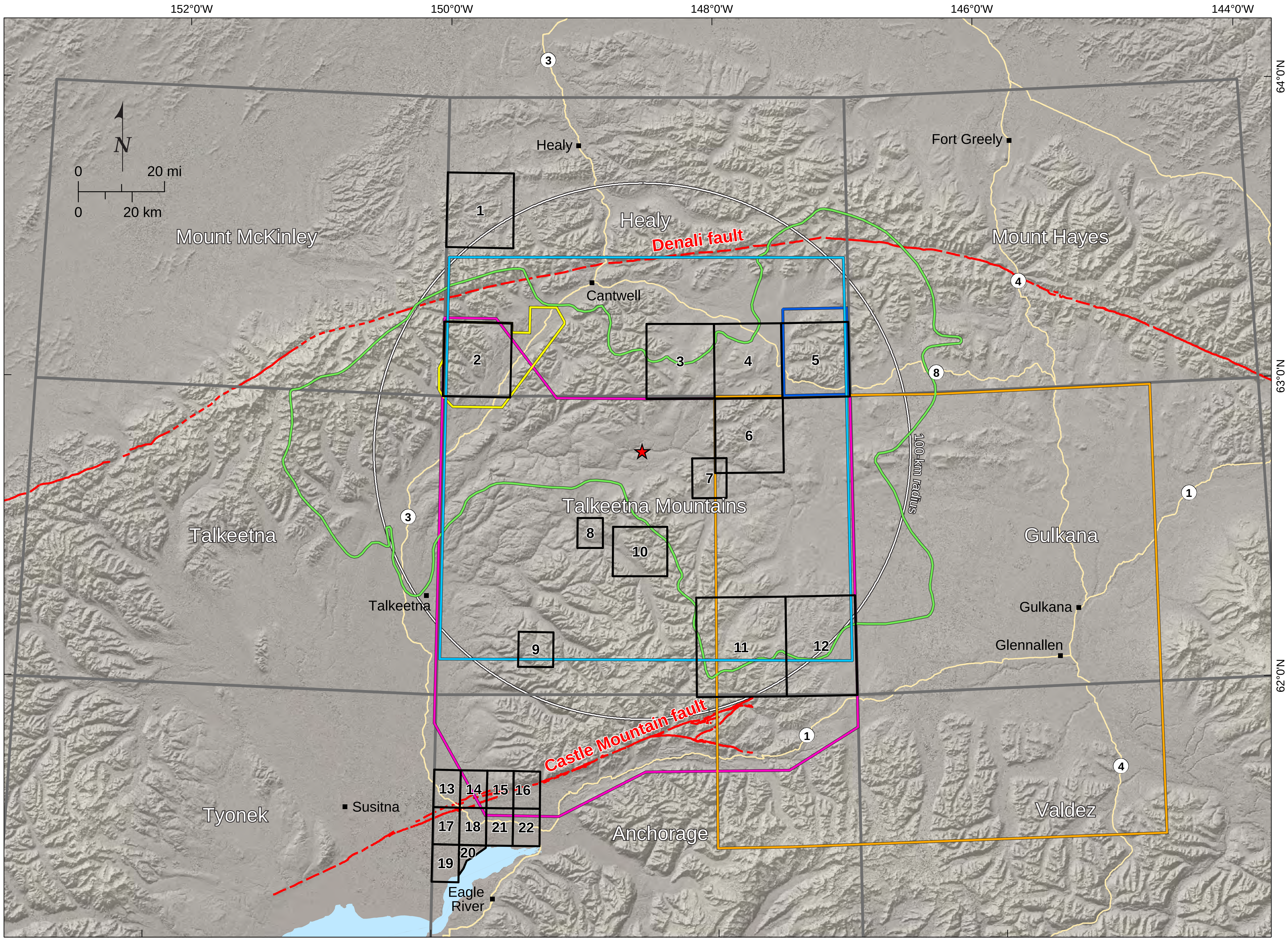
SIGNIFICANT FEATURES FROM WCC (1982)

FIGURE
FIGURE 2-4



Explanation

★ Proposed Watana site

Extent of geologic maps published as 1:250,000-scale quadrangles

1:250,000-scale Quadrangles Compiled for This Study

Wilson et al., 2009: Talkeetna, Talkeetna Mountains, Tyonek, Anchorage

Wilson et al., 1998: Mount McKinley, Healy, Mount Hayes, Talkeetna, Talkeetna Mountains, Gulkana, Tyonek, Anchorage, Valdez

Nokleberg et al., 1992: Mount Hayes

Reed et al., 1980: Talkeetna

Csejtey et al., 1992: Healy

22 *Extents of Other Geologic Maps*

1 Gilbert and Redman, 1975
2 Clautice et al., 1999
3 Reger, 1990
4 Smith et al., 1988
5 Silberling et al., 1981
6 Kline et al., 1990
7 Csejtey, 1974
8 Csejtey, 1974
9 Csejtey, 1974
10 Rose, 1967
11 Grantz, 1960
12 Grantz, 1960
13 Reger et al., 1994
14 Reger et al., 1994
15 Reger et al., 1994
16 Reger et al., 1994
17 Reger, 1981
18 Reger, 1981
19 Reger, 1981
20 Reger, 1981
21 Daniels, 1981
22 Daniels, 1981

Geologic Maps with Non-standard Extent

Clautice, 1990

Csejtey et al., 1978

Smith, 1981

Clautice et al., 2001

Williams and Galloway, 1986

Kachadoorian and Moore, 1979

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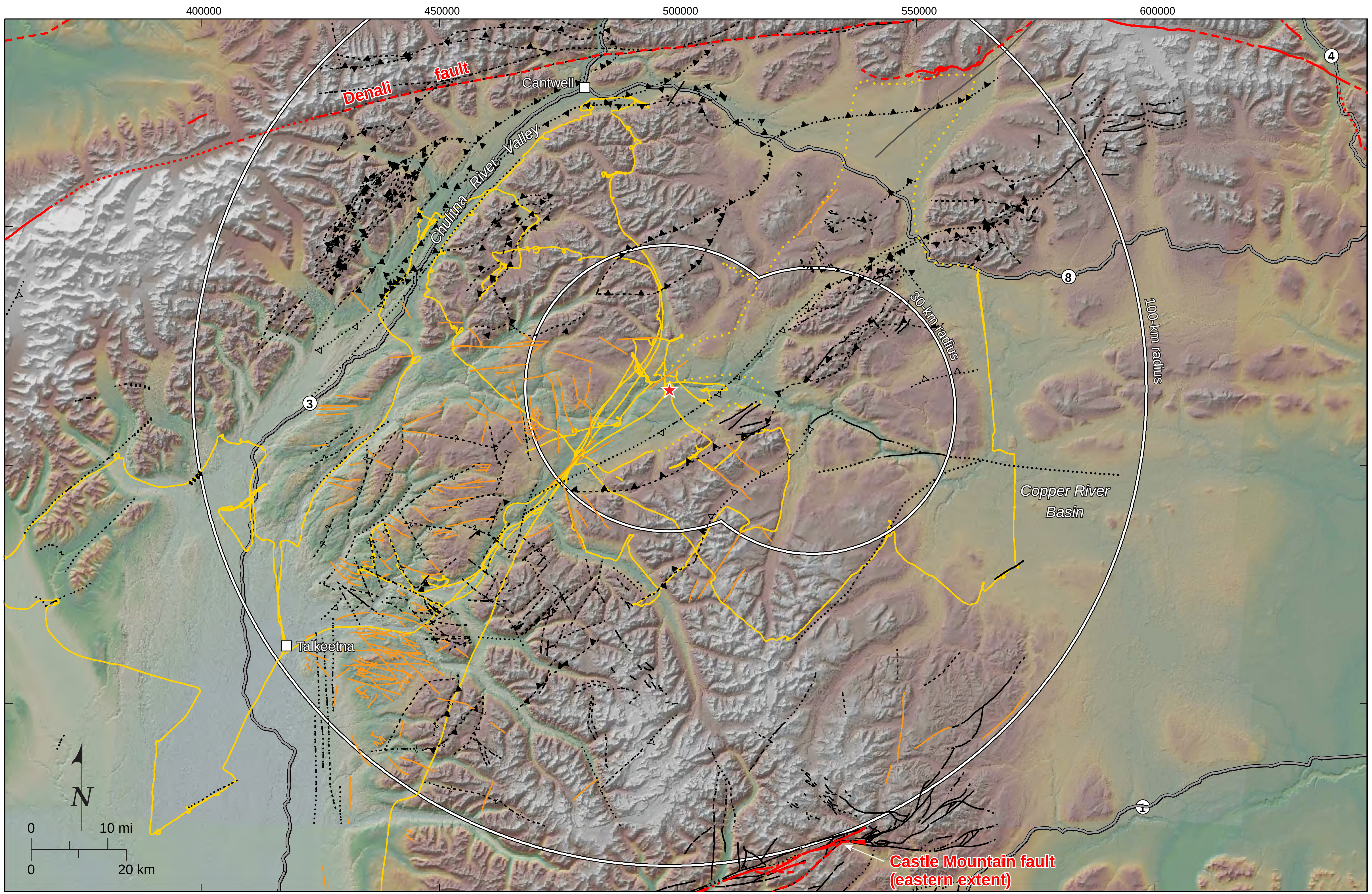
							ALASKA ENERGY AUTHORITY	INDEX MAP OF GEOLOGIC MAPPING COMPILED FROM PUBLISHED SOURCES	FIGURE 2-5



Explanation

Quaternary fault, solid where well constrained, long dash where moderately constrained, short dash where inferred (Koehler et al., 2012)

Other fault, solid where certain, dashed where approximate or inferred, dotted where concealed, teeth on downthrown side

Lineament (Wilson, 2009)

Proposed Watana site

GPS track, dotted where estimated (September 2012 reconnaissance)

Note: Map sources for faults other than those from Koehler et al., 2012 are:
- Clautice, 1990
- Clautice, 2001
- Csejtey, 1978
- Csejtey, 1992
- Kachadoorian and Moore, 1979
- Kline et al., 1990
- Reed et al., 1980
- Silberling et al., 1981
- Smith, 1981
- Smith et al., 1988
- Williams and Galloway, 1986
- Wilson et al., 1998
- Wilson et al., 2009

Coordinates on NAD83 UTM 6 North.
Elevation from IFSAR data and USGS SRTM data.

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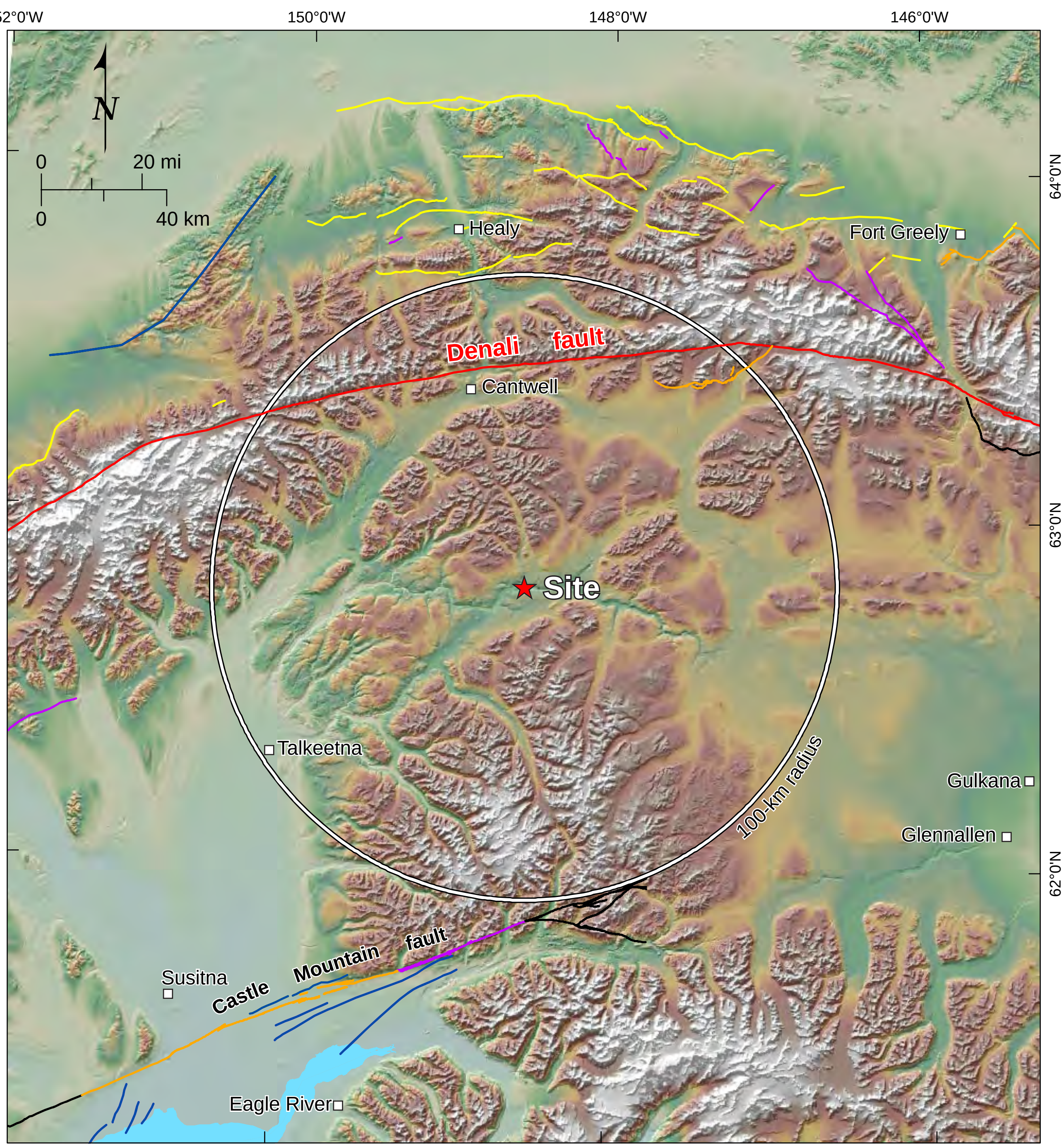
SUSITNA-WATANA HYDROELECTRIC PROJECT

FAULTS AND LINEAMENTS COMPILED FROM PUBLISHED SOURCES

FIGURE

FIGURE 2-6



Explanation

Quaternary Faults and Folds (color indicates fault slip rate in mm/year)

- >5
- 1 to 5
- 0.2 to 1.0
- <0.2
- unknown
- Fold axis

Notes: 1. Faults and folds from Koehler et al., 2012.
2. Elevation from USGS NED, 60 m.
3. 100-km radius centered on proposed Watana site.

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SUSITNA AREA
FAULTS AND FOLDS

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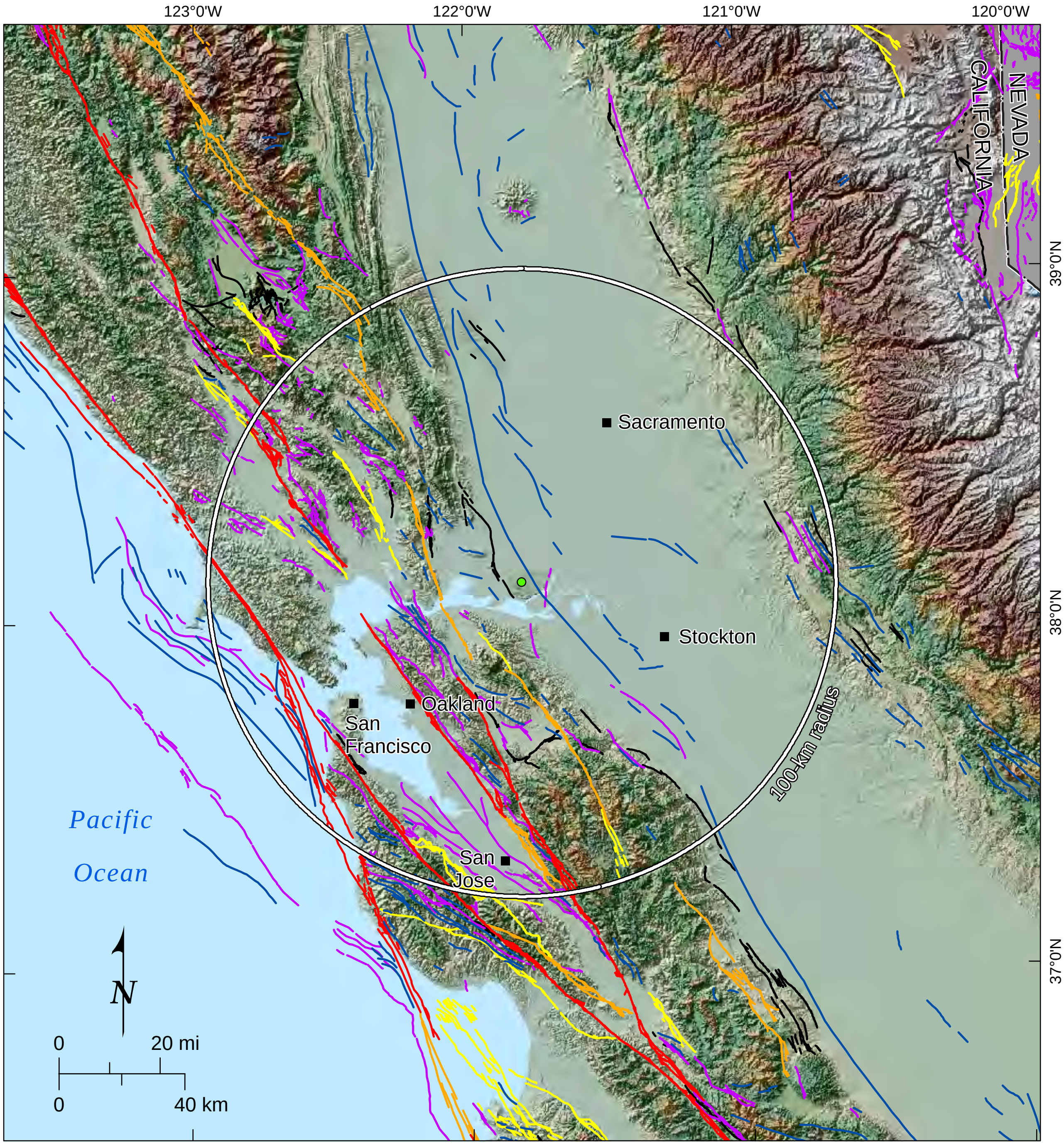
FIGURE 2-7



Explanation

Fold axis (age of activity and growth rate undefined)

Center of 100-km radius

Slip Rates for Quaternary Faults (mm/year)

- >5
- 1 to 5
- 0.2 to 1.0
- <0.2
- unknown

Notes: 1. Faults from USGS Quaternary Fault and Fold Database. Fold axes from California Geological Survey, Geologic Map of California, v. 2.0.

2. Elevation from USGS NED, 30 m.

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SAN FRANCISCO BAY AREA FAULTS AND FOLDS

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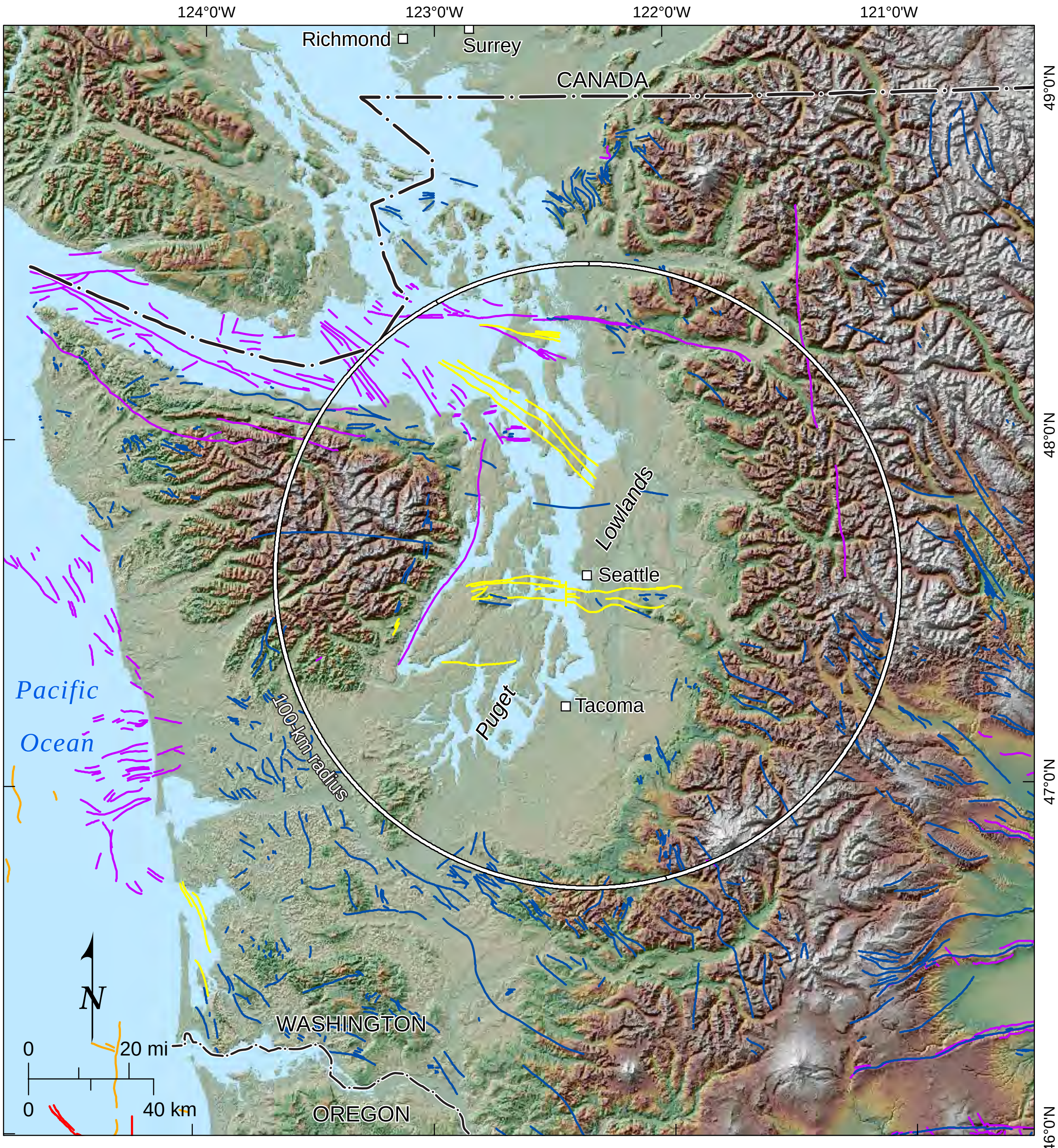
FIGURE 2-8



Explanation

Fold axis (age of activity and growth rate undefined)

Slip Rates for Quaternary Faults (mm/year)

- >5
- 1 to 5
- 0.2 to 1.0
- <0.2
- unknown

Notes:
1. Faults from USGS Quaternary Fault and Fold Database. Fold axes from Washington State DNR, Division of Geology and Earth Resources, Digital Geology at 1:100,000 scale, v. 3.0, 2010.
2. Elevation from USGS SRTM, 60 m.
3. 100-km radius centered on Seattle.

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SEATTLE AREA
FAULTS AND FOLDS

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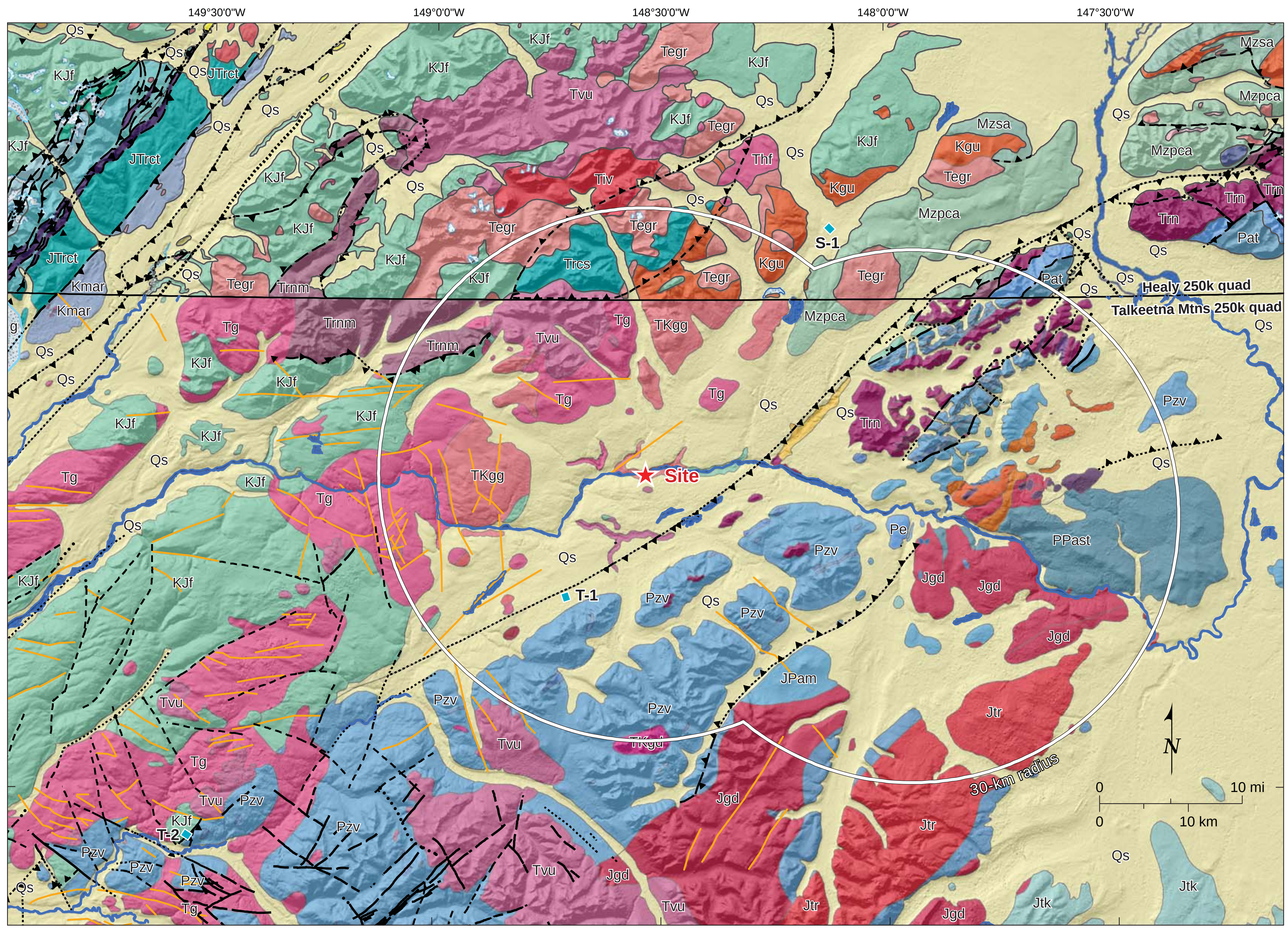
FIGURE 2-9



Geology from Wilson et al., 1998 (USGS Open-file Report 98-133 Healy and Talkeetna Mountains 250,000 quadrangles)

See Figure 2-10B for map legend

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SUSITNA-WATANA HYDROELECTRIC PROJECT

SITE REGION GEOLOGY

FIGURE

FIGURE 2-10A

- g — Ice fields or glaciers

QUATERNARY DESPOSITS

- Qs — Surfical deposits, undifferentiated

TERTIARY ROCKS

Sedimentary Rocks

- Tsu — Sedimentary rocks, unidivided
- Tn — Nenana Gravel
- Tcb — Coal-bearing rocks
- Tfv — Fluviatile sedimentary rocks and subordinate volcanic rocks

Igneous Rocks
Volcanic and Hypabyssal Rocks

- Tvu — Tertiary volcanic rocks, undivided
- Thf — Hypabyssal felsic and intermediate intrusions
- Thm — Hypabyssal mafic intrusions

Intrusive Rocks

- Tiv — Granite and volcanic rocks, undivided

EOCENE

- Tegr — Granite and granodiorite

PALEOCENE

- Tg — Granitic rocks

TERTIARY AND/OR CRETACEOUS

Igneous Rocks
Intrusive Rocks

- TKg — Granitic rocks
- TKgd — Granodiorite, tonalite and monzonite dikes, and stocks

Metamorphic Rocks

- TKgg — Gneissose granitic rocks

UNDIVIDED MESOZOIC ROCKS
METAMORPHIC ROCKS

- Mzsa — Schist and amphibolite
- Mzpca — Phyllite, pelitic schist, calc-schist, and amphibolite of the McClaren metamorphic belt

Geology from Wilson et al., 1998 (USGS Open-file Report 98-133)

CRETACEOUS

Melange

- Kmar — Melanges of the Alaska Range
- TrSl — Limestone blocks

Igneous Rocks
Volcanic and hypabyssal rocks

- Ksva — Andesite subvolcanic rocks

Intrusive Rocks

- Kgu — Granitic rocks
- Kgk/Keg — Granitic rocks younger than 85 Ma
- Kmum — Ultramafic rocks

CRETACEOUS AND/OR JURASSIC

Sedimentary Rocks

- KJs — Argillite, chert, sandstone, and limestone
- KJf — Kahiltna flysch sequence
- KJcg — Conglomerate, sandstone, siltstone, shale, and volcanic rocks

JURASSIC

Igneous Rocks

- Jmu — Mafic and ultramafic rocks
- Jgd — Alaska-Aleutian Range and Chitina Valley batholiths, undifferentiated

Metamorphic Rocks

- JPaur — Uranatina metaplutonic complex

Sedimentary Rocks

- JTrlm — Limestone and marble
- Jtk — Talkeetna Formation

TRIASSIC

Sedimentary Rocks

- Trcs — Calcareous sedimentary rocks
- Trk — Kamishak limestone

Plutonic Rocks

- Trgb — Gabbro, diabase, and metagabbro

Volcanic Rocks

- Trn — Nikolai Greenstone and related similar rocks

Metamorphic Rocks

- Trnm — Metavolcanics and associated metasedimentary rocks

MESOZOIC AND PALEOZOIC

Assemblages and Sequences

- JTrsu — Red and brown sedimentary rocks and basalt
- JTrct — Crystal tuff, argillite, chert, graywacke, and limestone
- Trr — Red beds
- TrDv — Volcanic and sedimentary rocks
- Dmgs — Serpentinite, basalt, chert and gabbro

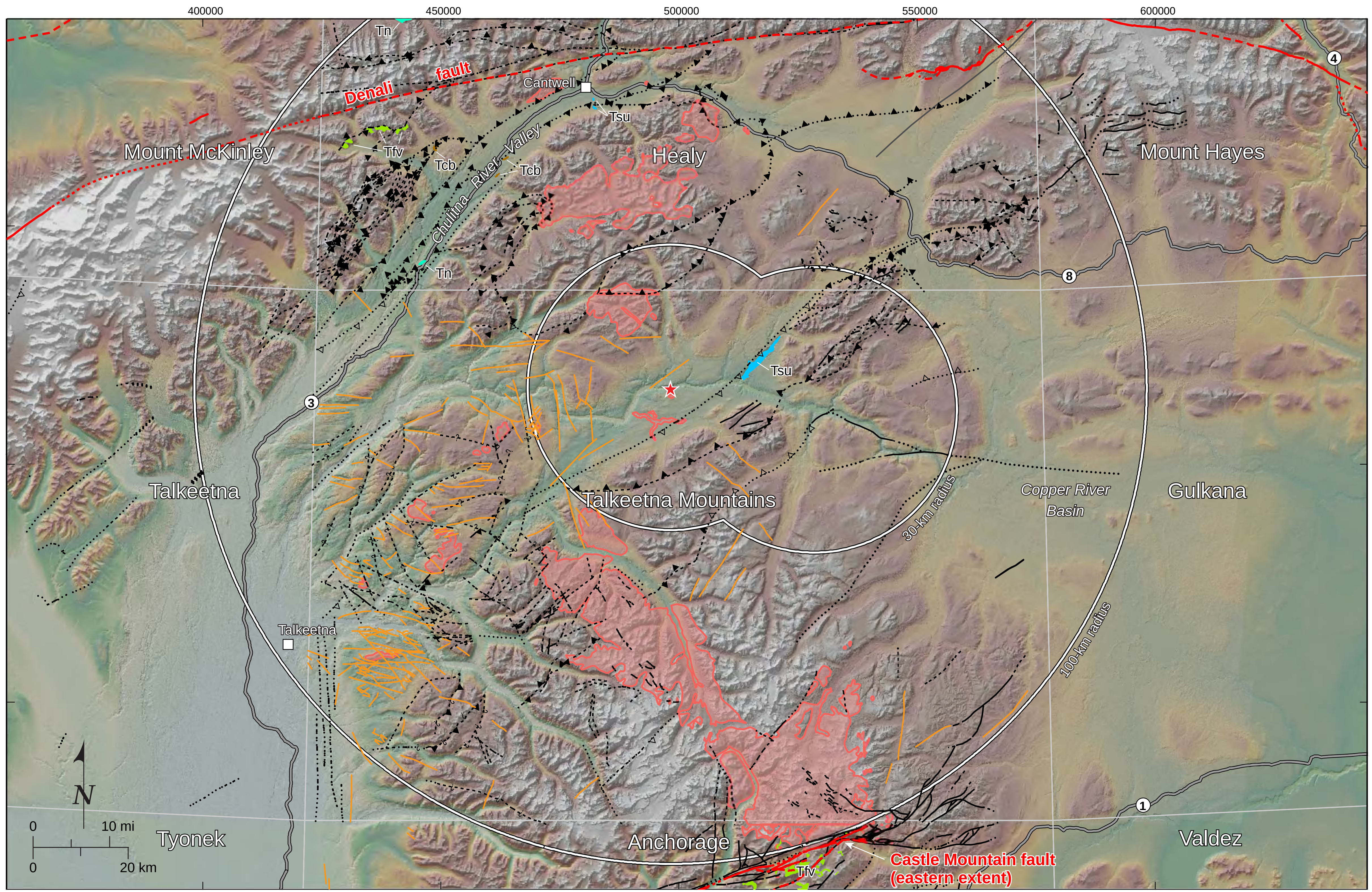
PALEOZOIC

Assemblages and Sequences
(Skolai Group)

- Pe — Eagle Creek Formation
- Pzv — Station Creek and Slana Spur Fm., and equivalent rocks
- Pat — Teteina Volcanics
- Jpmu/Jpam PPast — Streina metamorphic complex
- JPzmb — Marble

- Stratigraphic contact
- Shoreline or riverbank
- Ice contact (glacier limit)
- Lineament
- Fault - certain
- Fault - approximate
- Fault - inferred
- Fault - concealed
- Thrust fault - certain
- Thrust fault - approximate
- Thrust fault - inferred
- Thrust fault - concealed

- T-1 — Trench location from WCC (1982)



Explanation

- Quaternary fault, solid where well constrained, long dash where moderately constrained, short dash where inferred (Koehler et al., 2012)
- Other fault, solid where certain, dashed where approximate or inferred, dotted where concealed, teeth on downthrown side
- Lineament (Wilson, 2009)
- Valdez — USGS 1:250,000-scale map index
- Proposed Watana site
- Tertiary volcanics (Wilson et al., 1998, and Wilson et al., 2009)

Tertiary Sediments

- Tsu — Sedimentary rocks, unidivided
- Tn — Nenana Gravel
- Tcb — Coal-bearing rocks
- Tfv — Fluviatile sedimentary rocks and subordinate volcanic rocks

Note: Map sources for faults other than those from Koehler et al., 2012:
Clautice, 1990
Clautice, 2001
Csejtey, 1978
Csejtey, 1992
Kachadoorian and Moore, 1979
Kline et al., 1990
Reed et al., 1980
Silberling et al., 1981
Smith, 1981
Smith et al., 1988
Williams and Galloway, 1986
Wilson et al., 1998
Wilson et al., 2009

Coordinates on NAD83 UTM 6 North.
Elevation from IFSAR data and USGS SRTM data.

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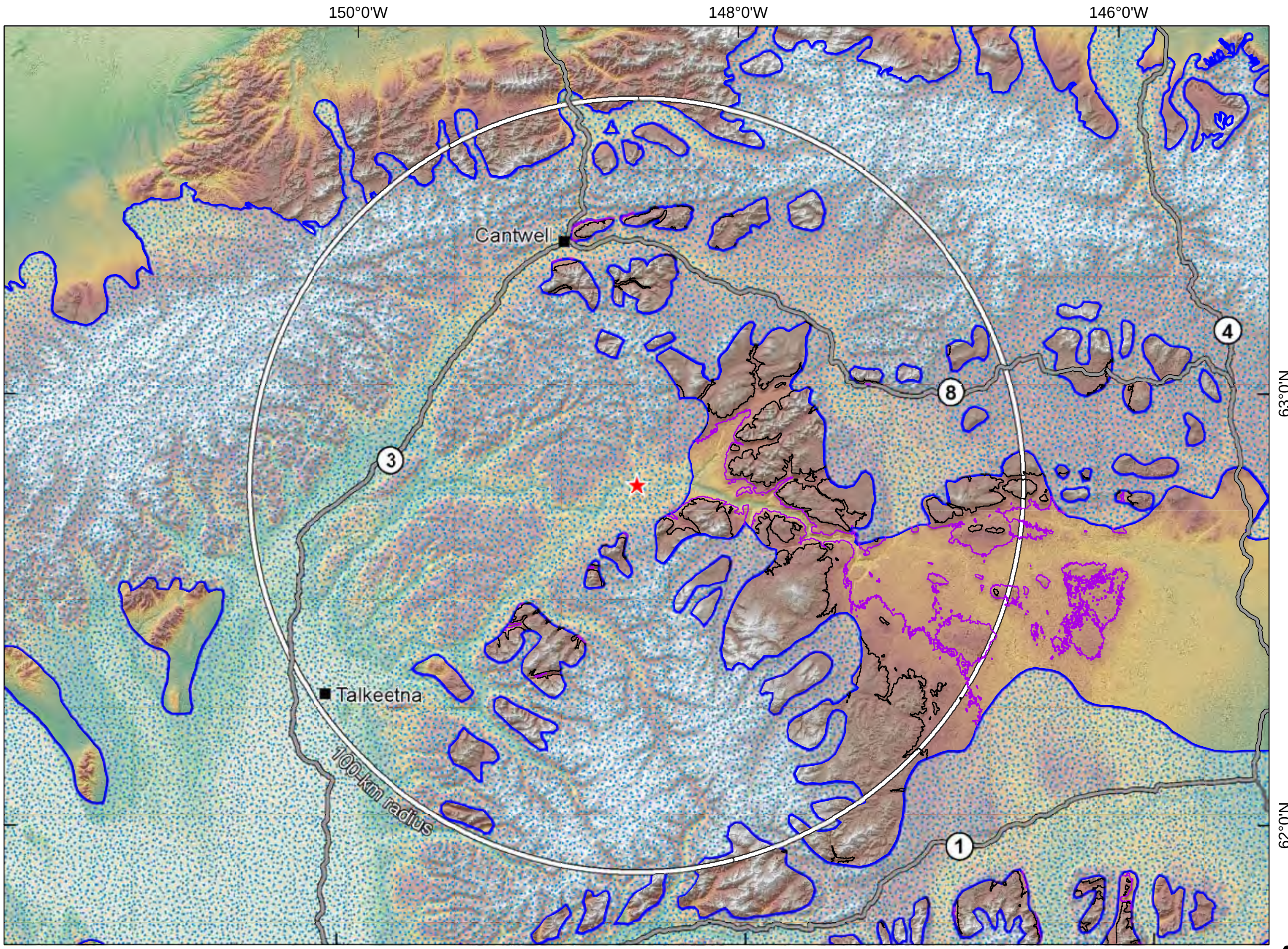
SUSITNA-WATANA HYDROELECTRIC PROJECT

MAPPED TERTIARY SEDIMENTS AND VOLCANIC UNITS

FIGURE
FIGURE 2-11



Explanation

Limit of late Wisconsin glaciers (Kaufman et al., 2012, Alaska PaleoGlacier Atlas v. 2)

★ Proposed Watana site

Lake Levels

800 meters (~2625 feet)

975 meters (~3200 feet)

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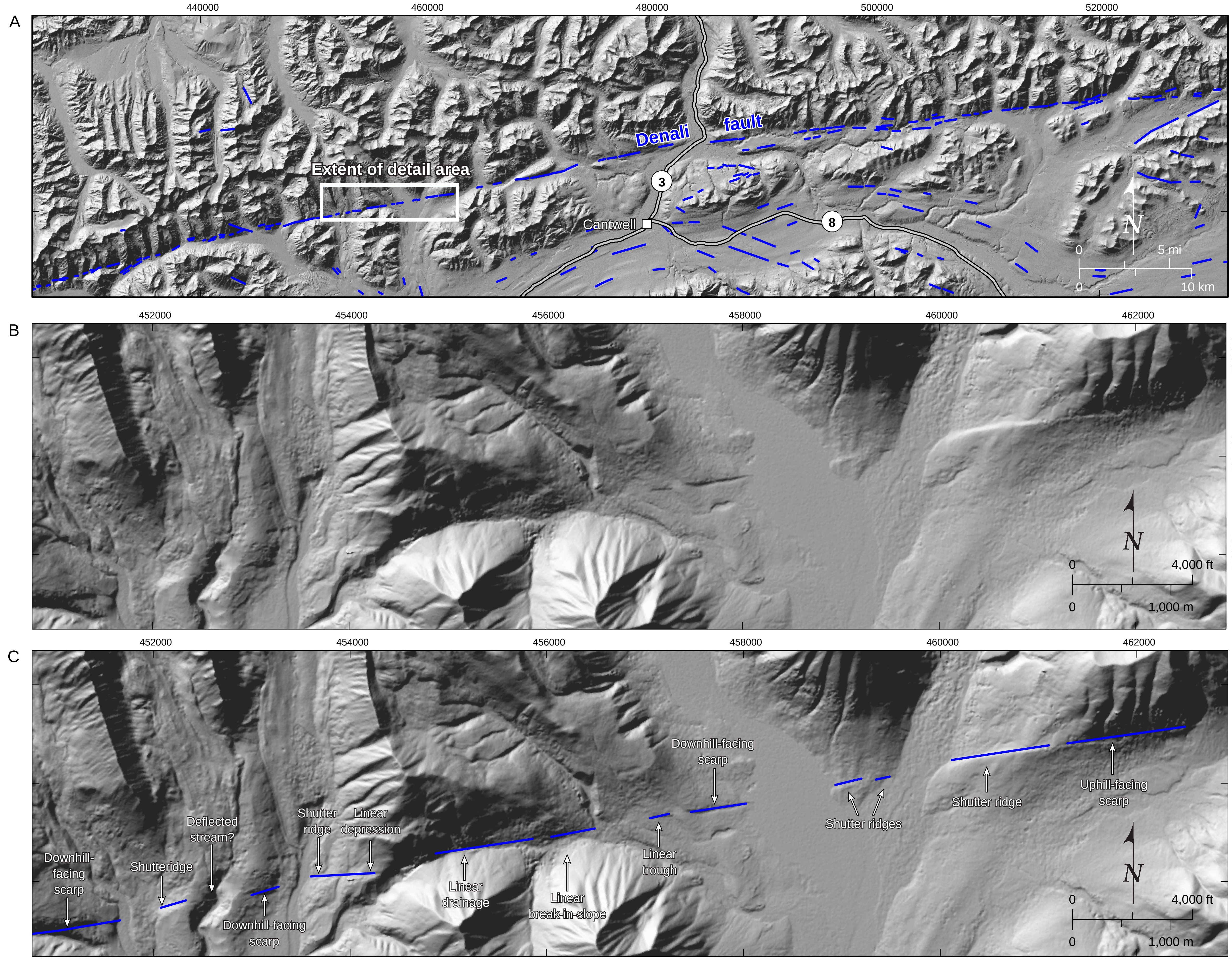
PALEOGLACIAL LAKE ELEVATIONS AND LATE WISCONSIN GLACIER LIMITS

03/25/13

FIGURE 2-12



Coordinates on NAD83 UTM Zone 6 North meters

Explanation

Lineament mapped by Fugro Consultants, Inc. (this study)

Note: Detailed panels are 1:40,000 scale when figure is printed on 11 x 17-inch paper.

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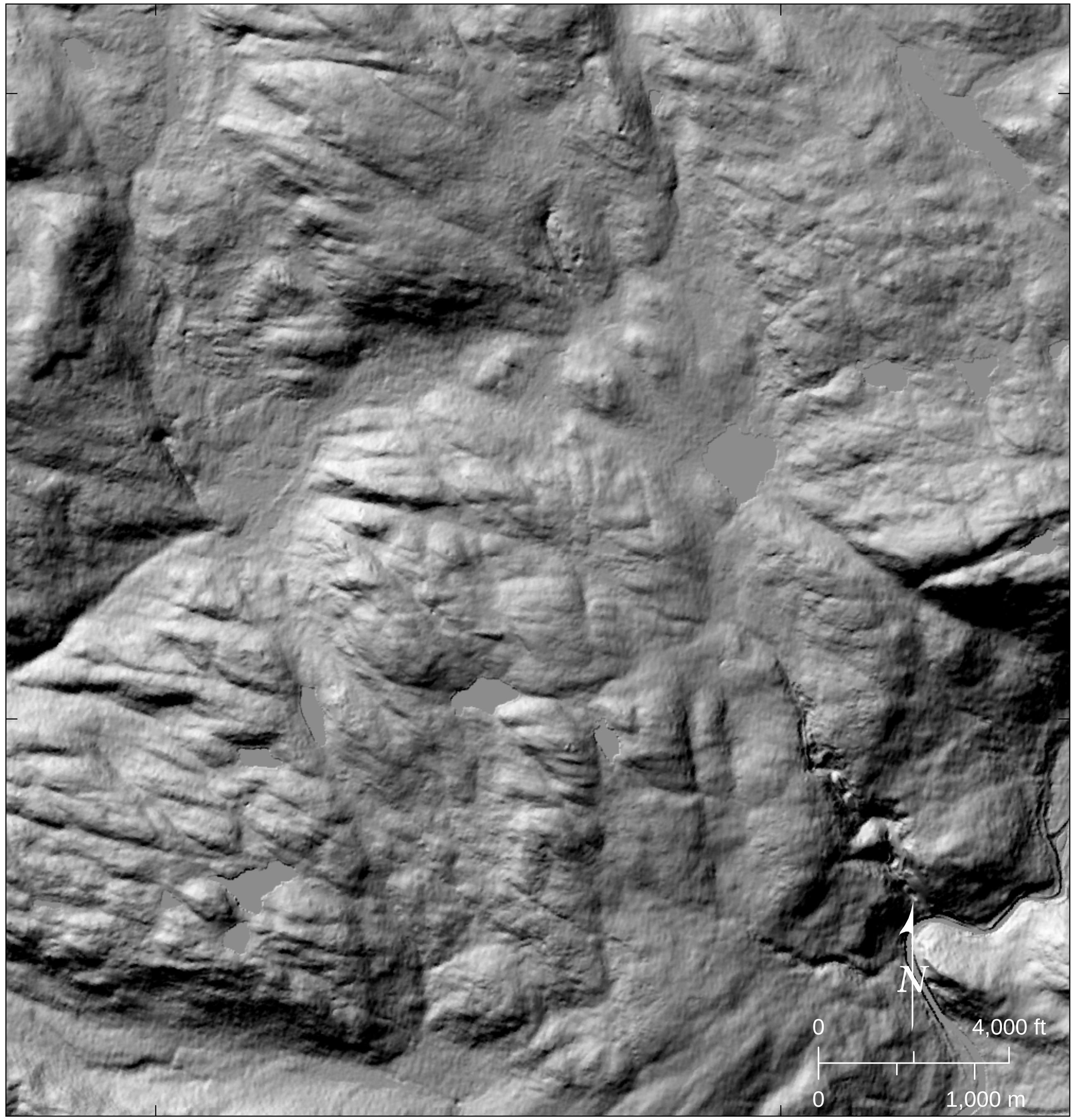
DENALI FAULT
INSAR DATA EXAMPLE

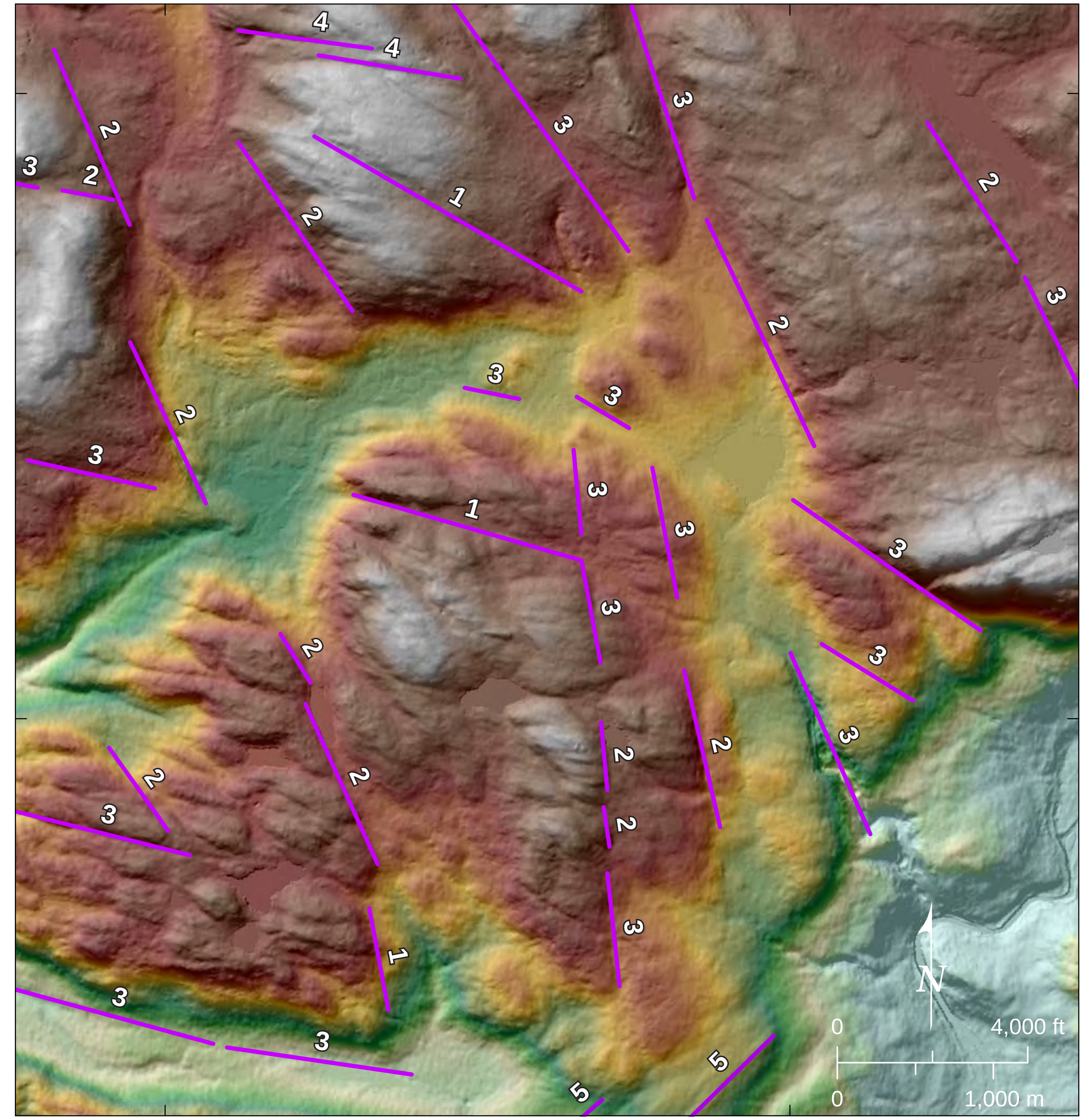
FIGURE

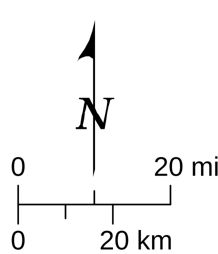
FIGURE 3-1

A



B





Explanation

3 Mapped lineament

Note: See Table 3.2 for explanation of numbered attributes for mapped lineaments.

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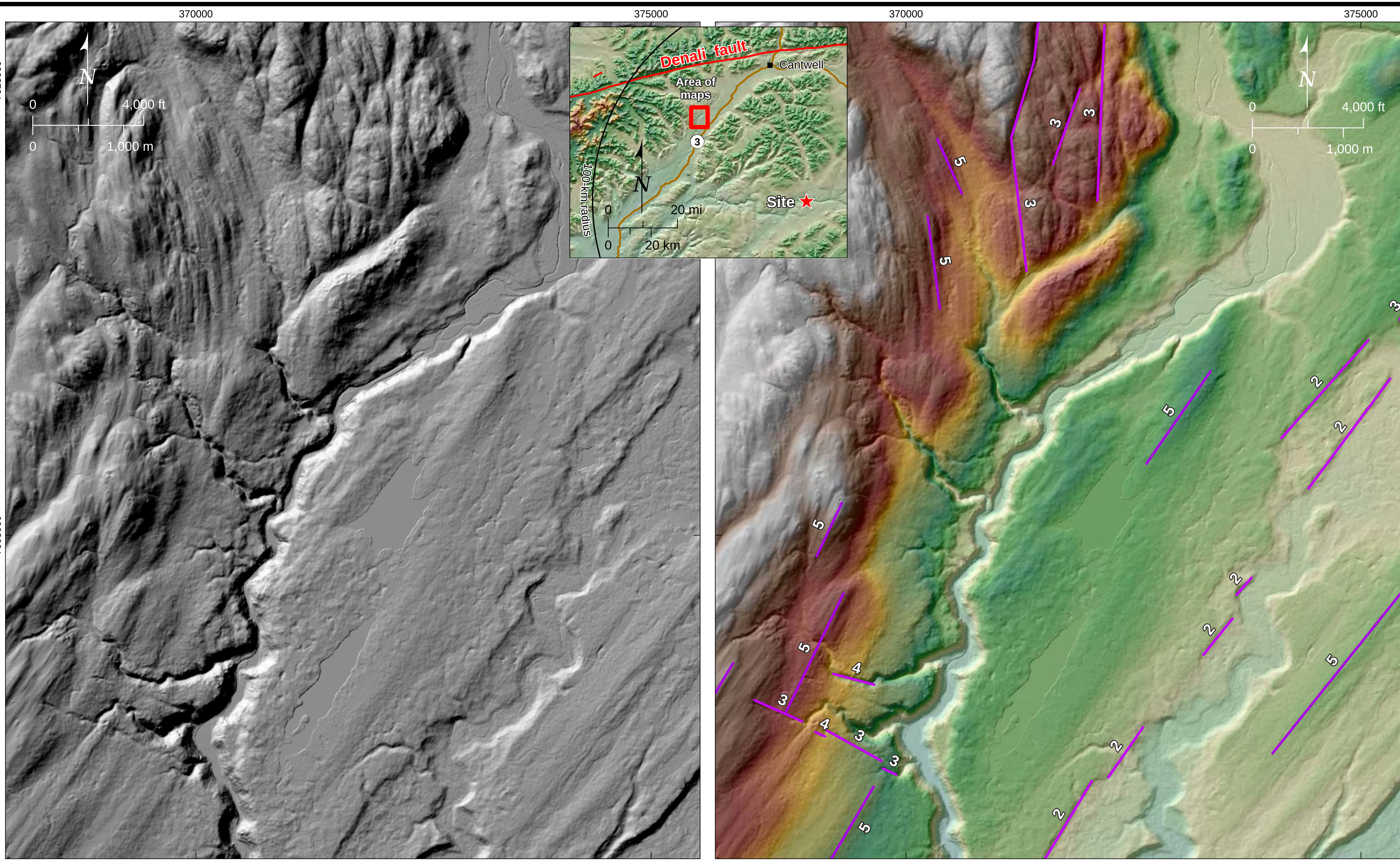
EXAMPLE OF BEDROCK FABRIC-DERIVED LINEAMENTS

FIGURE

FIGURE 3-2



Explanation

3 Mapped lineament

Note: See Table 3.2 for explanation of numbered attributes for mapped lineaments.

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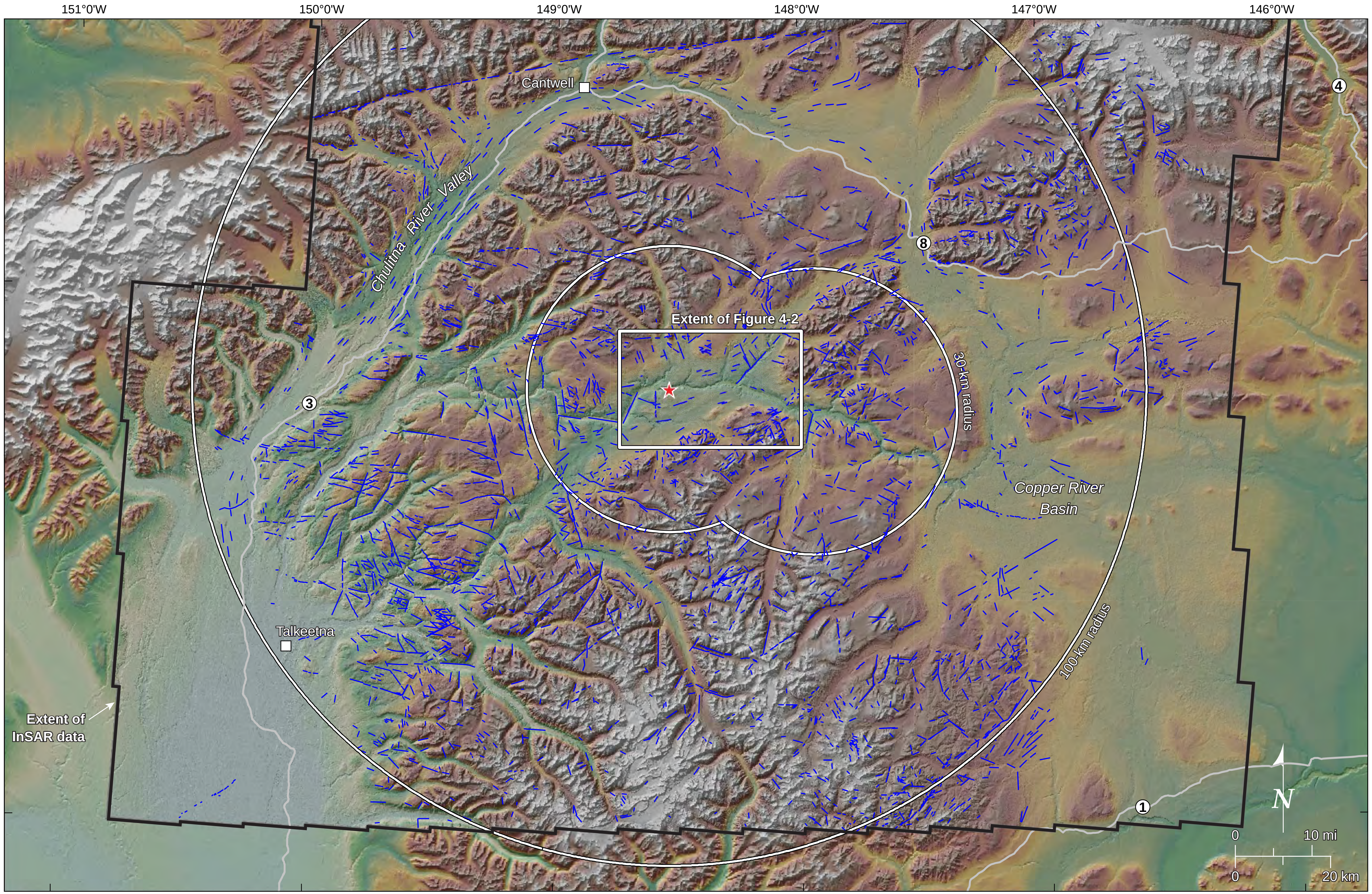
EXAMPLE OF
ICE SCOUR-DERIVED LINEAMENTS

FIGURE

FIGURE 3-3



Explanation

Lineament mapped by Fugro Consultants, Inc. (this study)

Proposed Watana site

Note: See Figure 4-2 for detailed lineament mapping on LiDAR.

Elevation from IFSAR data and USGS SRTM data.

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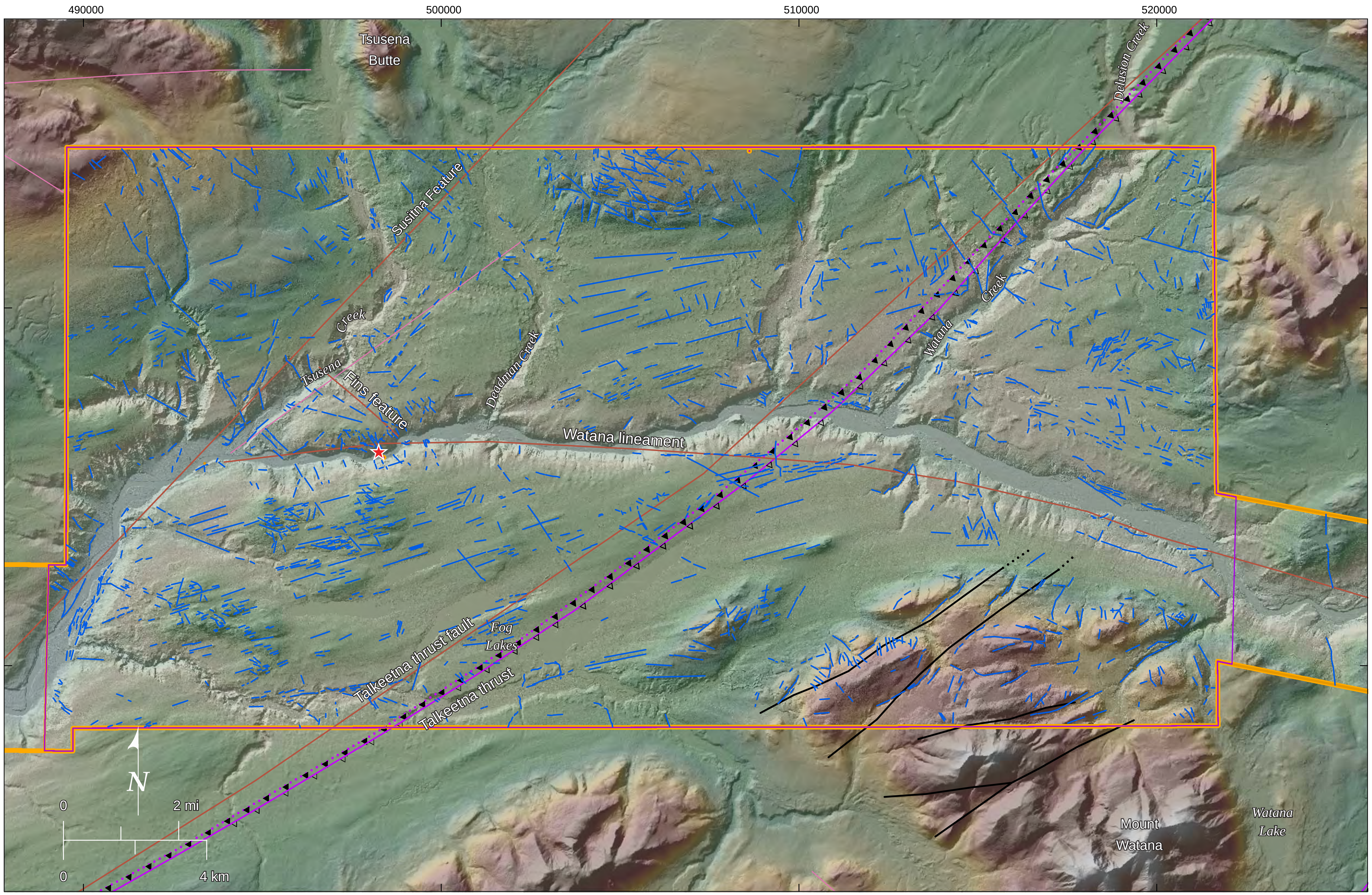
LINEAMENTS MAPPED BY FUGRO CONSULTANTS, INC. ON INSAR DATA

FIGURE

FIGURE 4-1



Coordinates on NAD83 UTM 6 North.
Elevation from Matanuska-Susitna Borough LiDAR data, 2011 and IFSAR data.

Explanation

- Lineament mapped by Fugro Consultants, Inc. (this study)
- Lineament, mapped by (Wilson et al., 2009)
- High-angle reverse fault, concealed (Wilson et al., 2009)
- Fault, solid where certain, dotted where concealed (Clautice, 1990)
- Thrust fault, concealed (Csejtey, et al., 1978)
- Significant feature from WCC report, 1982
- Proposed Watana site
- Extent of LiDAR data
- Extent of Block C LiDAR data

Notes:
1. Talkeetna thrust and lineaments from USGS OFR 09-1108, Wilson et al., 2009 mapped at 1:250,000 scale, and from USGS OFR 78-558-A, Csejtey et al., 1978 mapped at 1:250,000 scale.
2. Talkeetna thrust fault, Susitna feature, Fins feature, Watana lineament from Woodward Clyde, 1982.
3. Other faults from DGGS PDF 90-30. Clautice, K. H., 1990 mapped at 1:250,000 scale.
4. Fins feature of WWC (1982) is equivalent to GF1 of Acres (1981, 1982) and Harza Ebasco (1984).

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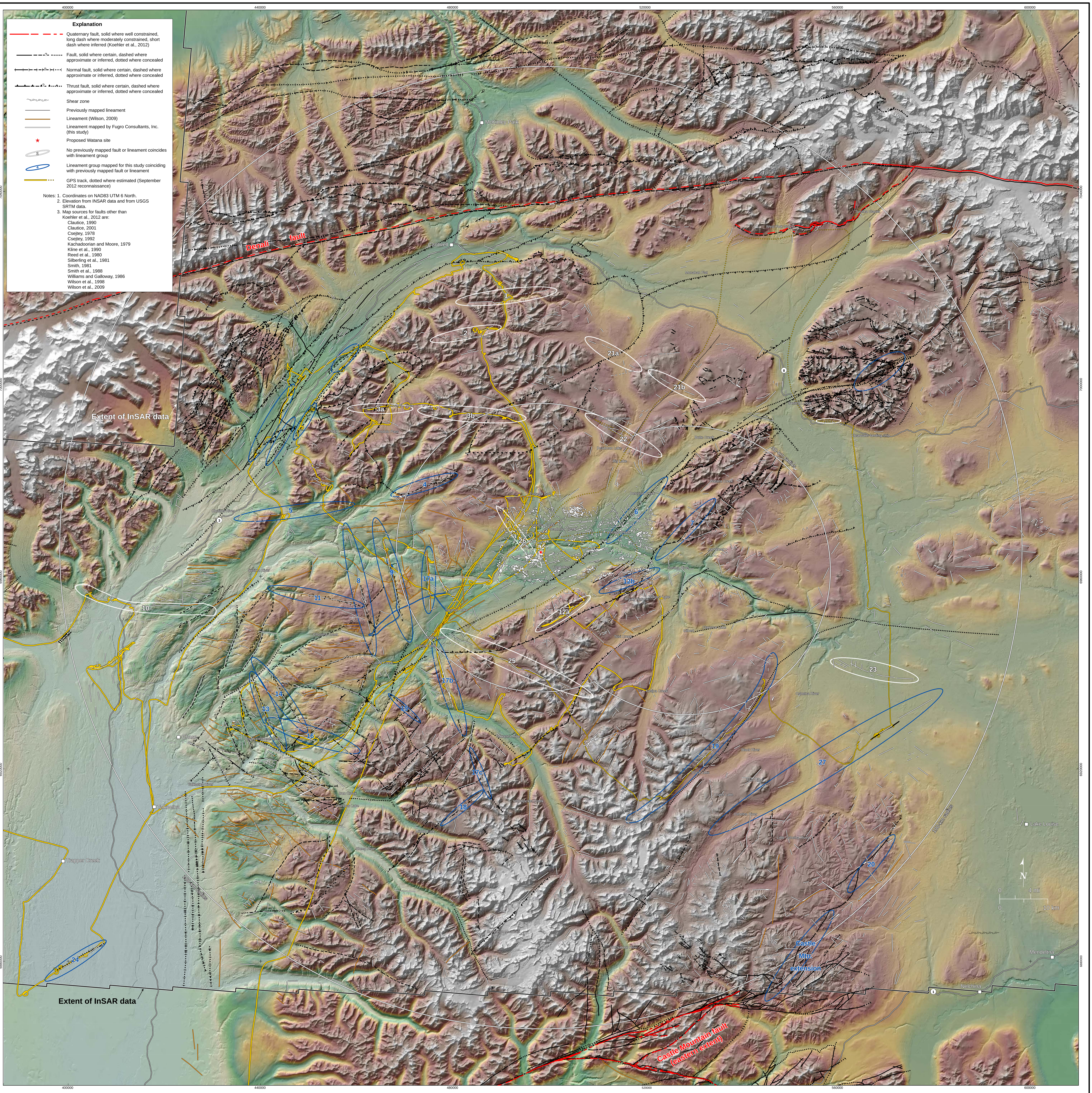
DETAIL OF LINEAMENTS MAPPED BY FUGRO CONSULTANTS, INC, ON LiDAR DATA

FIGURE
FIGURE 4-2



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LINEAMENTS MAPPED BY FUGRO CONSULTANTS, INC. AND PREVIOUSLY MAPPED TECTONIC FEATURES

PLATE 1