3.15 GEOHAZARDS AND SEISMIC CONDITIONS

This section provides information currently available regarding seismic and other geological hazards (geohazards) in the vicinity of the project. Geohazards include tectonic processes (e.g., earthquakes, volcanoes), surficial or geomorphological processes (e.g., landslides) and other hazards (e.g., ice effects, erosion, tsunamis). Regional-scale descriptions of the geohazards are presented in this section, enhanced with local information gathered from geotechnical engineering studies where available. The project area is in a region of active tectonic processes, and the potential for multiple types of geohazards across the project area depends on location, topography, natural materials present, and proximity to hazard sources. The Environmental Impact Statement (EIS) analysis area for geohazards ranges from the immediate vicinity of the project footprint for each alternative (e.g., slope instability) to regional areas with geohazards that could affect project facilities from long distances (e.g., earthquakes, volcanoes).

3.15.1 Earthquakes

3.15.1.1 Active Faults

The project is in a tectonically active region of southern Alaska near the subduction zone between the Pacific and North American plates. Both shallow crustal earthquakes and deeper earthquakes associated with the subduction zone megathrust affect this region. A description of the regional tectonic setting is provided in Section 3.13, Geology.

In general, faults that have demonstrated geologic displacement and earthquakes during the Holocene epoch (the last 11,000 years) are considered to be active, and have potential for future movement. Evidence for fault activity might include offset surface features (such as stream channels), sag ponds along a fault, surface vegetation changes, lineaments depicted by remote sensing data, and subsurface seismicity (earthquake record) aligned with a certain fault. In the absence of surficial evidence, subsurface seismicity could indicate the presence of an active buried fault such as a low-angle blind thrust.

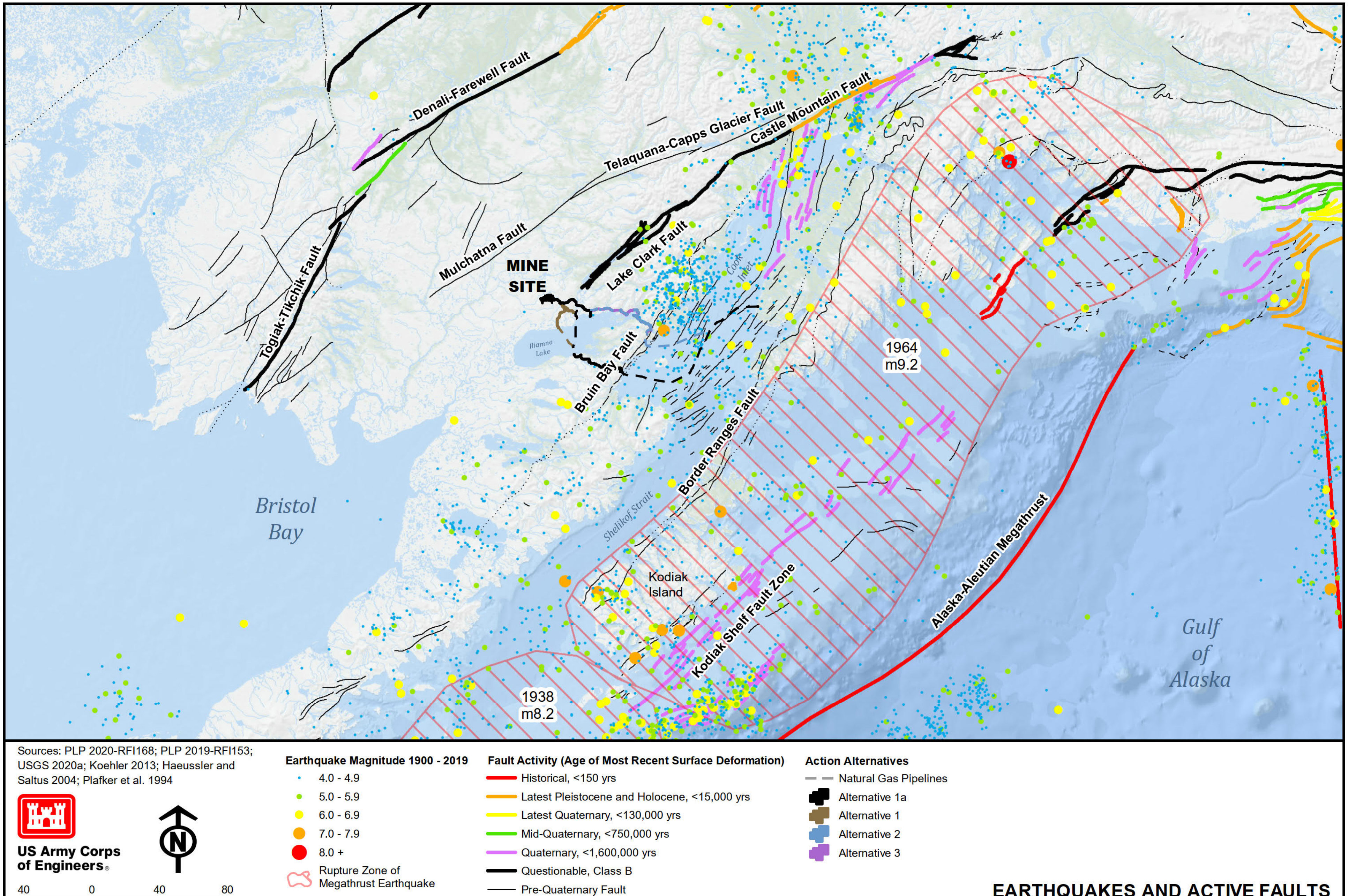
Earthquake hazards generally increase with the magnitude (M) of the event, proximity to the site, and fault length. The likelihood of fault movement is typically described in terms of average recurrence interval or return period (i.e., how often the fault is expected to generate a large earthquake based on field evidence and past seismic record). This is described below under "Ground Shaking," and in Section 4.15, Geohazards and Seismic Conditions, and Appendix K4.15 as applied to project facilities. Active and suspected or potentially active faults in the project area are shown on Figure 3.15-1, and include the following:

- The closest active surface fault to the project area is the northeast-trending Lake Clark-Castle Mountain Fault, which has been mapped at the surface to about 14 miles northeast of the mine site at the western end of Lake Clark (Haeussler and Saltus 2004). This fault exhibits evidence of Holocene (about 11,700 years ago to present) activity in the Susitna Valley area, where it is considered capable of a maximum earthquake of M7.1 (Wesson et al. 2007); however, the fault shows no evidence of activity younger than Late Pleistocene (about 126,000 to 11,700 years ago) along the Lake Clark segment southwest of Tyonek (Koehler and Reger 2011). Past studies have suggested the fault may extend farther southwest of Lake Clark based on regional aeromagnetic and gravity data. Several extensions or splays of the fault have been postulated to be as close as 6 miles from the mine site, where the fault is interpreted to dissipate into multiple strands around the Kaskanak batholith, which may have acted as a buttress to continuation of the fault as a single major strand

(SRK 2008; Knight Piésold 2019d; Rankin 2009; PLP 2019-RFI 139) (Figure 3.15-2). However, field studies in this area have not found evidence of Holocene fault activity on any of the potential splays (Hamilton and Klieforth 2010; Koehler 2010; Koehler and Reger 2011; Haeussler and Waythomas 2011; Knight Piésold 2015a), suggesting they could be erosion and deposition features that perhaps follow weak zones along old fault lines, but are not necessarily active faults. This conclusion is further supported by a review of Light Detection and Ranging (LiDAR) data collected in 2004 in the vicinity of the mine site, which show that no lineaments were observed in surficial deposits that suggest possible fault-related movement southwest of the previously mapped termination point of the Lake Clark fault (AECOM 2018m). Other field studies have shown evidence of repeated paleo-liquefaction events in Holocene to late-Pleistocene surficial deposits southwest of the mine site (Higman and Riordan 2019; PLP 2019-RFI 139), which could suggest earthquake activity on either a buried Lake Clark fault extension, or deeper subduction-related seismicity. Based on the body of evidence to date, Koehler and Carver (2018) conclude that the Lake Clark fault could be active, but with a very low slip rate; the fault remains poorly characterized.

- The Alaska-Aleutian Megathrust, associated with the subduction zone of the Pacific Plate beneath the North American Plate, is responsible for some of the largest earthquakes globally, including the 1964 M9.2 Great Alaskan (Good Friday) Earthquake and 1938 M8.3 Alaska Peninsula earthquake. The megathrust lies at the seafloor more than 200 miles southeast of the project area, and dips northwest beneath the project area. Its 30-mile zone of seismicity ranges from 20 to 50 miles deep beneath the eastern end of the natural gas pipeline corridor to about 90 to 120 miles deep near the mine site (Plafker et al. 1994; Knight Piésold 2015a). The Kodiak and Prince William Sound areas of the megathrust are considered capable of a maximum M9.2 earthquake every 650 years (Wesson et al. 2007).
- Intraslab faults associated with the deeper part of the subduction zone are considered capable of earthquakes in the range of M7+ (Wesson et al. 2007). These are generally of smaller magnitude and occur at greater depth than megathrust earthquakes. Figure K4.15-8 and Figure K4.15-9 show the distribution of earthquakes associated with both megathrust and intraslab faulting. The M7.1 earthquake that struck the Anchorage area on November 30, 2018 was an intraslab event with numerous aftershocks that continue to the present time. Recent large intraslab earthquakes in the Alaska Peninsula and Kodiak area ranged from M6.6 to M7.1, and the largest intraslab earthquake recorded in Alaska was a M7.9 in the western Aleutians (Knight Piésold 2019d).
- The Denali-Farewell Fault, about 120 miles northwest of the project area, was the source of the 2002 M7.9 Denali earthquake that originated along the central part of the fault in Interior Alaska. The westernmost extension of this fault system, called the Togiak-Tikchik Fault, about 140 miles west of the mine site, exhibits evidence of mid-Quaternary activity. Although evidence of Holocene activity along the western part of the fault is limited compared to that of Interior Alaska, it is considered capable of generating large earthquakes in the range of M7.5 to M8.0 (BGC 2011; Knight Piésold 2015a).
- The Telaquana-Capps Glacier and Mulchatna faults are about 40 miles north and northwest of the mine site, respectively (Haeussler and Saltus 2004; Gillis et al. 2009). Evidence of Holocene activity along these faults has not been established. If active, they are considered capable of maximum earthquakes in the range of M6.0 to M7.0 (Knight Piésold 2015a).

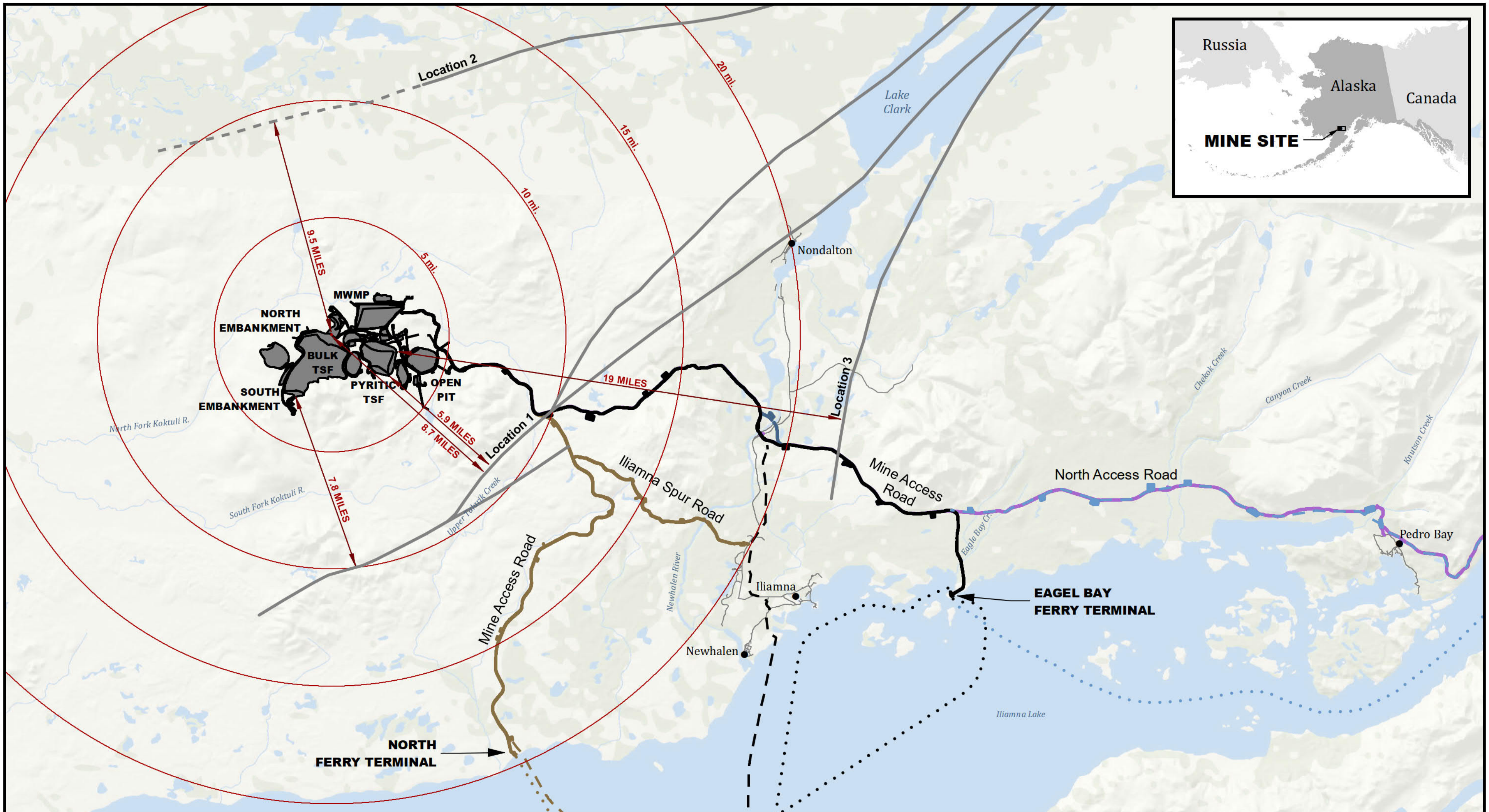
- The Bruin Bay Fault extends along the western shore of Cook Inlet near the Amakdedori and Diamond Point port sites. Although the surface expression of the Bruin Bay Fault shows no evidence of movement since the Neogene (about 24 to 1.8 million years ago) (Detterman et al. 1975), this fault is near an area of seismicity north of Iniskin Bay where several deep, small to moderate earthquakes occurred up to M7.3 in 1943 (Stevens and Craw 2003). Several faults and lineaments trending sub-parallel to the Bruin Bay Fault have been mapped in bedrock west of the Bruin Bay Fault along drainages northeast of Iliamna Lake, such as the Iliamna and Pile Bay rivers. These do not exhibit offset of Quaternary deposits (Detterman and Reed 1980; Nelson et al. 1983).
- Several fault-cored folds in Upper Cook Inlet show evidence of Quaternary activity and possible bending of the seafloor. The closest of these lies about 130 miles east of the mine site and 10 miles north of the eastern end of the pipeline corridor. These structures are considered capable of generating earthquakes up to M6.8 (Haeussler et al. 2000). Recent activity has not been documented on similar folds and faults in Lower Cook Inlet near the Amakdedori port and natural gas pipeline corridor underwater crossing (Haeussler and Saltus 2011; Koehler et al. 2012).
- The Kodiak Shelf fault zone, composed of a series of northeast-trending faults, lies in the upper plate of the subduction zone. These faults, about 120 miles southeast of the closest project components, show geomorphic evidence of Holocene activity, and are considered capable of earthquakes up to M7.5 (Wesson et al. 2007; Carver et al. 2008).
- The level of activity on the Border Ranges Fault, extending northeast through Kodiak Island and Kenai Peninsula, is controversial, and evidence is limited (Stevens and Craw 2004). Although it has not exhibited definitive surficial evidence of movement since the Paleogene to early Neogene (about 65 to 24 million years ago with no record of younger activity) (Plafker et al. 1994), it extends through an area with extensive Pleistocene glaciation that may have removed or buried evidence. MacKevett and Plafker (1974) have suggested that ground breakage near the fault during the 1964 earthquake was related to a buried inferred trace of the fault. It contains a 3- to 6-mile shear zone that is considered by some to be capable of a future earthquake in the range of M7.0 (Knight Piésold 2015a; Suleimani et al. 2005).
- Several faults have been mapped at the mine site that offset bedrock only, with no evidence of Holocene activity (see Figure 3.17-11). These faults are interpreted to have been active between 90 and 40 million years ago (Cretaceous to Paleogene), before a change in tectonic plate direction caused long strike-slip faults such as the Lake Clark-Castle Mountain and Denali faults to develop. There is no direct relationship between these faults and the Lake Clark fault zone or its splays (SRK 2008; PLP 2019-RFI 139).
- Shallow crustal faults can be capable of background earthquakes even in the absence of associated historical seismicity. Studies suggest that earthquakes as large as M6.5 could occur at relatively shallow depths and not result in significant surface evidence (dePolo 1994; Knight Piésold 2019b).



EARTHQUAKES AND ACTIVE FAULTS

PEBBLE PROJECT EIS

FIGURE 3.15-1



Sources: PLP 2020-RFI168; PLP 2019-RFI153; PLP 2019-RFI139; Knight Piesold (2019d)

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Possible Fault Extension
Hypothetical Extension

Action Alternatives

Ferry Routes
Natural Gas Pipelines
Alternative 1a
Alternative 1
Alternative 2
Alternative 2 Newhalen River North Crossing Variant
Alternative 3

Other Features

Local Roads

POSSIBLE EXTENSIONS OF LAKE CLARK FAULT NEAR MINE SITE

PEBBLE PROJECT EIS

FIGURE 3.15-2

3.15.1.2 Ground Shaking

Earthquake-induced ground shaking is typically expressed in terms of peak ground acceleration (pga), measured as a fraction of gravity (g), with a probability of exceeding a certain level over a specific period of time in the future. For example, a pga of 0.1g in bedrock is considered the approximate threshold at which damage occurs in buildings that are not specially constructed to withstand earthquakes (Arnold 2006). An earthquake with a 10 percent probability of exceedance in 50 years (about a 500-year return period) is the most common event used in building codes for seismic design (e.g., Gould 2003). Larger, more infrequent seismic events, such as those between a 2,500-year return period earthquake (a 2 percent probability of exceedance in 50 years) and a 10,000-year event or maximum credible earthquake (MCE), are typically used for design of critical structures such as dams (ADNR 2017a; CDA 2014).

Ground shaking prediction in Alaska has been studied both regionally by the US Geological Survey (USGS) (Wesson et al. 2007) and for the project area by Knight Piésold (2011c, 2015a, 2018c, 2019d). Based on published USGS data for the 2,500-year event, Figure 3.15-3 depicts a general trend from high ground shaking near the subduction zone offshore of Kodiak to less ground shaking farther inland. Predicted ground shaking for the 2,500-year event ranges from a pga of about 0.3g near the mine site to 0.6g at the eastern end of the natural gas pipeline corridor. In comparison, predicted ground shaking for a smaller 500-year earthquake ranges from about 0.2g near the mine site to 0.4g at the eastern end of the natural gas pipeline corridor (Wesson et al. 2007). Site-specific seismic hazard analyses conducted for project facilities are discussed in Section 4.15, Geohazards and Seismic Conditions, and Appendix K4.15.

3.15.1.3 Liquefaction

Liquefaction is an earthquake-caused phenomenon that reduces the strength and stiffness of a soil by ground shaking. Where the groundwater table is near surface, or the ground is otherwise saturated, the pore space between soil particles containing water can increase (i.e., increase pore pressure), changing the physical character of the landform and weakening the natural material; in essence, the ground temporarily behaves like a liquid. Liquefaction generally affects unconsolidated, fine-grained sand and silt deposits in lowland areas. The susceptibility of an area to liquefaction is a consideration in design and construction in earthquake-prone areas because the loss of strength of the foundational material can cause structural damage. The potential for liquefaction from ground shaking at the mine site is less for features built where bedrock is near the surface, than in lowland areas underlain by unconsolidated material. A more detailed explanation of liquefaction and implications for the depth of liquefaction in tailings deposits are provided in Appendix K3.15. Locations in the project area believed to be susceptible to liquefaction are described below.

Areas susceptible to liquefaction are typically found along rivers, streams, lake and marine shorelines, and in areas with relatively shallow groundwater. Lateral spread of liquefied soil can occur on gentle slopes or in areas near a free face, such as an incised river channel. Section 3.18, Water and Sediment Quality, provides a description of sediment types in areas of the project that could be subject to liquefaction. These include portions of the mine site with shallow groundwater and fine-grained soils, such as the glacial lake deposits in the eastern part of the mine site (see Section 3.13, Geology), and in project facilities that contain fine-grained saturated tailings (bulk and pyritic tailings storage facilities [TSFs]). Wide stream crossings along the road and pipeline corridors and marine sediment at port sites that contain predominantly sand and silt, such as along the northern portion of the mine access road, protected bays in Iliamna Lake, and Cottonwood and Iliamna bays in Cook Inlet, may be subject to liquefaction.

Sediments with high gravel content are less likely to liquefy. These include beach and lake terrace deposits at the Alternative 1 north ferry terminal, high-energy stream crossings along the port access road and north road route (Alternative 2—North Road and Ferry with Downstream Dams, and Alternative 3—North Road Only) (PLP 2018-RFI 036), and nearshore Kamishak Bay. Marine cores extending up to 3 feet below the seafloor in the Amakdedori dock area contained primarily silty fine to coarse sand with about 20 to 40 percent gravel content (PLP 2018-RFI 039; Intecsea 2019). Likewise, areas underlain by bedrock, such as the Eagle Bay ferry terminal (Alternative 1a) and the incised bedrock and cobble/boulder substrates described at the Newhalen and Gibraltar river crossings (PLP 2020d, e), are not likely to liquefy.

3.15.2 Geotechnical Conditions

Subsurface geotechnical conditions form the basis of foundation design and stability analysis of major structures such as dams, buildings, tanks, facilities, bridges, docks, and fills. Geotechnical conditions important to the analysis of potential geohazard effects on the project are summarized below, including discussion of features (e.g., roads and port sites) described in alternatives and related environmental impacts.

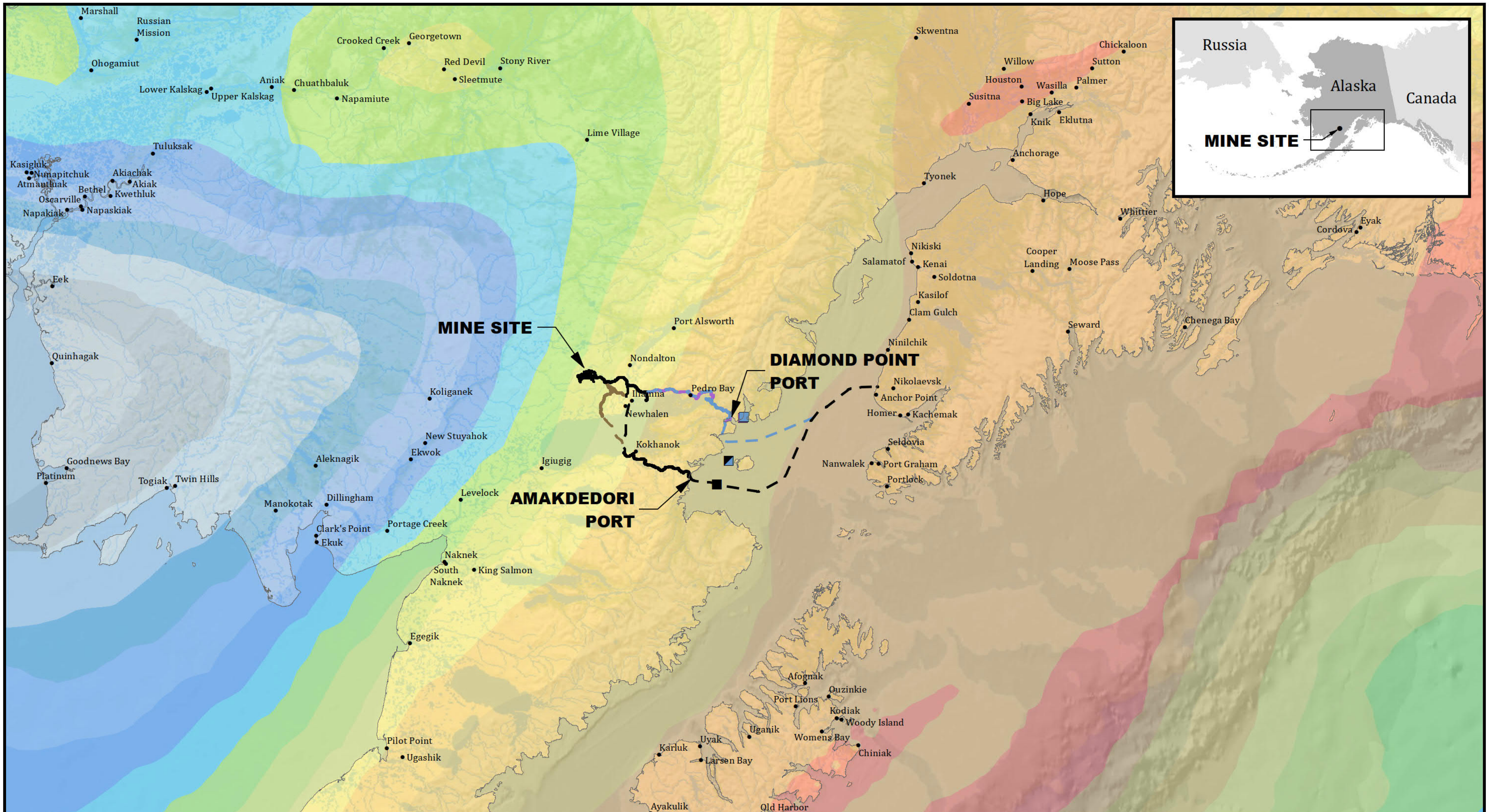
3.15.2.1 Mine Site

Geotechnical data from site-wide geologic reconnaissance and mapping, drill holes, test pits, and geophysical (seismic) surveys were collected at the mine site between 2004 and 2018 (Hamilton and Klieforth 2010; Knight Piésold 2011c; PLP 2013a; PLP 2018-RFI 014; PLP 2019-RFI 014b). Knight Piésold (2011a) divided the mine site into several study areas based on geomorphology and watershed divisions for the purposes of baseline characterization. These areas are listed in Appendix K3.15, along with the number of drill holes, test pits, and seismic survey lines beneath locations of major facilities in each area. As discussed in Section 3.14, Soils, permafrost has not been encountered at the mine site. Geotechnical data locations, the mine site footprint, and depths to moderately weathered bedrock are shown on Figure 3.15-4, as provided in PLP 2018-RFI 014) for 2018 drillholes, and in Knight Piésold (2011c: Appendix 6B and PLP 2019-RFI 014b) for earlier drill holes. In some cases, these depths are below the base of overburden due to the presence of a highly weathered zone in upper bedrock characterized by intense fracturing and frost disturbance (Knight Piésold 2018a).

A summary of geotechnical conditions in each of the mine areas is provided below. A more detailed description of drill holes beneath major embankments is provided in Appendix K4.15, Geohazards and Seismic Conditions, as pertains to potential weak foundation zones.

- **North Fork Koktuli (NFK) West—**Most of the data collected in this north-draining watershed, which contains the bulk TSF, are in the northern part of the watershed, with fewer data points beneath the southern part of the bulk TSF. Overburden deposits consist of frost-shattered angular boulders, glacial drift, and colluvium containing mostly sand and gravel with varying amounts of silt and peat in the valley bottom. Overburden overlies sedimentary, volcanic, or intrusive bedrock in this area. Depths to bedrock are variable; ranging from 3 to 135 feet. Bedrock quality, measured using a Rock Mass Rating (RMR) system on a scale of 0 to 100, with higher numbers representing stronger rock quality (Bieniawski 1989), ranges from 35 to 66 (i.e., poor to good). Weathered bedrock tends to be deeper in the southern part of this area than the northern part.

- **NFK East—**Field investigations in this north-draining watershed that would contain the pyritic TSF and associated seepage collection ponds indicate that depth to bedrock ranges from 3 feet on hilltops to 255 feet in the valley. In the NFK East, bedrock is generally more fractured and has deeper weathering than beneath the bulk TSF area in NFK west. Overburden consists of sand and gravel with variable amounts of silt.
- **NFK North—**This area contains seepage and sediment ponds downstream of the bulk TSF main embankment and the main water management pond (WMP). Overburden consists mainly of alluvial and morainal gravel and sand deposits with glacial lake deposits mapped in the northern half of the main WMP footprint, and morainal ridges in the southern half (Hamilton and Klieforth 2010). Depths to bedrock range from 4 feet to more than 150 feet. Bedrock in this area consists of basalt with RMRs from 52 to 65 (i.e., fair to good).
- **Pit Area—**Geotechnical data in the area of the open pit and rim indicate the presence of overburden consisting of varying mixtures of gravel, sand, silt, and clay of glacial origin, with occasional peat. Depths to bedrock range from about 25 to 150 feet (Knight Piésold 2011c, Figure 6-9). Bedrock types consist primarily of volcanic and sedimentary rock, with average RMRs ranging from 45 to 55 (fair).
- **Bulk TSF South—**The northern portion of this south-flowing watershed contains the footprints of the bulk TSF southern embankment and associated seepage and sediment ponds. Previous investigations indicate depths to bedrock ranging from about 2 to 160 feet, with thicker overburden deposits in the valley bottom consisting of primarily sand and gravel with variable amounts of fines. Bedrock is of similar type and quality to the southern part of NFK west.
- **South of Pit Area—**The northern end of this south-flowing tributary, which drains towards Frying Pan Lake, contains the open pit WMP, pit overburden stockpile, and sediment ponds related to these facilities. Depths to bedrock range from about 25 feet on lower slopes up to 185 feet in the valley. Overburden consists of mostly silty sand and gravel glacial deposits with peat and glacial lake deposits in the valley bottom (Hamilton and Klieforth 2010; Knight Piésold 2011c).



Sources: PLP 2020-RFI168; PLP 2019-RFI153; Wesson et al. 2007

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Action Alternatives

- Lightering Locations
- Natural Gas Pipelines
- Alternative 1a
- Alternative 1
- Alternative 2
- Alternative 3

Peak Ground Acceleration (% g [1])

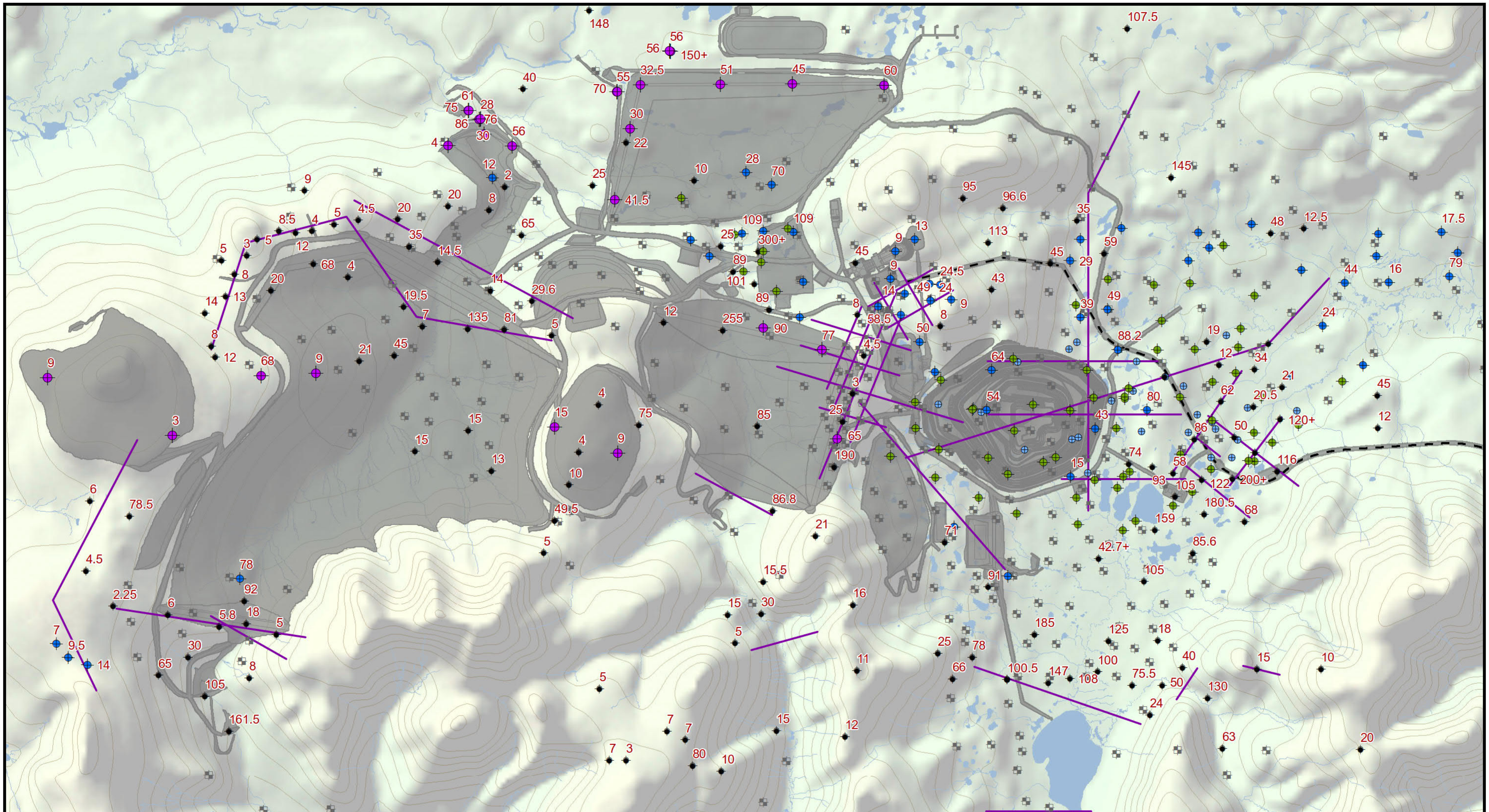
5 - 6	9 - 11	17 - 21	32 - 40	61 - 76
6 - 7	11 - 14	21 - 26	40 - 49	76 - 94
7 - 9	14 - 17	26 - 32	49 - 61	94 - 117

1. Ground shaking expressed as the probability of exceeding a certain amount of peak ground acceleration (PGA), measured in % of gravity (g), over a 2,500-year time period (return period), which is equivalent to a 2% probability of exceedance in 50 years.

SEISMIC HAZARD MAP

PEBBLE PROJECT EIS

FIGURE 3.15-3



Sources: PLP 2019-RFI153; Knight Piesold (KP) 2011c; PLP 2013a; PLP 2018 - RFI 014

Note: 1. For 2004-2008 drillholes, denotes depth to bedrock from KP (2011c) Appendix 6B; for 2010-2018 drillholes, denotes depth to moderately weathered bedrock in KP (2011h, 2012b) and PLP (2018-RFI014; 2019-RFI014b).

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Geotechnical Investigations

- 2004 to 2008 Geotechnical Drillhole
- 2010 to 2012 Geotechnical Drillhole
- 2011 to 2012 Sonic Drillhole
- 2018 Geotechnical Drillhole
- Oriented Geotechnical Drillhole
- Test Pit
- Seismic Line
- 96 Depth to Bedrock (feet)[1]

Alternative 1a

- Natural Gas Pipeline
- Mine Site/Transportation

Other Features

- River/Stream
- Lake/Pond
- 100' Contour (Existing)

GEOTECHNICAL DATA COVERAGE AND DEPTH TO BEDROCK

PEBBLE PROJECT EIS

FIGURE 3.15-4

3.15.2.2 Other Project Components

Surficial deposits, near-surface soils, and stream substrates along the transportation corridor are described in Section 3.13, Geology; Section 3.14, Soils; and Section 3.18, Water and Sediment Quality, respectively. Geotechnical conditions along the northern part of the mine access road would be similar to those described above for the mine site.

Zonge (2017) geophysical data suggest that overburden ranges from 50 to 100 feet thick in the onshore Amakdedori port area. Topographic and stratigraphic relationships in Amakdedori Valley indicate that alluvium, alluvial fan, and beach deposits fill a bedrock-sided valley about 2 miles across between Chenik Mountain to the south, and Peak "1996" to the north. These deposits may extend below sea level in the port area, where valley fill and nearshore delta fan material have been deposited towards the east and southeast, following trends of deepening bathymetric contours between Augustine Island and Douglas Reef (NOAA 2015; PLP 2018-RFI 039).

Geophysical survey data and marine vibracores in the Amakdedori dock area have encountered numerous boulders on the seafloor, likely derived from sloughing of rocky cliffs and ice-raft movement, silty sand and gravel in the subsurface to 3 feet below mudline (maximum depth of core penetration), and possible shallow bedrock about 20 to 30 feet below mudline, likely extending from outcrops to the north (PLP 2018-RFI 039, 2019b, 2020-RFI 160; Terrasond 2019).

Surficial deposits mapped beneath the footprint of the Alternative 2 Diamond Point port site consist of thin alluvial fan deposits on top of shallow bedrock (Detterman and Reed 1973). Offshore deposits in the Diamond Point area, and along the road corridor between Diamond Point and Williamsport, consist primarily of silt and fine sand, with extensive mudflats, buried alluvial gravels, and loose sands in the upper reaches of Cottonwood and Iliamna bays (Knight Piésold 2011f; USACE 2011b). Surficial deposits at the Alternative 3 port facilities are expected to consist of consist of similar material backed by steep bedrock cliffs and rockfall deposits. Subsurface sediments in Iliamna Bay are expected to be composed of more than 70 percent fines, with the remainder sand and gravel. Geophysical data indicate that bedrock in the vicinity of the Alternative 3 dredge channel and dock occurs at a depth of greater than 100 feet (PLP 2020d). Scattered boulders lie on the mudflats, and extensive reefs, shoals, and offshore rocks occur near the entrance to the bays (see Figure 3.18-7) (Pentec Environmental/Hart Crowser and SLR 2011). A combination of marine siltation and tectonic uplift is raising the seafloor near Williamsport at a rate of about 0.3 inch per year (ADNR 2014a).

Site-specific geotechnical information is not available for the eastern landfall pipeline section that is planned to be installed by horizontal directional drilling (HDD) beneath Cook Inlet bluff. The coastal bluff is about 230 feet high at this location; has a relatively steep slope angle of about 1.4H:1V; and is composed primarily of Pleistocene glacial deposits (Reger and Petrik 1993; Karlstrom 1964). A stratigraphic section of the bluff 2 miles south of the pipeline landfall contains sand and gravel with occasional boulders overlying a 50-foot-thick glaciolacustrine clay-silt unit (Reger and Petrik 1993). Perched groundwater is known to seep out of the bluff above similar fine-grained units along eastern Cook Inlet. Neogene sedimentary rocks of the Beluga Formation are exposed in the lower sea cliff several miles further to the south and may underlie glacial deposits at the pipeline landfall in the depth of the HDD. These rocks consist of weakly indurated, interbedded sandstone, siltstone, and shale with thin layers of coal (Reger and Petrik 1993). The potential for slope stability impacts on the project from these deposits is provided in Section 4.15, Geohazards and Seismic Conditions.

3.15.3 Unstable Slopes

Unstable slopes typically occur under combined conditions of steep terrain, heavy precipitation, and certain types of surficial deposits, weathered bedrock, or weak stratified layers. Slope failure can also be triggered by earthquakes. Increased precipitation due to climate change is predicted to occur as rain and snow in the Iliamna Lake and Cook Inlet areas over the next few decades (SNAP 2019), which could locally increase the risk of landslides and avalanches.

Mine Site—The terrain and geomorphology of the mine site consists primarily of gently rolling hills with rounded exposed bedrock hilltops and valleys of glacial deposits with low-angle slopes and mostly low potential for slope instability. Surficial deposits that have the potential to produce unstable slopes occur sporadically around the mine site, and include the following (Hamilton and Klieforth 2010):

- Colluvium, consisting of rock rubble and debris with fines deposited at the base of slopes, may be subject to frost creep and gradual mass wasting slope processes related to freeze-thaw activity (solifluction). These deposits have been mapped throughout much of the bulk TSF footprint: on slopes adjacent to the bulk TSF south embankment, beneath the southern sediment pond, on the western side of the pyritic TSF, beneath several overburden and growth media stockpiles, and in the northeastern corner of the pit area.
- Solifluction deposits, consisting of moderately sloped sheets of stony and organic silt, are subject to gradual downslope movement related to freeze-thaw action. These have been mapped on the eastern side of the pyritic TSF footprint.
- Active talus rubble deposits have been mapped on the northern slope of Kaskanak Mountain (southeastern slope of the bulk TSF).

Transportation Corridors and Port Sites—Small areas of colluvium, solifluction, and steep alluvial fan deposits have been mapped along the western portion of the mine access road alternatives and Iliamna spur road. These occur at the following locations:

- About 2 miles east of the mine site and about 6 miles east of the mine site on the northern side of Koktuli Mountain, both of which are along the portion of the road corridor common to all alternatives
- Near the Iliamna spur road junction of Alternative 1
- Between 3 and 6 miles west of the Newhalen River crossing and along the southern flank of Roadhouse Mountain north of Eagle Bay, which both apply to Alternative 1a, Alternative 2, and Alternative 3 (Detterman and Reed 1973; Hamilton and Klieforth 2010)

Steep alluvial fan, talus, and landslide deposits occur in incised valleys crossed by the eastern portion of Alternative 2 and Alternative 3, along the lake front south of Knutson Mountain, and at the head of Lonesome Bay. The steep slopes and valleys between Pile Bay and Williamsport are well known for landslide and avalanche risks. Talus deposits have been mapped on the south side of Williams Creek near Williamsport (Detterman and Reed 1973). Rockfall is evident along the steep coastal slopes between Williamsport and Diamond Point (INL 2019). Steep alluvial fan deposits have also been mapped at the southern end of the port access road alternatives: about 1 mile north of the Amakdedori port site, and beneath some of the shore-based facilities of the Alternative 2 Diamond Point port site (Figure 3.13-4) (Detterman and Reed 1973).

Pipeline Corridor—Factors that contribute to unstable coastal bluffs near the pipeline landfall on the eastern side of Cook Inlet are described above under "Other Project Components." The bluffs in this area have a history of erosion problems caused by wave action, tidal currents, groundwater seepage, and overland flow. Bluff retreat estimates range from 0.3 to 0.5 foot per year in lower Cook Inlet near Kachemak Bay, to as much as 3 feet per year near the town of Kenai (Adams et al. 2007; USACE 2007a). The bluffs have experienced gullying, periodic landsliding, and debris flows following major storms (Reger and Petrik 1993; USACE 2008). In particular, a recent arcuate landslide scar on the northern side of the eastern end of the pipeline route is visible on the aerial photograph in Figure 3.17-16. This feature lies within 100 feet of both the Sterling Highway and the pipeline route.

The 1964 Great Alaskan Earthquake caused numerous landslides, rockslides, debris flows, soil slumps, and avalanches along the shoreline of Cook Inlet and slopes of Kodiak Island. The earthquake also caused translational landslides, tension cracks, and earth fissures on the top of bluffs, and rotational slides in Neogene sedimentary rocks, such as those that outcrop along the eastern coast of Cook Inlet (Plafker and Kachadoorian 1966; Waller 1966).

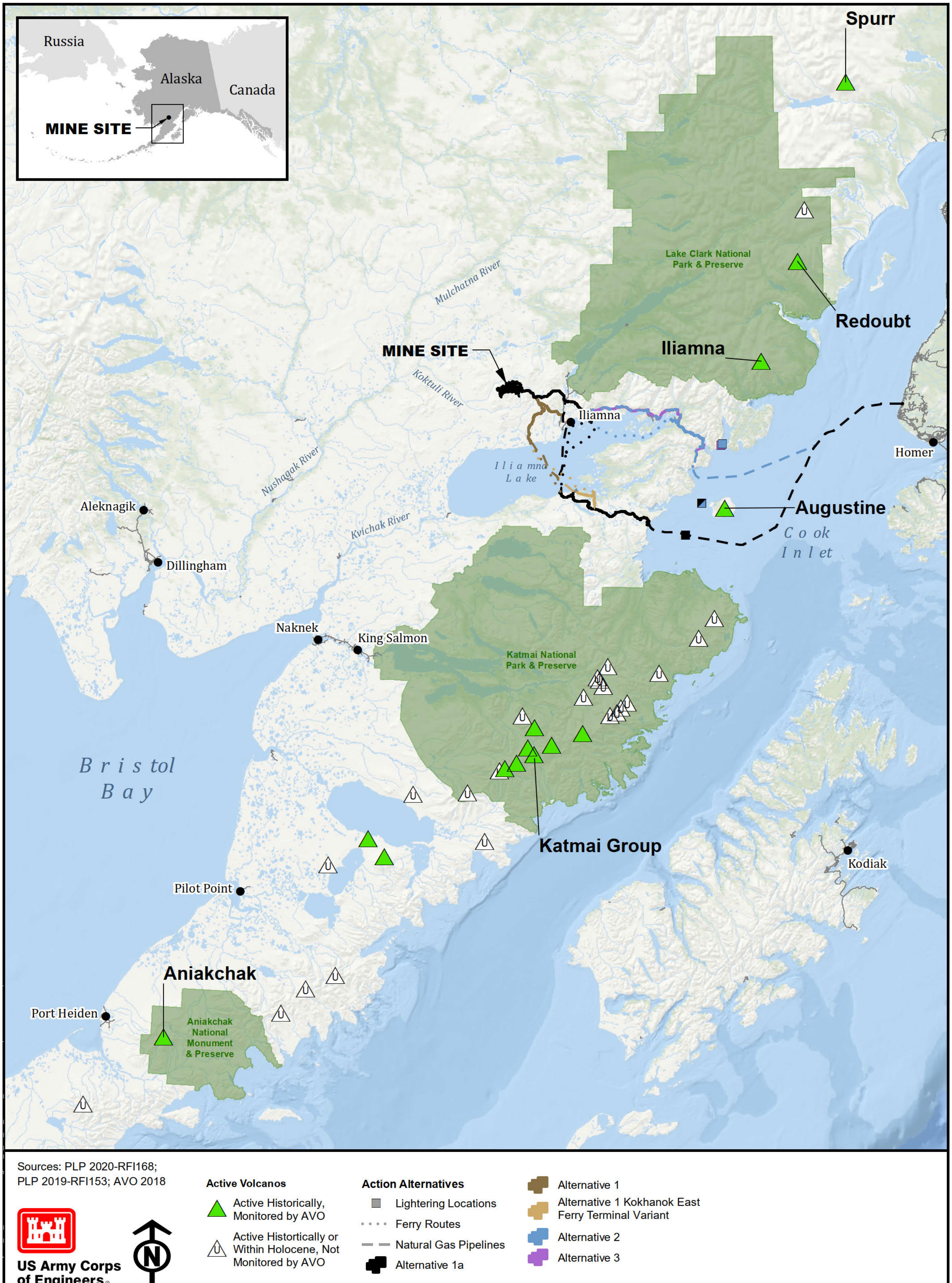
3.15.4 Volcanoes

Alaska contains more than 50 volcanoes considered to be historically active, having erupted in the last few hundred years (Alaska Volcano Observatory [AVO] 2018a). Several are about 100 miles from proposed project infrastructure (Figure 3.15-5), including Mount Augustine, 20 miles east of the Amakdedori port site; Mount Iliamna and Mount Redoubt volcanoes, north of the project area; and a cluster of volcanoes on the northern Alaska Peninsula.

Mount Augustine volcano is the most historically active volcano in the Cook Inlet region. It has erupted seven times since the late 1700s, averaging one eruption every 35 years, and was last active in 2015 (Miller et al. 1998). Past eruptions of Mount Augustine caused ashfall accumulations of up to 0.25 inch on the Alaska and Kenai peninsulas; floating rafts of pumice that interfered with boat traffic in Cook Inlet; and ash clouds that disrupted air travel for hundreds of miles (Waythomas and Waitt 1998). Volcanic debris flows into Cook Inlet are known to occur with an average recurrence interval of about 150 to 200 years (Begét and Kienle 1992). It is estimated that 12 to 14 have reached the sea in the last 2,000 years, with flow paths extending in all directions around the volcano (Figure 3.15-6). Derived from the collapse of summit lava domes and flows, these debris flows consist of rock debris, gravel, sand, and silt (Waitt et al. 1996; Waythomas et al. 2006). Outcropping rock likely associated with Mount Augustine has been mapped at the seafloor between Augustine Island and Amakdedori port site (Intecsea 2019).

Mount Redoubt and Mount Iliamna volcanoes were recently active. Mount Redoubt has had three major eruptions in the last 100 years, the most recent of which (2015) created significant ash plumes that disrupted air traffic on and off for months, and trace amounts of ashfall in Southcentral Alaska communities. Mount Iliamna is mainly known for active steam vents and avalanches related to seismic activity (AVO 2018a). It had a small eruption in 2016.

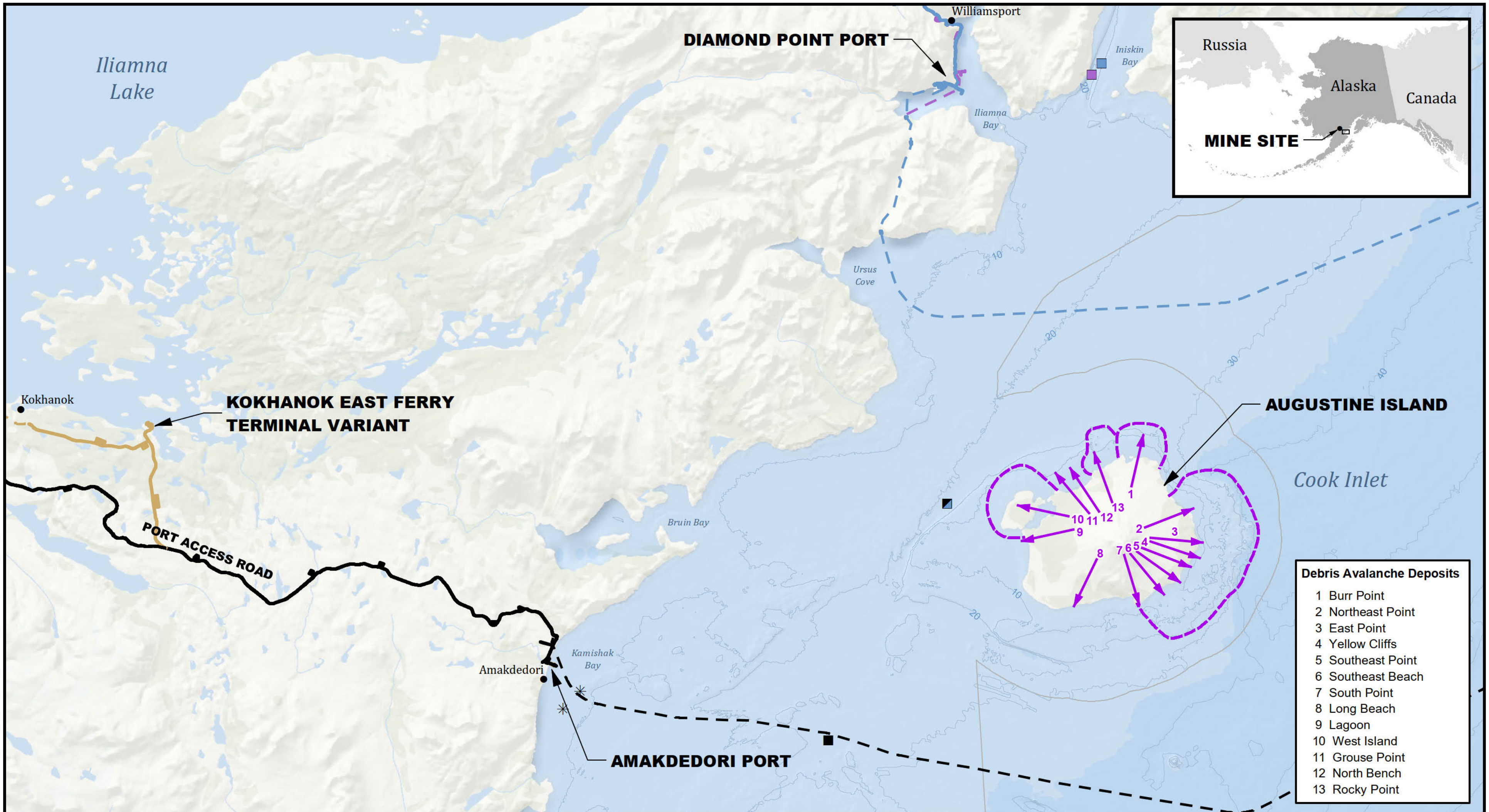
The Katmai group of seven volcanoes on the northern Alaska Peninsula includes three that have experienced historical eruptions (Katmai, Novarupta, and Trident), and four that are primarily known for steaming fumaroles (Snowy, Griggs, Martin, and Mageik) (AVO 2018a). The largest historical eruption in this group occurred at Katmai and Novarupta in 1912, resulting in deposition of approximately 1 foot of ash in Kodiak, 100 miles away (Fenner 1920). Trident's last eruption began in 1953, producing ballistic blocks about 2 miles away from the vent, and intermittent ash clouds over a period of 21 years (AVO 2018a).



ACTIVE VOLCANOES

PEBBLE PROJECT EIS

FIGURE 3.15-5



Sources: PLP 2020-RFI168;
PLP 2019-RFI153; Waythomas et al. 2006

US Army Corps of Engineers

3 0 3 6

Miles

Approximate offshore extent of debris-avalanche deposits

Approximate drbris avalanche flow path

Action Alternatives

Lighted Navigation Buoys

Lightering Locations

Natural Gas Pipelines

Alternative 1a

Alternative 1 Kokhanok East Ferry Terminal Variant

Alternative 2

Alternative 3

Other Features

Bathymetric Contour (meters)

Three Nautical Mile Line

HISTORICAL DEBRIS AVALANCHES ON AUGUSTINE ISLAND

PEBBLE PROJECT EIS

FIGURE 3.15-6

3.15.5 Tsunamis, Seiches, and Coastal Hazards

A tsunami is a sea wave that results from large-scale seafloor displacement caused by a large earthquake or major submarine slide. A seiche is a series of standing waves in a fully or partially enclosed body of water caused by earthquakes or landslides (Kabiri-Samani 2013).

Lower Cook Inlet has the potential for tsunamis and related coastal geohazards from seismic events. Impacts from tsunamis are dependent on bathymetry, coastline configuration, and tidal interactions. The 1964 Great Alaskan Earthquake generated numerous tsunami waves, including several that destroyed the harbor at Kodiak (Plafker and Kachadoorian 1966). Recent tsunami modeling by American Society of Civil Engineers (ASCE) (2017b) predicts a runup elevation of 28.5 feet above mean high water (MHW) for a 2,500-year return period event at high tide at the Amakdedori port site. This is equivalent to a runup elevation of roughly 42 feet mean lower low water (MLLW)[1]. Lower tsunami runup elevations are predicted for the Alternative 2 Diamond Point port site (22 to 25 feet MHW, or 36 to 39 feet MLLW[2]), the Alternative 3 dock site (24 to 27 feet MHW, or 38 to 41 feet MLLW), and the eastern end of the pipeline on Kenai Peninsula (18.6 feet MHW, or about 36 feet MLLW) (ASCE 2017b, 2018b). Higher runup elevations are predicted for the Alternative 3 port site located further north in Iliamna Bay (31 to 33 feet MHW, or 45 to 47 feet MLLW) (ASCE 2018b).

Older tsunami modeling by Crawford (1987) provides information on smaller, more frequent tsunamis that could occur. For example, wave height predictions for 100- to 500-year return period events (combined with high tide) are estimated to be 12 to 23 feet above mean sea level (amsl) (about 19 to 30 feet MLLW[3]) in the Amakdedori area of Kamishak Bay, and 13 to 15 feet amsl (21 to 23 feet MLLW) near the eastern end of the pipeline on Kenai Peninsula.

Volcanic eruptions can also produce tsunamis from catastrophic dome collapses and rapidly moving pyroclastic flows entering the sea (Allen 1994; Armes 1996; Waythomas and Neal 1998; Waythomas et al. 2009; AVO 2018a). One of the debris avalanches at Mount Augustine created West Island on the western side of Augustine Island 300 to 500 years ago (Figure 3.15-6). Based on numerical modeling of this deposit by Waythomas et al. (2006), it is estimated that a tsunami with a maximum wave amplitude of about 30 to 55 feet may have struck the mainland shore south of Ursus Cove, reaching about 10 feet near the Amakdedori port site. A secondary 60-foot wave may have occurred near West Island during this event. (For context, maximum wind-generated storm waves in lower Cook Inlet can reach 40 feet.) The 1883 eruption of Mount Augustine produced a debris avalanche–generated wave that affected areas up to 55 feet above high tide on the northern side of the island, and 23 feet above high tide on Kenai Peninsula (Begét et al. 2008). Numerical modeling suggests that this event may have produced a tsunami in the range of 5 to 20 feet near Diamond Point and the mouth of Iniskin Bay. These events are estimated to have been capable of transporting gravel- to cobble-sized sediment in northern Kamishak Bay, Ursus Cove, and Iliamna Bay (Waythomas et al. 2006).

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[1] MHW is estimated to be in the range of 13 to 14 feet MLLW at Amakdedori, based on an interpolation of tide gage data from Iniskin Bay (Pentec/Hart Crowser and SLR 2011; Hart Crowser 2015a), northern Shelikof Strait, and southern Kenai Peninsula (NOAA 2018f; PLP 2019-RFI 112). A site-specific MHW for Amakdedori would be determined from ongoing field data collection (PLP 2019-RFI 112).

[2] MHW is 13.8 feet MLLW at Diamond Point (Iniskin Bay) and 17.6 feet MLLW at Anchor Point (Pentec/Hart Crowser and SLR 2011; Hart Crowser 2015a; NOAA 2018f).

[3] Mean sea level (MSL) is estimated to be about 7.3 to 7.4 feet MLLW at Amakdedori, based on an interpolation of tide gage data from Iniskin Bay and northern Shelikof Strait (Pentec/Hart Crowser and SLR 2011; Hart Crowser 2015a; NOAA 2018f); MSL is 8.2 feet MLLW at Anchor Point (NOAA 2018f).

The occurrence of seiches and tsunamis in large lakes in the region has not been documented, and their occurrence in Iliamna Lake during past large earthquakes is unknown (PLP 2018-RFI 013). During the 1964 Great Alaskan and 2002 Denali earthquakes, seiches several feet high occurred in the intracoastal waterways of Southeast Alaska, and in a number of lakes and reservoirs in the contiguous 48 states (McGarr et al. 1968; Barberopoulou et al. 2004; CBJ 2018). Modeling of an earthquake-induced landslide into Bradley Lake in Southcentral Alaska predicted that a 10-foot wave would occur (Stone and Webster 1987); Bradley Lake is in a similar seismic zone but is much smaller than Iliamna Lake. Coastal planning in Southeast Alaska anticipates that seiches up to 20 feet high could occur from large distant earthquakes originating in Southcentral Alaska (Community and Systems Analysis [CASA] 1982). For context, storm-driven waves on Iliamna Lake have been documented as high as 6 feet in the community of Iliamna, where they have caused shoreline erosion and damage to the dock and boats (USACE 2009a). The likelihood of seiches and tsunamis to occur in Iliamna Lake is further addressed in Section 4.15, Geohazards and Seismic Conditions.

The 1964 Great Alaskan Earthquake generated additional coastal hazards in Cook Inlet, such as tectonic uplift and subsidence, ground fissuring, and submarine landslides, which destroyed the Homer Harbor breakwater. Vertical uplift was on the order of 1 to 2 feet along the western shore of lower Cook Inlet, and subsidence in the range of 0.5 foot to 4 feet along the eastern shore of lower Cook Inlet (Foster and Karlstrom 1967). Ground cracking, liquefaction, and local subsidence up to several feet occurred in saturated beach and alluvial deposits around Kodiak Island, along Cook Inlet shorelines, and around large lakes in the area (Plafker and Kachadoorian 1966). Along the western shore of Cook Inlet, stream mouths were drowned and narrow beaches experienced vigorous erosion at bluff faces (Stanley 1968).

Other coastal and marine hazards in lower Cook Inlet include large sand waves (large deposits of moving sand forming shallows), scour features (areas where the seabed is being eroded), and boulders on the seafloor (BSEE 2018; Intecsea 2019). The boulders originate from coastal bluff slumping or as glacial erratics, and can be ice-rafted along shore during winter, causing potential navigation hazards. Boulders and rocky shallows have been mapped along the coast 1 to 2 miles north and south of the mouth of Amakdedori Creek (PLP 2018-RFI 039) and extend offshore in an east-trending ridge from 1 to 5 miles due east of the creek. Rocky areas and boulders are common on mudflats in the upper reaches of Cottonwood and Iliamna bays (Pentec Environmental/Hart Crowser and SLR 2011). Reconnaissance geophysical surveys indicate the presence of rocks and boulders on the seabed and buried in shallow sediment in the vicinity of Diamond Point, reaching a maximum density near the mouth of Iliamna Bay (PLP 2018-RFI 063). Boulders are common along the eastern Cook Inlet shoreline near the pipeline landfall (NOAA 2015; Intecsea 2019). Rocky lakebed areas are also known to occur in Iliamna Lake (PLP 2019-RFI 071b).