6. GEOTECHNICAL STUDIES, SEISMICITY AND VOLCANISM

6.1 Introduction

This chapter describes the baseline geotechnical characteristics for the mine study area and the seismicity characteristics of the Bristol Bay drainages study area. There are no active volcanoes located within the Bristol Bay drainages study area, but the study area could be affected by volcanoes located near Cook Inlet. Regional volcanism associated with the Cook Inlet volcanoes is presented in Chapter 30. Geotechnical characteristics comprise aspects of surficial geology, overburden and bedrock geology, hydrogeology, physiography, topography, and soils as they pertain to engineering design. Geotechnical information of interest includes rock mass characterization and classification of bedrock; the depth, composition, and characteristics of overburden (surficial materials and organic soils); and the presence and movement of groundwater within these materials. The description of geotechnical conditions within the study area is based on geotechnical site investigations from 2004 to 2008. The description of seismic characteristics is based on a desktop overview of available regional information.

6.2 Methods

The mine study area was geographically divided into reference areas, shown on Figure 6-1. The 2004 to 2008 geotechnical site investigation programs involved test pitting, overburden and bedrock drilling, piezometer/well installations, in situ testing, and geophysical surveys throughout the study area. The results of the site investigations were related to surficial geology and physiography to develop linkages between landscape features and subsurface characteristics.

A review of current publications and historical data on the tectonics and seismicity of the region and the Bristol Bay drainages study area was completed. The review included technical publications from the United States Geological Survey (USGS) and, Alaska Department of Natural Resources among others.

6.3 Results and Discussion

6.3.1 Geotechnical Investigations

Geotechnical site investigations were completed between 2004 and 2008.

6.3.1.1 Pebble West Area

The Pebble West Area comprises the western part of the Pebble Deposit Area, located on the drainage divide between the South Fork Koktuli River and Upper Talarik Creek. The area is terraced with many small ponds and kettled moraine features resulting from the Brooks Lake glaciation (Detterman and Reed, 1973). The overburden generally consists of glaciofluvial, glaciolacustrine, and glacial drift deposits. Tertiary basalt, basalt breccia, volcaniclastic matrix-supported breccia/conglomerate, and mudstone/siltstone/wackes were encountered. Depth to the groundwater table is relatively close to the surface but is variable because of topographic variation and aquifers at different elevations. Hydraulic conductivity test results were in the low to very low range (10^{-7} to 10^{-3} cm/s) in the bedrock and overburden.

6.3.1.2 Pebble East Area

The Pebble East Area comprises the eastern part of the Pebble Deposit Area, located on the drainage divide between the South Fork Koktuli River and Upper Talarik Creek. The subsurface overburden materials consist of glaciofluvial, glaciolacustrine, and glacial drift deposits composed of sand and silt with varying amounts of gravel, silt, and clay. Seismic refraction data have revealed a buried paleochannel that runs in a northeast to southwest direction along the western side of Koktuli Mountain. The bedrock encountered in the vertical geotechnical drillholes in the Pebble East Area consisted of weathered Tertiary rhyolite, Tertiary basalt and basalt breccia, bedded andesites, and Tertiary volcaniclastic breccia/conglomerate. The piezometric surface ranged from above or very near the ground surface to depths of approximately 65 feet below ground because of topographic variation and aquifers encountered at differing elevations. Hydraulic conductivity test results were in the low to very low range (10^{-7} to 10^{-3} cm/s) in the overburden and at the overburden/bedrock contact.

6.3.1.3 Upper Talarik Creek Area

The Upper Talarik Creek Area is located north of the Pebble Deposit Area. The Upper Talarik Creek Area is a wide, relatively flat valley containing many streams and small, seasonal lakes that feed into the upper reaches of Upper Talarik Creek. A surficial layer of topsoil was typically encountered. The overburden is predominantly composed of sand with varying amounts of silt and gravel. Overburden in the west bordering Area E was largely composed of sand and gravel deposits. The bedrock encountered consists of Tertiary sandstone/wacke/conglomerate, Tertiary volcaniclastic breccia/conglomerate, Tertiary basalt, Cretaceous siltstone (bedded andesite), granodiorite, and diorite. Piezometric water levels ranged from above surface to approximately 40 feet below the surface as a result of aquifers at different elevations and topographic variation. Hydraulic conductivity test results of the overburden/bedrock contact were in the low range (10^{-5} to 10^{-3} cm/s).

6.3.1.4 Area E

Area E consists of a broad valley located immediately west of the Pebble Deposit Area. The overburden consists of a veneer of glacial drift beneath a thin layer of topsoil, comprising predominantly sands and gravels with varying amounts of silt. The bedrock varied from Cretaceous monzonite/granodiorite and siltstone to Tertiary sediments and intrusives. The piezometric surface ranged from above ground surface to approximately 85 feet below surface as a result of encountering aquifers at different elevations and variation in topography. Hydraulic conductivity test results were in the low to very low range (10^{-7} to 10^{-3} cm/s).

6.3.1.5 North Fork Koktuli River Area

The North Fork Koktuli River Area is a wide, relatively flat valley located approximately four miles northwest of the Pebble Deposit Area. The overburden was deeper in the north with a thick layer of organics. Thinner overburden was encountered farther to the south and closer to the edge of the valley. The overburden materials encountered were generally compact, with gravel and cobbles present. The bedrock types encountered were Tertiary andesite, Tertiary basalt, and Tertiary mudstone/siltstone/wacke. The groundwater levels ranged from approximately 14 to 31 feet below ground surface as a result of topographic variation and aquifers at differing elevations. Hydraulic conductivity test results were in the low range for the overburden materials. Hydraulic conductivity test results were in the very low range (10^{-7} to 10^{-5} cm/s) in the more competent bedrock.

6.3.1.6 Area G

Area G is a valley surrounding a northward-draining tributary of the North Fork Koktuli River, located approximately five miles west of the Pebble Deposit Area. Topsoil varies from a thin veneer at higher elevations to a thicker layer at lower elevations and is often intermixed with rubble formed by frost action at higher elevations. The overburden is largely composed of sand and gravel with varying proportions of silt and is largely frost action rubble, glacial drift, and loose accumulations of rock and soil debris. Bedrock in the northern part is primarily of volcanic origin and mostly composed of monzonite/granodiorite of the Kaskanak Batholith with some basalt, gabbro, pyroxenite, and Tertiary sediments. Bedrock in the southern and eastern part includes Cretaceous granodiorite/monzonite, Tertiary rhyolite, basalt, volcaniclastic fragmented rocks, and brecciated Tertiary sediments and volcanics. The piezometric surface ranged from above the ground surface to a depth of 85 feet below ground surface; a result of differing elevations of aquifers and topographic variation . Hydraulic conductivity test results were in the low to medium range in the overburden/ bedrock contact. The hydraulic conductivity in the bedrock in the north is medium to low (10^{-5} to 10^{-1} cm/s). The bedrock of the south exhibited generally low hydraulic conductivity (10^{-5} to 10^{-3} cm/s).

6.3.1.7 Area L

Area L is a southward-draining tributary valley to the South Fork Koktuli River, located approximately six miles southwest of the Pebble Deposit Area. The topsoil ranges from 0 to 5 feet thick and consists of dark brown silt, sand, gravel, and cobbles. The overburden varies from 0 to 105 feet with the thicker overburden in the valley bottom areas. The overburden deposits consist of sand and/or gravel with varying amounts of finer materials. Glacial drift, loose accumulations of rock and soil debris, frost action rubble, and bedrock are found at surface in this area. The bedrock encountered is of igneous and volcanosedimentary origin. Bedrock types encountered include granodiorite, monzonite, and monzodiorite of the Kaskanak Batholith; and Tertiary siltstone, rhyolite, andesite, dacite, volcaniclastic breccia, basalt, and brecciated basalt. The piezometric surface varies from above ground surface to approximately 205 feet below ground surface because of topographic variation in this area and differing elevations of aquifers. Hydraulic conductivity test results were in the low to medium range (10^{-5} to 10^{-1} cm/s) in the bedrock.

6.3.1.8 South Fork Koktuli River Area

The South Fork Koktuli Area is located approximately six miles south to southwest of the Pebble Deposit Area. A surficial layer of topsoil covers most of the area, and overburden thickness is highly variable. The overburden is predominantly sand and gravel. The materials consist of glacial drift, stream deposits, and loose deposits of rock and soil debris. The depth to bedrock varies from approximately 10 to greater than 390 feet deep. The bedrock composition is variable: granodiorite, monzonite, basalt, sandstone, siltstone/mudstone, dacite, and andesite. The groundwater levels ranged from 5 to 136 feet below ground surface because of differing aquifer elevations and variation of the topography. This area is underlain by predominantly sand and gravel with high hydraulic conductivity. A limited number of hydraulic conductivity tests were conducted in the bedrock resulting in low range values. Hydraulic conductivity tests were conducted in overburden material; however, the groundwater recovery was too rapid to obtain accurate results, indicative of medium to high hydraulic conductivity (10^{-3} to 10 cm/s).

6.3.1.9 Area J

Area J is a long, narrow, steeply incised valley that drains southward into the South Fork Koktuli River, southwest of the Pebble Deposit Area. Topsoil covers much of the surface of this valley with frost action rubble at higher elevations. The overburden is predominantly composed of sand, grading to sandy gravel, with varying proportions of silt. The bedrock most commonly encountered in this area is Cretaceous granodiorite/diorite of the Kaskanak Batholith, Tertiary basalt and minor Cretaceous siltstone. The piezometric surface was encountered at depths ranging from slightly above ground surface to approximately 40 feet below surface. The range is a result of topographic variation and aquifers at different elevations. Hydraulic conductivity values of the bedrock were in the low range (10^{-5} to 10^{-3} cm/s).

6.3.1.10 Area A

Area A is located directly to the south of the Pebble Deposit Area. Area A is characterized by four different geomorphic domains.

Valley Bottom—The Valley Bottom is characterized by relatively flat topography with extensive swamp/wetlands present. The thickness of the overburden across the Valley Bottom varied between approximately 100 and 185 feet. The peat thickness varied between 1 and 15 feet, while the thickness of the more recent glaciofluvial deposits varied between 15 and 30 feet. The materials encountered in the drill holes consist primarily of sand and gravel with varying amounts of silt, clay, and cobbles. The bedrock is primarily igneous in origin, varying from granodiorite/diorite to Tertiary rhyolite and Tertiary dacite/latite. The piezometric surface was generally encountered at or within 10 feet of the ground surface. Topographic variation and aquifers at differing elevations account for the range.

Southern Upland Area—The overburden is predominantly composed of glacial drift and glaciofluvial deposits and there are many kettle depressions. The overburden depth ranged between approximately 7 and 390 feet below ground surface, the depth increasing southward. The bedrock encountered includes both sedimentary and volcanic units. The sedimentary units varied from mudstone/siltstone to breccia. Andesite, monzodiorite, latite, granodiorite, diorite, and basalt dikes are the volcanic units encountered. The groundwater levels ranged from approximately 30 to 140 feet below surface. The groundwater level range is due to topographic variation and aquifers encountered at different elevations. Hydraulic conductivity test results were low (10^{-5} to 10^{-3} cm/s) in the bedrock and overburden.

Lower/Mid Side Slopes—Overburden materials encountered typically consisted of sand and gravel with varying amounts of silt. The bedrock was primarily diorite and granodiorite; however, dacite, andesite, Tertiary basalt, volcaniclastic breccia, siltstone/mudstone, and wackes were also encountered. The piezometric surface was variable, ranging from above ground surface to depths of approximately 38 feet below ground. The range of is the result of aquifers being encountered at different elevations and the variation of the topography in this area. Hydraulic conductivity tests were conducted in the bedrock resulting in values in the low range (10^{-5} to 10^{-3} cm/s). Hydraulic conductivity test results ranged from low to medium (10^{-5} to 10^{-1} cm/s) in at the overburden/bedrock contact and in the bedrock.

Upper Side Slopes—A veneer of loose accumulations of soil or rock debris or glacial drift overlies frost shattered bedrock. The bedrock along the Upper Side Slopes consists of granodiorite/diorite /monzonite, and bedded andesites. Groundwater was typically encountered approximately 0 to 90 feet below the ground surface. The range of groundwater depth is due to topographic variation and aquifers being encountered at different elevations. Hydraulic conductivity test results ranged from extremely low to medium in the bedrock.

6.3.2 Regional Seismicity and Faulting

A fault is defined as a planar fracture or discontinuity in a volume of rock that can range from less than an inch in length to many miles long as is often found along the boundaries of tectonic plates. Active faults are moving over time due to building stresses. Inactive faults had movement along them at one time but have no evidence of movement or associated seismic activity within the Holocene epoch. Alaska is the most seismically active state in the United States, and in 1964 it experienced the second largest earthquake recorded worldwide. The seismicity of southern Alaska is associated with interplate subduction earthquakes, intraplate earthquakes in the subducted oceanic plate, and shallow crustal earthquakes within the North American continental plate (Figure 6-2).

6.3.2.1 Alaska-Aleutian Megathrust Subduction Zone

Historically, the level of seismic activity is highest along the south coast of Alaska, where earthquakes are generated by the Pacific plate subducting under the North American plate. Evidence suggests these tectonic plates are locking as they pass each other, building up pressure that can sometimes be released as large Magnitude 8 to 9+ earthquakes. This seismic source region is known as the Alaska-Aleutian Megathrust. There have been a large number of deeper earthquakes along the south coast of Alaska and extending northwards, in addition to the shallow earthquakes associated with the subducting plate boundary and crustal faulting. Intraplate subduction earthquakes are typically generated by a normal faulting mechanism in the subducted oceanic lithosphere. These deep earthquakes have potential to cause great damage, typically affecting a large area and producing a distinctive rolling motion.

6.3.2.2 Active Fault Systems

There are a number of active and potentially active fault systems in southern Alaska related to the tectonic pressures and crustal flexure caused by the subducting Pacific plate. Active and potentially active fault systems in the Bristol Bay and Cook Inlet drainages are discussed below. Cook Inlet faults are included in this chapter because their seismicity may affect the Bristol Bay drainages study area.

The western end of the northeast-southwest trending Lake Clark-Castle Mountain fault system is located northeast of the study area. Published information indicates the Lake Clark fault terminates at the western end of Lake Clark, over 15 miles from the eastern edge of the mine study area. This distance is based on a recent study by Haeussler and Saltus (2004) who used aeromagnetic data to refine the position of the western end of the fault. Haeussler suggested that the fault may extend farther to the southwest, based on a preliminary review of regional aeromagnetic data developed by the USGS. Haeussler also indicated that there may be a southerly splay of the fault along the Newhalen River valley (east of the mine study area) toward Iliamna Lake. A detailed study of the surficial geology and geomorphology at the study area did not demonstrate any surficial evidence of fault activity in the vicinity of the study area, which is located on outcrops that likely provide resistance to fracturing of the earth’s crust. The study indicated that large Pleistocene glaciers followed zones of crustal fracture (weakness) associated with the Lake Clark fault (Hamilton et al, 2010). The mapped direction of primary glacial advance suggests that any potential extension of the Lake Clark fault may pass north and/or east of the mine study area, and would not cross the mine study area. The Castle Mountain fault system is capable of generating large earthquakes. Research studies by the USGS indicate major earthquakes have occurred along this fault about every 700 years over the last 2,700 years, and that a major (M6 to M7) earthquake may occur on the fault in the next 50 to 100 years. The potential for earthquakes of similar magnitude may also exist along the Lake Clark fault. However, unlike the Castle Mountain fault, Haeussler and Waythomas (2011) have found no known evidence of movement along the currently mapped Lake Clark fault since the last glaciation (the Holocene epoch) or evidence of historical seismicity during the last 1.8 million years, which indicates that the Lake Clark fault is not active. The Lake Clark fault is now classified by the USGS as inactive. (Haeussler and Waythomas, 2011).

Studies imply the presence of another fault northwest and parallel to the Lake Clark fault called the Telaquana fault (Haeussler and Saltus, 2004). The Mulchatna fault is farther north, trending parallel to the Lake Clark fault. The maximum potential magnitude for earthquakes generated on these two faults would likely be similar or smaller compared to the longer Lake Clark and Castle Mountain fault system.

The Bruin Bay fault runs northeast-southwest along the west shore of Cook Inlet starting from Mt. Susitna to the south shore of Becharof Lake. The fault is a major reverse fault and is predominantly buried under Quaternary deposits. The Bruin Bay fault has experienced a small number of earthquakes, the largest of which was a M7.3 event in 1943 (Stevens and Craw, 2003).

The Border Ranges fault is a major, but currently inactive, north-northwest trending fault system that crosses the Kenai Peninsula and continues southwest. The last movement on this fault occurred during the Cretaceous or early Tertiary period. This fault system likely has the potential to generate large earthquakes.

The Kodiak Island and Narrow Cape faults are part of a series of northeast-trending strike-slip faults that extend across southeastern Kodiak Island and into the northwestern Gulf of Alaska. These faults are considered to be active and capable of producing earthquakes of up to M7.5 (Wesson et al., 2007).

6.3.3 Regional Volcanism

There are no active volcanoes located within the Bristol Bay drainages study area, but the study area could be affected by Cook Inlet volcanoes. Regional volcanism associated with the Cook Inlet volcanoes is presented in Chapter 30.

6.4 References

Detterman, R.L., and B.L. Reed. 1973. Surficial Geology of the Iliamna Quadrangle, Alaska. U.S. Department of the Interior. Geological Survey Bulletin # 1368-A.

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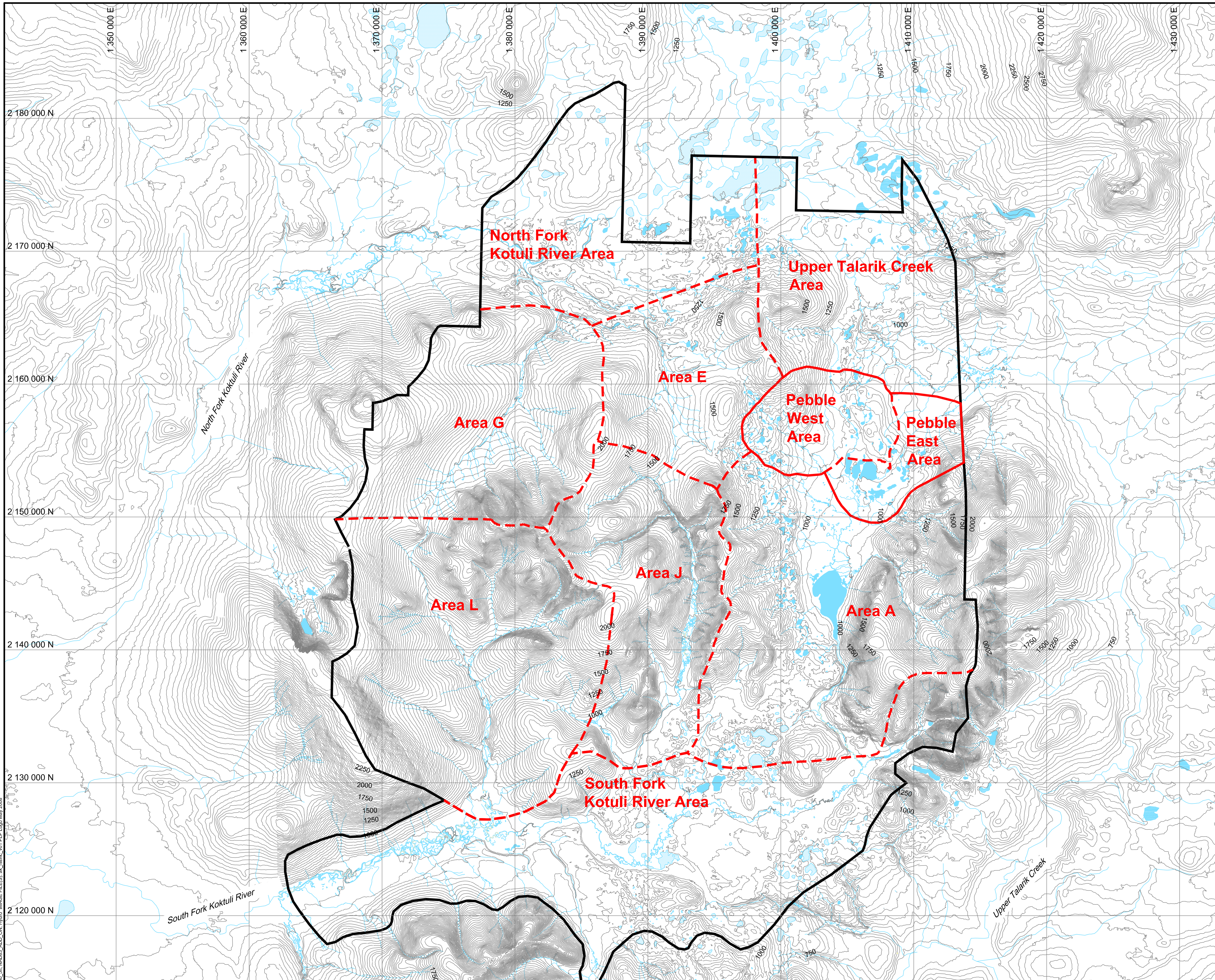
Hamilton, T.D., and R.F. Klieforth. 2010. Surficial geologic map of parts of the Iliamna D-6 and D-7 quadrangles, Pebble Project area, southwestern Alaska: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2009-4, 19 p., 1 sheet, scale 1:50,000. (reproduced with permission from David Szumigala, Apr. 21, 2010).

Stevens, D.S.P., and P.A. Craw. 2003. Geologic Hazards in and near the Northern Portion of the Bristol Bay Basin. Misc. Publication 132, State of Alaska, Department of Natural Resources, Alaska Division of Geological and Geophysical Surveys. December.

Wesson, R.L., O.S. Boyd, C.S. Mueller, C.G. Bufe, A.D. Frankel, and M.D. Petersen. 2007. Revision of Time-Independent Probabilistic Seismic Hazard Maps for Alaska, U.S. Geological Survey Open-File Report 2007-1043.

THE pebble PARTNERSHIP

Figure 6-1
Mine Study Area and 10 Reference Areas

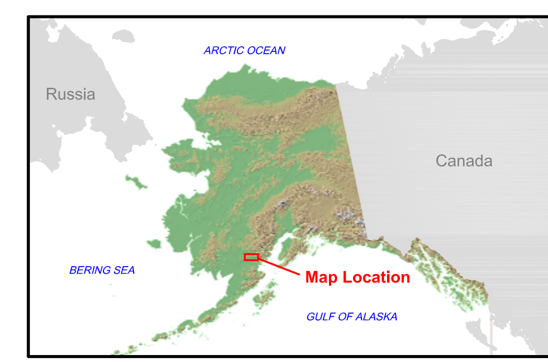


Legend

- Mine Study Area Boundary
- Reference Area Boundaries
- General Deposit Location

Notes

The reference areas defined in this figure are based on KP, 2009.



Meter: 1000 0 2000 4000
Feet: 2500 0 2500 5000 7500 10000

Alaska State Plane Zone 5 (units feet)
1983 North American Datum

File: B01.dwg	Date: October 15, 2010
Version: 2008-1	Author: Knight Piesold Ltd.

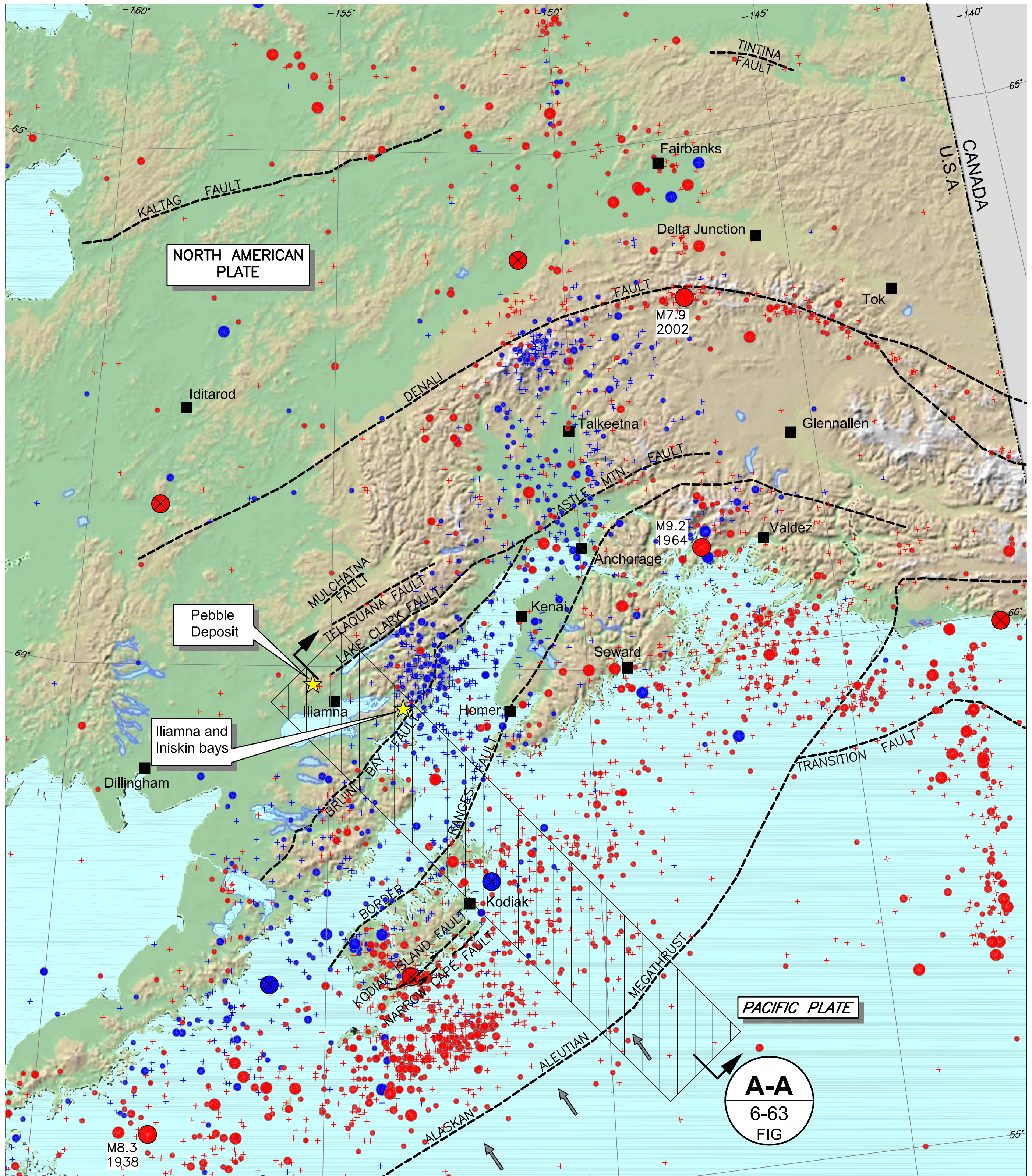


Figure 6-2
Seismicity of Southern Alaska Showing Distribution of Earthquakes by Depth

Legend

- Active and potentially active faults
- Zone of recorded earthquakes included on SECTION A-A

EARTHQUAKE FOCAL DEPTH

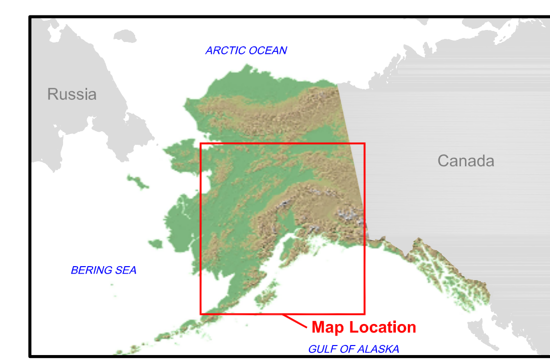
- Depth ≤ 25 miles
- Depth > 25 miles

EARTHQUAKE MAGNITUDE

- 4.0 - 4.9
- 5.0 - 5.9
- 6.0 - 6.9
- 7.0 - 7.9
- 8.0 +
- Large magnitude earthquakes recorded between 1899 & 1904
- Location and direction of view for Geological Section

Notes

1. Historical seismicity data supplied by geoForecaster Inc., California.



Kilometers: 50 0 50 100 150 200 250

Miles: 50 0 50 100 150

N

File: B54.dwg	Date: September 20, 2010
Version: 2008-1	Author: Knight Piesold Ltd.