4.15 GEOHAZARDS

This section describes potential impacts of geologic hazards (geohazards) on project components that could affect the environment. The Environmental Impact Statement (EIS) analysis area for geohazard ranges from the immediate vicinity of the project footprint (e.g., slope instability) to regional areas with geohazards that could affect project facilities from long distances (e.g., earthquakes, volcanoes).

The impact analysis for geologic hazards considered the following factors:

- Magnitude – impacts are assessed based on the magnitude of the impact, as indicated by the anticipated effects of various possible geologic hazard events (e.g., repairable damage to mine features, ground settlement).
- Duration – impacts are assessed based on the project phase that they are expected to occur in (e.g., certain structures removed at closure), and how long repair of potential damage or interruption of activities may last.
- Geographic extent – impacts are assessed based on the location and distribution of occurrence of the expected effects from potential geologic hazard events (e.g., distant earthquake effects on mine site and port structures).
- Potential – impacts are assessed based on the likelihood of a geologic hazard event to occur during and after project development (e.g., based on expected recurrence interval[1] for certain geologic hazards).

The impact analysis incorporates an understanding of the probability of occurrence, and of planned mitigation in the form of planning, design, construction, operations, maintenance, and surveillance that can meaningfully reduce impacts from geohazards through closure and post-closure. Based on Pebble Limited Partnership (PLP) plan documents and engineering reports, planned mitigation methods (e.g., design and monitoring to withstand or detect geohazards) are considered part of the project description, and the impacts analysis includes this understanding. In some cases, planned mitigation may not be specified, but is considered typical or standard engineering practice. In cases where planned mitigation is unknown or unclear and the situation is not commonly addressed, the impact analysis takes the lack of planned mitigation into account.

This section describes the following potential impacts related to geohazards:

- stability of major mine structures during operations and closure.
- effects of earthquakes on project facilities.
- effects of unstable slopes on project facilities.
- effects of geotechnical conditions and coastal hazards on port structures and pipeline landfalls.
- effects of tsunamis and seiches on port and ferry terminals.
- effects of volcanoes on project facilities.

Potential impacts to the environment resulting from geohazard-caused upset conditions, such as an embankment failure, are addressed in Section 4.27, Spill Risk. As described in Section 3.14, Soils, permafrost has not been encountered in the mine site or other project areas based on field investigations; therefore, potential effects from permafrost hazards are not addressed in this section.

[1] **Recurrence interval** (or return period) is an estimate of the probability or frequency that certain geohazards are expected to occur, based on geologic and seismologic evidence.

Scoping comments expressed concerns that major faults occur in the proposed project area and may affect project facilities. Commenters requested that the EIS include detailed information about seismically active areas, geological faults and tectonic activity, and corresponding design features. They also requested information on how the proposed project facilities, particularly the tailings storage facility (TSF), would withstand earthquakes, and an analysis of potential impacts from volcanic activity, especially at Amakdedori port and along the pipeline, from Augustine Volcano.

4.15.1 No Action Alternative

Under the No Action Alternative, the Pebble Project would not be undertaken. No construction, operations, or closure activities would occur. Therefore, effects on project components from geohazards, seismic events, and other geotechnical conditions would not occur as a result of this alternative, and no impacts on the environment would result from such effects. Permitted resource exploration activities currently associated with the project may continue (ADNR 2018-RFI 073). PLP would have the same options for exploration activities that currently exist. In addition, there are many valid mining claims in the area and these lands would remain open to mineral entry and exploration. Natural geohazards such as those described in Section 3.15, Geohazards, would continue to affect existing communities and infrastructure in the region.

4.15.2 Alternative 1 – Applicant's Proposed Alternative

4.15.2.1 Mine Site

This section describes potential effects of seismic events and other geohazards on major structures at the mine site; the ability of the structures to withstand these hazards; and the likelihood that such hazards could produce related environmental impacts. Figures in Chapter 2, Alternatives, display the mine site layout; and Table K4.15-1 in Appendix K4.15 provides the buildout dimensions of embankments and impoundments that would contain tailings, waste rock, and/or contact water at the mine site. This section also addresses potential geohazard effects on the open pit.

Embankment Construction Material

The embankments for the tailings and water management facilities would be constructed of drilled and blasted bedrock removed from quarries A through C[2], and the overburden in the open pit (Chapter 2, Alternatives, Figure 2-4). Analyses were completed to determine the quantities of on-site embankment construction materials and project-related needs. Appendix K4.15 (Table K4.15-2 and Table K4.15-3) provide embankment material quantities that would be generated by quarries A through C and the open pit overburden, as well as the embankment material needs for the relevant mine site-related facilities, respectively.

Based on review of material properties and quantities provided by PLP (2018-RFI 015b; PLP 2019-RFI 108a), the combination of the three quarries and the open pit overburden would generate sufficient materials (between 6 and 32 percent more rockfill material than needed) to construct the embankments. Thus, the likelihood that additional material needs would be identified as the project progresses (with related project footprint increases) is low.

[2] Quarry A is shown as situated in the footprint of the bulk TSF; this quarry would be developed before the construction of the bulk TSF.

Embankment and Impoundment Design and Construction

The embankments and impoundments could be impacted by geohazards, including instability associated with seepage, internal erosion[3], and seismic (earthquake) events. The embankments would therefore be designed and constructed to be stable under both static (non-seismic) and seismic conditions, which is also required by relevant draft dam safety guidance documents (ADNR 2017a). The following summarizes the geohazard considerations for the proposed design and construction of the major embankments and impoundments, including the bulk TSF, pyritic TSF, water management ponds (WMPs), and seepage collection ponds (SCPs). More detailed information is provided in Appendix K4.15.

Bulk TSF. The bulk TSF would be designed to impound the bulk tailings, and includes a main (north) and south embankment with the following design and construction elements to prevent geohazard-related impacts:

- Siting in a single tributary watershed surrounded by bedrock knobs to focus potential impacts in one watershed and incorporate natural containment elements.
- Main (north) embankment centerline constructed[4] to reduce the footprint, with a buttressed downstream slope to enhance stability, which would result in 2.6 horizontal: 1 vertical (H:V) downstream embankment slope and a serrated near-vertical upstream face at the dam crest for the upper 280 feet of the embankment (Chapter 2, Alternatives, Figure 2-8).
- Permeable flow-through design with core/filter/transition zones materials to minimize water buildup in the TSF, prevent internal erosion, and remain functional after a seismic event.
- South embankment constructed using downstream methods[5], to include a downstream liner combined with a grout curtain to prevent upgradient groundwater flow into and beneath the impoundment.
- Bottom of south embankment core/filter/transition zones would tie into the top of the grout curtain zone, which would be keyed into bedrock to prevent leakage beneath the embankment.
- Underdrains beneath the TSF to further manage seepage flow.
- Water management to protect the dam from seepage pressure-related instability.
- Drainage ditches at the toe of the embankment slopes to prevent erosion and undercutting.
- Freeboard to contain the entire inflow design flood above the tailings beach.
- Excess pond water to be pumped to the main TSF SCP or main WMP.
- Higher south embankment elevation to direct overflow to water catchment facilities.

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[3] **Internal erosion**, also referred to as piping, is the formation of voids in a soil caused by the removal of material by seepage, and occurs when the hydraulic forces exerted by water seeping through the pores and cracks of the material in the embankment are sufficient to detach particles and transport them out of the embankment structure.

[4] **Centerline construction** is a method of dam (embankment) construction in which a rockfill dam is raised by concurrent placement of fill on top of the dam crest, the upstream slope including portions of the tailings beach, and the downstream slope of the previous raise.

[5] **Downstream construction** is a method of dam (embankment) construction in which a rockfill dam is raised in the downstream direction by placement of fill on top of the dam crest and downstream slope of the previous raise.

- Wide tailings beach to reduce seepage pressure on embankments, and promote subsurface drainage to the north with pond development against bedrock high to the southeast.
- Reduced tailings volume by using thickening methods or additional pumping capacity.
- Foundations to be placed on competent bedrock for increased stability.
- Each dam lift to undergo a thorough safety review, and adjusted as necessary.
- Dry closure methods to improve the stability for permanent in-place closure, with a closure cover design that would minimize infiltration.
- Monitoring performed during construction, operations, closure, and post-closure.

Pyritic TSF. The pyritic TSF would be designed to impound the pyritic tailings and potentially acid-generating (PAG) waste rock, and would include a continuous embankment around the northern, southern, and eastern sides with the following design and construction elements to prevent geohazard-related impacts:

- Fully lined, subaqueous storage cell during operations to minimize acid generation.
- Majority of the pyritic TSF in a single tributary valley.
- Liner protected with processed materials (sand and gravel) after installation to prevent damage from punctures or damage during waste rock placement.
- Liner installation completed in accordance with standard industry practices, and closely monitored.
- Water levels maintained for the life of the facility.
- Water levels and freeboard maintained to account for the inflow design flood, wave run-up, and wind set-up.
- Excess pond water controlled by pumping to the main WMP.
- Embankments prepared by removing overburden to competent bedrock.
- Tailings and waste rock moved into the open pit at closure.
- After closure, the liner removed and embankments graded/recontoured to conform to surrounding landscape and promote natural runoff and drainage.
- Monitoring included in all phases.

WMPs and SCPs. Two primary WMPs would be at the mine site (the main WMP north of the pyritic TSF, and the open pit WMP) to impound contact and open pit water, respectively. The SCPs would be downstream of the TSF embankments, and include those associated with the bulk TSF main and south embankments, and the pyritic TSF north, east, and south embankments. The facilities would include the following design and construction elements to prevent geohazard-related impacts:

- Fully lined to minimize seepage and risk of internal erosion.
- Rockfill embankments to promote stability.
- Main WMP embankment prepared by removing overburden to competent bedrock.
- Open pit WMP embankment design concept requiring potential weak foundation conditions encountered in the overburden materials (e.g., glacial lake deposits) to be excavated.
- Pond water volumes managed through reuse in the process plant, and treatment and discharge.

- Monitoring/seepage pumpback wells downgradient to detect and capture potential liner leakage.
- At closure, the WMPs to be removed and embankments graded/recontoured to conform to the surrounding landscape and promote natural runoff and drainage.
- Monitoring included during all phases.

Static Stability Analyses

Analyses were completed to evaluate the stability of the proposed embankments under static and non-seismic conditions. The following summarizes the static stability analysis. A more detailed discussion is presented in Appendix K4.15. The following major embankments and impoundments were analyzed:

- Bulk TSF main and south embankments
- Pyritic TSF north embankment
- Main WMP
- Bulk TSF main SCP
- Open pit WMP

The static stability analyses were completed using the computer program SLOPE/W. Input parameters were based on the results of field and office studies, and included the embankment configurations and assumed rockfill material, foundation materials, and stored materials. The results predicted the analyzed embankments would have a static factor of safety (FoS) between 1.7 and 2.0 (a static FoS of 1.1 or greater is considered stable). Additional static stability analyses would be completed in support of the final design.

As noted above, the Alternative 1 bulk TSF main embankment design would result in a serrated near-vertical upstream face at the dam crest for the upper 280 feet of the embankment that would partially rest on tailings. The potential for this configuration to liquefy during seismic events was reviewed by a panel of geotechnical experts during the EIS-Phase Failure Modes and Effects Analysis (FMEA) (AECOM 2018l). The stability analysis results do not rely on the strength of these materials, but rather on the strength of rockfill materials directly beneath and downstream of successive raises in the core zone and buttresses (Figure 2-8 and Figure K4.15-2). In other words, regardless of the low strength assigned to the tailings, the overall embankment did not fail in a downstream direction in the stability analysis. Therefore, the FMEA panel concluded that the likelihood of global instability of the buttressed centerline embankment design would be very low.

Seismic Stability Analysis

Active Surface Faults. The mine site is situated in a regionally seismically active area caused by the convergence of the Pacific and North American tectonic plates. The most significant seismically active geologic structure near the mine site is the Bruin Bay fault, which is situated about 70 to 80 miles to the east-southeast.

No mine facilities would be constructed on top of known active surface faults. As presented in Section 3.15, Geohazards, the closest potentially active fault to the mine site, the Lake Clark fault, is about 15 miles to the northeast. Recent mapping at the mine site and vicinity has not shown evidence of offset of surficial deposits along faults or lineaments in the area (Hamilton and Klieforth 2010; Haeussler and Waythomas 2011; Koehler 2010). This conclusion is further supported by Light Detection and Ranging (LiDAR) data that were collected in 2004 in the mine site area. The LiDAR-derived image was reviewed for possible indications of fault-related movement in surficial deposits. No lineaments were observed that suggest possible Quaternary fault-related movement southwest of the mapped termination (AECOM 2018m).

More detailed discussion regarding seismic sources and hazards in the greater project area is presented in Section 3.15, Geohazards, Appendix K3.15, and Appendix K4.15.

Seismic Hazard Analyses. The TSF embankments at the mine site would be regulated as Class I (high) hazard potential dams under the Alaska Dam Safety Program (ADSP) draft dam safety guidelines (ADNR 2017a; PLP 2017). Based on these draft guidelines, two levels of design earthquake must be established for Class I dams:

- *Operating Basis Earthquake* (OBE) that has a reasonable probability of occurring during the project life (return period of 150 to more than 250 years), for which structures must be designed to remain functional, with minor damage that could be easily repairable in a limited time. In other words, minor damage within allowable design criteria may be sustained at the TSF embankments following an OBE earthquake.
- *Maximum Design Earthquake* (MDE) that represents the most severe ground shaking expected at the site (return period from 2,500 years up to that of the Maximum Credible Earthquake [MCE]), for which structures must be designed to resist collapse and uncontrolled release.

The OBE can be defined based on probabilistic evaluations, with the level of risk (probability that the magnitude of ground motion would be exceeded during a particular length of time) being determined relative to the hazard potential classification and location of the dam (ADNR 2017a). The MDE may be defined based on either probabilistic or deterministic evaluations, or both (ADNR 2017a).

Ground-shaking from earthquakes is typically presented in terms of PGA, measured as a fraction (or percent) of gravity (g), which represents the intensity of an earthquake as it is applied to a structure, such as the TSF embankments. The degree of ground shaking and structural damage expected is related to earthquake magnitude, distance from active faults, and duration of shaking. For example, small local earthquakes may cause more ground shaking than large, more distant earthquakes; and large distant earthquakes with a lower PGA but longer shaking duration may cause more damage than smaller nearby earthquakes with a higher PGA. As such, the selected OBE or MDE may be based on more than one earthquake scenario. A number of potential earthquakes were evaluated in the probabilistic and deterministic seismic hazard analyses (see Appendix K4.15) to develop the OBE and MDE.

A conservative OBE corresponding to a return period of 475 years was adopted for the Pebble TSF designs (Knight Piésold 2013). Based on this return period, the estimated PGA has been determined to be 0.14g (or 14 percent of gravity acceleration). The design earthquake magnitude associated with this level of ground shaking includes:

- A magnitude 7.5 earthquake determined based on probabilistic seismic hazard analysis which considers a combination of potential faults (Appendix K4.15, Table K4.15-7) (Knight Piésold 2013; Wesson et al. 2007).
- A magnitude 9.2 earthquake on the Alaska-Aleutian megathrust (having the same PGA of 0.14g because it is more distant) based on deterministic seismic hazard analysis (Appendix K4.15, Table K4.15-8).

The MCE was selected as the MDE for the Pebble TSFs (KP 2013). Earthquake magnitudes and ground shaking associated with the MCE considered in TSF embankment design include:

- A magnitude 6.5 shallow crustal earthquake from an unknown fault assumed to occur directly beneath the mine site, with a PGA of 0.61g.
- A magnitude 8.0 intraslab subduction earthquake (similar to the source of the magnitude 7.0 Anchorage earthquake on November 30, 2018), with a PGA of 0.48g.

- A magnitude 7.5 earthquake on the Lake Clark fault, with a PGA of 0.29g.
- A magnitude 9.2 megathrust earthquake with a PGA of 0.14g.

Appendix K4.15 provides further discussion of the seismic sources and probabilistic and deterministic evaluations completed for the project to evaluate potential ground shaking associated with these earthquakes. The seismic hazard analyses would be updated in final design to support ADSP design and reporting requirements, incorporating best practices for analysis published since the Knight Piésold (2013) study (Bozorgnia et al. 2014) and updated USGS ground motion data as available (PLP 2018-RFI 008c).

Seismic Deformation Analysis. A pseudo-static deformation analysis was completed to predict the response of the largest embankment (the bulk TSF) to a seismic event, based on the OBE, as well as MCEs from four potential seismic sources (faults) with magnitudes ranging from 6.5 to 9.2 (Appendix K4.15). Predicted displacements in the embankment were estimated to be negligible for the OBE, and on the order of 4 to 5 feet of horizontal displacement and crest settlement under MCE loading conditions. The displacements were not large enough to truncate the filter or transition zones, and would not affect the functionality of embankment. The results were used to design the minimum freeboard requirements for the bulk TSF embankments.

The deformation and settlement analyses would be updated as part of the ongoing design of the TSFs and other embankments. Additional detailed modeling, including analyses using Fast Lagrangian Analysis of Continua (FLAC) numerical modeling software, would be completed during detailed design of the facilities to better define embankment displacements.

Summary of Stability Effects. The magnitude of direct effects on mine embankments from earthquakes, floods, static loading, slope failure, and foundation conditions could range considerably. Effects would not be measurable where designs are adequate for expected geohazards, such as moderate earthquakes, large precipitation events, or known unstable foundation conditions that are removed in construction. In terms of duration, effects could include damage that would be repairable in the short term (e.g., months) in the event of an OBE; or in the event of an MDE, effects could range up to damage that would not be easily repairable, but would not be expected to lead to structural collapse or uncontrolled release of contaminated materials. Assuming that facilities are planned, designed, constructed, operated, maintained, and surveilled as proposed and in accordance with ADSP guidelines (ADNR 2017a), in terms of extent, potential damage to facilities and indirect effects on the environment would be expected to remain within the footprint of the mine site. In addition to ADSP oversight, PLP would also establish an independent review board to review embankment designs and stability analyses as engineering analysis progresses (AECOM 2018k).

The duration of effects would vary depending on the facility and likelihood of geohazard occurrence. In the case of earthquake damage that would be easily repairable, impacts would be infrequent, but not longer than the life of the mine for facilities that would be removed at closure (e.g., embankments at the pyritic TSF). Impacts could occur in perpetuity for structures that would remain in place (e.g., bulk TSF embankments). Based on the conceptual designs, and assuming that current standard of engineering practice would be followed, the likelihood of global instability of the major embankments was considered to be very low (i.e., less than 1 in 10,000 probability) by geotechnical experts in the EIS-Phase FMEA (AECOM 2018l). Indirect effects on other downstream resources in the unlikely event of an embankment spill or release are discussed in Section 4.27, Spill Risk.

Open Pit Slopes

Numerical modeling was completed to predict the stability for three sections of the open pit walls with known weak rock conditions (Appendix K4.15, Figure K4.15-10). As described in Appendix

K4.15, the analyses evaluated both static and seismic conditions, and included modeling of disturbance factor zones that represent the predicted bedrock damage caused by rock mass relaxation[6] and crustal rebound[7] due to the excavation of the open pit, as well as blast damage close to the excavation surface (Hoek 2012). The modeling targeted a minimum acceptable FoS for the open pit walls of 1.3 for static conditions, and 1.05 for dynamic (earthquake) conditions. These values recognize that there would only be a single entry into the pit, and any instability involving the ramp could impact the operations. After closure, the static FoS would be reduced to an FoS of 1.1 due to the lack of access required into the pit, but this would be further reviewed during detailed design.

In terms of magnitude, the modeling results showed an FoS of 1.1 or greater for two of the three pit sections, indicating they would be stable under both static and earthquake loadings, and an FoS below 1.1 (indicating potentially unstable conditions) for the section through the northwestern side of the pit under both static and dynamic loadings in early closure after dewatering ceases.

Two additional closure scenarios were examined for the northwest section: 1) early closure with continued groundwater depressurization focused on the toe of the slope; and 2) with pit lake levels recovered to about half full (above the area of instability). The results indicate an FoS of 1.1 and 1.4, respectively, for the two scenarios (Appendix K4.15, Figure K4.15-12 and Figure K4.15-13), and suggest that with continued depressurization in the localized area of the northwestern section during early closure activities (e.g., backfilling), the pit wall would be stable.

Other Geohazard Considerations

Quality Assurance/Quality Control (QA/QC). A Construction QA/QC Plan would be developed to assure all quarries, embankments, impoundments, and liners are constructed and operated in accordance with the approved designs and specifications. The plan would specify actions for approving embankment materials, construction methodology, field testing, surveying, monitoring, and documentation. Alaska Department of Natural Resources (ADNR) (2017a) guidelines provide details on plan requirements, personnel responsible for QA/QC, key inspection items, and required post-construction document submittals.

Mining-Induced Seismicity. Induced seismicity refers to earthquakes and tremors that are thought to be caused by human activity through altering the stresses and strains in the earth's crust. Mining-related activities such as rock mass relaxation, crustal rebound, and blasting associated with the excavation of an open pit, have the potential to generate induced seismicity.

The US Geological Survey (USGS) compiled a list of mining-related induced seismicity in the US over the 27-year period between 1973 and 2000, during which there were a total of 47 seismic events attributable to mining-related induced seismicity. The recorded tremors were generally small, ranging in magnitude between 2.0 and 4.8 (USGS 2018f). One of the events occurred at the Usibelli Coal Mine in Alaska, with a magnitude 3.3 attributed to blasting, and possibly concurrent rock mass relaxation. The Usibelli Coal Mine is an open pit operation situated in a seismically active area similar to the proposed Pebble mine site[8] (WSM 2018).

[6] **Rock mass relaxation** is the unloading of rock stresses due to the removal of bedrock (e.g., underground mines and/or open pits).

[7] **Crustal rebound** isthe rise of a land mass due to removing an overlying weight or mass, such as excavating bedrock during open pit mining, which could be significant enough to be measurable, and therefore included in the computer modeling.

[8] Both are situated in strike-slip regimes with similar associated seismic mechanisms, but the magnitude of stress is higher at the Usibelli Coal Mine due to the tectonic forces that created Denali.

There does not appear to be an observed direct correlation between the weight of TSFs and/or stockpiles and induced seismicity at mining sites.

The open pit slope analysis above assumed seismic conditions that are likely greater than the highest magnitude mining-related induced seismic event recorded by the USGS (2018f). In addition, the seismic stability analysis performed in support of the mine site design (Appendix K4.15) took into consideration unknown shallow crustal earthquakes (Knight Piésold 2013), which is how a large mining-related induced seismic event would likely behave.

Seismic Impacts on Hydrogeology. The potential exists for impacts on hydrogeology resulting from a seismic event. For example, at the mine site, there are near-surface groundwater occurrences such as seasonal seeps and deeper groundwater that could be impacted (see Section 4.17, Groundwater Hydrology). Potential groundwater impacts could include changes in groundwater levels, volumes, and chemistry, including the locations of seeps. However, these types of changes commonly occur in the absence of seismic events due to other factors such as weather conditions (e.g., precipitation, temperatures) and changes in water chemistry (e.g., precipitation of naturally occurring constituents and/or bacteria in the water).

Groundwater conditions would be monitored throughout all stages of the mine project for both flow and chemistry purposes (Section 4.17, Groundwater Hydrology and Section 4.18, Water and Sediment Quality). If a major earthquake were to occur during project operations, an "extraordinary inspection" for any impacts would be required in accordance with the ADSP draft dam safety guidelines (ADNR 2017a), and in compliance with specific requirements of an operations and maintenance manual. The inspection would also identify adherence to design criteria for all major structures to ensure they continue to perform as designed. Changes to the groundwater monitoring program, facility design, and/or operation would be implemented as necessary to ensure protection of the environment.

Summer-Only Ferry Operations Variant

Under the Summer-Only Ferry Operations Variant, copper-gold concentrate would be stored in shipping containers at the mine site during the winter at a storage area northeast of the pyritic TSF (Chapter 2, Alternatives, Figure 2-39). Based on the surficial geology map (Section 3.13, Geology, Figure 3.13-2); the proposed copper-gold concentrate storage area is primarily underlain by surficial glacial outwash deposits, which generally consists of a mixture of sand- to gravel-sized material. The glacial outwash appears to thin to the northeast, with possible bedrock exposed near the northeastern boundary of the storage area.

During a large earthquake, the potential would exist for the stacked shipping containers to be impacted by differential settlement of the underlying glacial outwash due to being thicker to the southwest than the northeast, potentially resulting in toppling of the containers. The likelihood would depend on the magnitude and duration of the seismic event, height of container stacking, the in-place density of the foundation materials, and other factors. The impact would likely be mitigated through further investigation and foundation preparation such as compaction of near-surface materials.

4.15.2.2 Transportation Corridor

Earthquakes and Seiches

The transportation corridor would not cross any known active surface faults (Section 3.15, Geohazards, Figure 3.15-1). A trace of the Bruin Bay fault zone crosses the port access road within several miles of the Amakdedori port site; however, there is no evidence of Holocene offset at the surface for this segment of the fault (Plafker et al. 1994; Koehler et al. 2013).

Therefore, effects on transportation corridor facilities related to surface fault displacement would not be expected to occur.

The magnitude of impacts from ground shaking in the event of a major earthquake would be direct effects on transportation facilities, such as cracking, spreading, and settlement of terminal platforms, or damage to the ferry during construction. However, because the ferry terminals would not include fuel tank storage facilities, indirect effects on the environment in the vicinity of the terminals from fuel spills due to tank rupture would not be expected.

Earthquake- or landslide-induced seiches can damage shoreline structures, boats, and moored vessels in enclosed waterbodies, particularly if the natural period of a moored ship matches that of a seiche (Kabiri-Samani 2013). The historical occurrence of seiches in Iliamna Lake is unknown (see Section 3.15, Geohazards) (PLP 2018-RFI 013). In terms of magnitude, seiches several feet high have been documented in Southeast Alaska and the contiguous 48 states during past major Alaska earthquakes (McGarr et al. 1968; Barberopoulou et al. 2004; CBJ 2018); they would be expected to be around the size of maximum storm-driven waves on Iliamna Lake (USACE 2009a). Larger predicted seiche heights of 10 to 20 feet have been suggested for Bradley Lake on Kenai Peninsula and Lynn Canal at Skagway, respectively (CASA 1982; Stone & Webster 1987); however, seiches are more likely to occur in these narrow bodies of water than in Iliamna Lake.

A preliminary estimate of seiche potential in Iliamna Lake was conducted based on a 60- by 15-mile area representing the wide part of the lake where the Alternative 1 ferry would operate (AECOM 2018d). The results indicate the natural oscillation period of an earthquake-induced seiche would fall well outside the period range where earthquake ground motions carry the most energy, suggesting that earthquake-induced seiches would not be expected to occur.

Unstable Slopes

As discussed in Section 3.15, Geohazards, the north ferry terminal location is underlain by surficial deposits consisting of beach and lake terrace sand and gravel, and the south ferry terminal location by both volcanic bedrock and similar surficial deposits, neither of which is prone to unstable slope conditions (Chapter 2, Alternatives, Figure 2-23 and Figure 2-25).

In terms of potential extent of impacts from unstable slopes, several small areas of unstable slope deposits occur along the mine access road, near the junction between the mine access and Iliamna spur roads, and near the southern end of the port access road (Section 3.15, Geohazards) (Detterman and Reed 1973; Hamilton and Klieforth 2010). Over-steepened, potentially unstable slopes could also be created during the development of the geologic material sites. Typical engineering and construction practices such as engineered cuts, benching, and drainage controls (Chapter 2, Alternatives, Figure 2-16) would be used at these locations to minimize the potential for landslide impacts on the roads, material sites, and disruption of truck haulage. Therefore, if such effects were to infrequently occur, the duration and extent of impacts on the project and related effects on environmental resources would be easily repairable in the short term, and of limited extent in the immediate vicinity of the road footprint.

Based on the topography along the road corridor, avalanches would not be expected to occur during mine operations.

Summer-Only Ferry Operations Variant

There would be no difference in the magnitude and extent of geohazard-related impacts under the Summer-Only Ferry Operations Variant. Lake ice hazards (for year-round ferry operations under Alternative 1) are discussed under Section 4.16, Surface Water Hydrology.

Kokhanok East Ferry Terminal Variant

As described in Section 3.15, Geohazards, the Kokhanok East Ferry Terminal Variant location would be underlain by beach deposits near the shoreline, and volcanic bedrock farther upslope. The magnitude and potential for seismically related and unstable slope impacts would be expected to be similar to the south ferry terminal location west of Kokhanok.

4.15.2.3 Amakdedori Port

Earthquakes

Site-specific seismic hazard analyses were conducted for the port site as described in Appendix K4.15. The port would be designed to an appropriate seismic design code (Knight Piésold 2013). A PGA of 0.51g associated with a 2,500-year earthquake was preliminarily adopted as the design earthquake for the Diamond Point port based on probabilistic seismic hazard analysis (Appendix K4.15, Table K4.15-10) and International Building Code requirements. Based on fault conditions and seismicity in the region (Section 3.15, Geohazards, Figure 3.15-2, and Appendix K4.15, Figure K4.15-7), the magnitude and extent of ground shaking effects at the Amakdedori port site would be expected to be similar to or less than effects predicted for the Diamond Point port site. The seismic hazard analyses would be updated in final design (Knight Piésold 2013; PLP 2018-RFI 008c).

In terms of magnitude, the predicted ground shaking at the port would be roughly double that predicted for the mine site, reflecting the closer proximity of the port to potential subduction zone earthquakes (Appendix K4.15, Figure K4.15-8). Based on the deterministic seismic hazard analysis (Table K4.15-11), a PGA of 0.51g is associated with an intraslab subduction earthquake in the range of magnitude 7.5 to 8.0 from an epicenter about 20 to 25 miles away and 50 to 60 miles deep.

Stability of Sheet Pile Dock

An assessment of the static and seismic stability of the proposed sheet pile dock is presented in Appendix K4.15 and summarized below. As described in Section 3.15, Geohazards, the foundation materials for the offshore components would be limited to shallow borings about 3 feet deep, a near-surface geophysical survey, and extrapolation from a deeper onshore geophysical survey, which suggest that subsurface deposits consist primarily of sand and gravel. Additional geotechnical investigation would be conducted as the project design progresses.

In the absence of the additional foundation information and related engineering analyses, the proposed rockfill causeway and sheet-pile dock would have the potential to result in adverse impacts to the environment during construction and operations. The potential magnitude and extent of impacts could include:

- Structural instability and potential failure of the sheet-pile wharf as a result of seismic loading, foundation conditions, erosion at the base of the sheet pile, icing increasing gravity load on the sheets, and corrosion requiring regular monitoring of cathodic protection systems.
- Damage to the structures due to liquefaction of the seabed during a seismic event.
- Damage to the sheet pile wall during installation due the presence of boulders in the nearshore sediment, which could result in the release of the earthfill during operations.

The additional field investigation-related information would support more detailed design analyses to confirm whether the design would be feasible, and if so ensure construction, operations, and closure would be protective of the environment.

The port would be closed and undergo reclamation after the off-site transport of concentrate would be completed at Year 20 of operations. All structures and related earthfill would be removed, and the site reclaimed (PLP 2018-RFI 024). The duration of potential geohazard-related impacts would therefore be long-term, and the extent would generally be limited to the close vicinity of the dock footprint. With additional geotechnical investigation and stability analyses, dock design would be refined to address the potential for failure that could lead to adverse impacts on the environment.

Unstable Slopes

The Amakdedori port site is underlain by raised beach terrace deposits consisting of sand and gravel (Section 3.15, Geohazards), which are not prone to unstable slope conditions.

Tsunamis

Recent tsunami modeling for lower Cook Inlet (ASCE 2017b) predicts a run-up elevation in the Amakdedori area of 28.5 feet above mean high water, or about 42 feet above mean lower-low water (MLLW), for a very large earthquake with a 2,500-year return period (Section 3.15, Geohazards). The probability of this size tsunami occurring over the life of the port is roughly 1 in 35, assuming the port needs to be operational through closure phase 3 for a total of 70 years (20 years operations, plus 50 years closure). Older modeling by Crawford (1987) predicts run-up elevations in the Amakdedori area for smaller, more frequent, medium to large earthquakes (100- to 500-year events) of about 19 to 30 feet MLLW. The proposed elevation of the terminal patio is 35 feet MLLW (Figure 2-28) (PLP 2018-RFI 093). As discussed in Section 3.15, Geohazards, tsunamis can also be generated by local landslide events, such as the debris avalanches that have occurred on the flanks of Augustine Volcano. These have reached the sea about every 150 to 200 years, and are estimated to be capable of generating wave amplitudes in the range of 5 to 60 feet (Waythomas et al. 2006).

The 2,500-yearr return period event is the “maximum considered tsunami” in the latest industry standards (ASCE 2017a), which specify that certain structures be designed such that they are able to provide essential functions immediately following this event. In terms of magnitude and extent of impacts, for a large tsunami of this size and return period, the predicted run-up elevation could exceed the design elevation of the terminal by about 7 feet, potentially affecting facilities such as fuel tanks and concentrate container storage. Assuming the causeway and wharf elevations are the same as the 35-foot terminal elevation, equipment and activities on top of these structures would also be affected. For smaller tsunamis with a probability of occurrence in the range of 1 in 100 to 500 years, the predicted run-up elevation is below that of the port facilities, and the magnitude and extent of impacts on terminal facilities and related effects on the environment would be expected to be no worse than waves from large storm events.

A detailed tsunami analysis would be conducted in accordance with American Society of Civil Engineers (ASCE) (2017a) standards prior to final port design that would include a probabilistic assessment of tsunami sources (from both earthquakes and landslides) and numerical modeling to provide site-specific maximum run-up, inundation, and current velocity that would be incorporated into final design. The final terminal elevation would be revisited in final design based on these analyses. The causeway elevation and footprint would be as currently proposed, but would transition to the final terminal elevation if a change would be required. The port diesel fuel facility would be designed to withstand the 2,500-year event. The concrete containment barrier wall around the fuel tank farm (Figure 2-28) would be designed to protect against tsunami run-up. A risk analysis would be undertaken for other port components to determine the associated risk level and associated design event. Structures would be designed to withstand tsunami forces, protect against debris impacts, resist uplift, and ensure that scour does not form, which could undermine structures (PLP 2019-RFI 112).

If unmitigated, the magnitude of effects from a large tsunami could include risks to worker safety, equipment, and structures, such as the fuel storage tanks, concentrate containers, trucks, and cranes. (The effects of potential spill releases from project facilities are discussed in Section 4.27, Spill Risk.) Damage during a tsunami could result from initial wave crushing or buoyancy failures, which can cause tipping or sliding of fuel storage containers (Brooker 2011). The sheet-pile bulkhead design would expose the cross-sectional area to the hydrodynamic impact of the wave. A critical loading condition for the bulkhead could be the very low water level during the retreat phase of the tsunami, during which the stabilizing effect of water on the outside of the sheet-pile would be absent or diminished. Wave impacts and flooding of the upper part of the causeway would be expected to cause little damage and erosion, because the same type of riprap would be used to protect both the upper and lower parts (PLP 2018-RFI 093), and because the riprap would be designed to resist tide buoyancy and storm impacts. Some boat damage could result from barge/wharf or barge/ship collisions if loading and lightering activities at the wharf or off-shore mooring locations were to coincide with the arrival of a tsunami wave; however, tsunami warning infrastructure, which typically sends warnings within minutes (NOAA 2018e), may provide enough time to move vessels to avoid these impacts. Advance warning of the potential for local landslide-generated tsunamis from Augustine Volcano would be expected to be longer due to tracking of volcanic activity by Alaska Volcano Observatory (AVO).

In addition to proposed design mitigation described above, other measures would be employed to reduce the risk to personnel, such as early warning systems, vertical evacuation structures, and operational procedures and training on when to move to higher ground and secure critical equipment. Impacts to vessels at the two lightering locations would be analyzed during the tsunami studies to understand the response if a vessel happened to be in place during an event. For the majority of potential events, the vessels would not remain moored. Operational procedures would be in place such that, if volcanic activity is predicted or a tsunami warning issued, vessels would cease lightering operations and move to safer locations in deeper water (PLP 2019-RFI 112).

The likelihood of a large tsunami occurring at the port ranges from to very unlikely in any given year (i.e., 1 in 2,500) to moderately unlikely (i.e., 1 in 35) over the life of the port. If a tsunami were to occur, the intensity of impacts could range from minimal disruption of activities or boat damage, to terminal flooding and damage to infrastructure, though critical infrastructure such as the fuel tank farm would be expected to remain intact with proposed mitigation in final design. Infrastructure damage would be localized in the near vicinity of the port and mooring sites. The duration of impacts could range from hours to months (in the event repairs to non-critical infrastructure would be required).

Volcanoes

A number of active volcanoes have erupted in the last few decades within about 100 miles of the project area (Section 3.15, Geohazards, Figure 3.15-4). Of particular potential concern is Augustine Volcano, approximately 20 miles east-northeast of the Amakdedori port site. The magnitude of impacts from any of the active volcanoes could include ash clouds transported by wind, and fallout that disrupts construction and operations of project components, depending on prevailing wind direction and plume height. Volcanic ash particles are particularly abrasive, corrosive, and pervasive.

In terms of extent and duration, due to the distance from the volcano, effects at the mine site would be expected to be rare, occurring only once or twice over the life of the mine. Because the port facilities would be closer to the Augustine Volcano (within 20 miles), impacts from an Augustine plume would be expected to be more common at the Amakdedori port and on and moored ships. If ash fallout were to occur, it could affect most activities within the port footprint. The magnitude and extent of direct effects could include damage to equipment, engines, and compressor stations; and disruption of staffing, shipping, and fuel supplies. The duration of effects would be temporary, potentially lasting several days per incident. Ashfall effects on the project would not be expected to result in indirect effects from the facilities on other environmental resources. Typical mitigation would include a vulnerability analysis of facilities and equipment and hazard planning (Chapter 5, Mitigation).

As noted in Section 3.15, Geohazards, volcanic debris avalanches that flow into Cook Inlet are known to occur once every 150 to 200 years on average (Beget and Kienle 1992). Therefore, the likelihood of this scenario occurring during the project's life would be low, as would be the potential for these flows to reach the pipeline or port facilities.

Stability of Pile-Supported Dock Variant

The pile-supported dock would be constructed on trestle and dock piles (Chapter 2, Alternatives, Figure 2-43), and the footprint area would be about 0.5 percent of that required for the rockfill causeway and sheet-pile dock.

As with the sheet-pile dock, detailed engineering analysis has not been completed in support of initial design. The stability of a pile-supported dock is typically a function of structural design details and pile-soil interaction. The current state-of-practice is to use bending in the pile to resist lateral loads (e.g., wind, seismic, vessel impacts, and mooring loads) that may control pile embedment depths. Static stability analysis is typically conducted to determine the ability of the dock to accommodate and control maximum displacements from these loads, as well as global stability issues such as liquefaction. The survivability of a pile-supported structure in a large earthquake is generally considered better than bulkhead type structures, which do not perform well in major earthquakes, and are difficult to repair. For example, sections of the existing Port of Anchorage pile-supported dock survived the 1964 earthquake.

In terms of magnitude of impacts, the piles would likely experience similar metal corrosion as the sheet-pile dock; similar issues with construction in the event of boulders in the subsurface; and ice-related impacts that could be worse due to exposure of the piles to the elements (PLP 2018-RFI 071). As with the sheet-pile, additional geotechnical investigation and stability analysis would be performed during final design, and the results would provide a better understanding of dock behavior in response to geohazards, and whether boulders would be present that would hinder pile installation.

Based on the conceptual level of design and experience with similar structures, the likelihood of stability issues would be generally considered lower with the pile-supported dock, and survivability in a major earthquake generally greater than the sheet-pile dock. Unlike the sheet-pile dock, the pile-supported dock would not have the potential to release fill into the marine environment as a result of geohazard-related event. In the event of potential geohazard-related impacts to the pile-supported dock, the duration of effects would range from temporary (e.g., ice loads that would be repairable) to long-term requiring weeks or months to repair, and the extent would likely be limited to the footprint of the structure.

Summer-Only Ferry Operations Variant

There would be no difference in geohazard-related impacts under this variant for this component.

4.15.2.4 Natural Gas Pipeline Corridor

Earthquakes and Surface Faults

As described above for the transportation corridor, the natural gas pipeline corridor would not cross any known active surface faults (Section 3.15, Geohazards, Figure 3.15-1). Therefore, direct effects on the pipeline from surface fault displacements would not be expected to occur.

A major earthquake could cause liquefaction in unfrozen lowlands, stream crossings, and marine areas with fine sandy soils. This condition has the potential to cause buried pipelines to become buoyant; which, if not properly accounted for in design, could lead to pipe flotation and possible damage. The loss of soil shear strength during liquefaction could also lead to permanent ground movements through lateral spreading, flow failure, and settlement. Control measures for liquefaction and buoyancy (e.g., estimation of lateral spreading, use of select compacted backfill, increased cover depth, swamp weights, and post-earthquake inspection) are considered typical state-of-practice for high-liquefaction areas so that design deflection and stress on the pipe would not be exceeded. The proposed use of thicker walled pipe in marine areas would also help reduce the effects of liquefaction in Cook Inlet and Iliamna Lake. Therefore, pipe rupture and potential related environmental effects in the event of liquefaction would be unlikely. If pipe damage were to occur, the extent would be expected to be limited to the immediate vicinity of the liquefaction, and because the pipeline could be repaired in a timeframe of days to months, the duration of impacts would be short-term.

Unstable Slopes

A relatively unstable bluff roughly 200 feet high exists between the Anchor Point compressor station on Kenai Peninsula and Cook Inlet. To avoid the bluff, the pipeline would be constructed using horizontal directional drilling (HDD) from the compressor station to the pipeline's emergence point on the Cook Inlet seafloor to the west.

The HDD would begin at an elevation of about 207 feet on the eastern side of Sterling Highway, and drop down to an elevation of -12 feet MLLW or deeper[9] in accordance with the Pipeline and Hazardous Materials Safety Administration requirements (PLP 2018-RFI 011). The exact water depth at which the pipeline would emerge at the seafloor has not been determined, but is proposed to be deep enough to avoid navigational hazards (PLP 2018d).

During the life of the project, the bluff at Cook Inlet would likely continue to erode and retreat landward as a result of natural causes. With the use of HDD methods, the pipeline would pass well below and landward of the steep bluff at Cook Inlet, and avoid the unstable slope hazards (PLP 2018-RFI 011). Therefore, potential impacts on the project and related effects on the environment from this geohazard would be minimal because of this avoidance.

Coastal Hazards

The depth of pipeline cover west of the HDD installation location, and below the 12-foot water depth on the western side of Cook Inlet and in Iliamna Lake, would be sufficient to ensure that the top of the pipeline lies below the mudline. The minimum depth of cover above the 12-foot water depth would be 3 feet, which would reduce potential effects from coastal hazards such as shoreline drift, ice-rafting of surface boulders, or shifting sand waves. Section 4.16, Surface Water Hydrology, provides additional discussion of potential effects on the submerged pipeline.

[9] A 1,800-foot-long HDD pipeline would exit in approximately 12 feet of water MLLW, while a 2,000-foot-long HDD would exit in approximately 18 to 24 feet of water at MLLW. Current technology can accommodate a 2,000-foot-long HDD for in the 12-inch-diameter range as proposed (PLP 2018-RFI 011).

Kokhanok East Ferry Terminal Variant

There would be no difference in geohazard-related impacts under this variant for this component.

4.15.3 Alternative 2 – North Road and Ferry with Downstream Dams

4.15.3.1 Mine Site – Downstream Embankment

The bulk TSF main embankment under Alternative 2 would be constructed using downstream raises (Chapter 2, Alternative, Figure 2-45 through Figure 2-47), as compared to the buttressed centerline design under Alternative 1 (PLP 2018d; PLP 2018-RFI 075). Under Alternative 2, the overall downstream slope would be 2.6H:1V, which would be the same as the buttressed centerline-constructed embankment under Alternative 1. The upstream slope of the main embankment under Alternative 2 would be 2H:1V, versus the upstream slope under Alternative 1 that would be a serrated near-vertical upstream face at the dam crest for the upper 280 feet, and partially rest on tailings (Chapter 2, Alternatives, Figure 2-8).

As described in Appendix K4.15, the preliminary stability analysis for the downstream constructed main embankment calculated a FoS value on the order of 1.9 to 2.0 under static loading conditions, similar to that of the buttressed centerline design (Appendix K4.15, Table K4.15-5), thereby offering minimal additional stability over the Alternative 1 design. A schematic section of the main embankment at its ultimate height with the predicted potential slip surface is shown on Chapter 2, Alternatives, Figure 2-47.

The bulk TSF main embankment under Alternative 2 would be raised approximately 25 feet higher than the Alternative 1 design (embankment height approximately 570 feet) to provide equivalent bulk TSF storage capacity. The embankment fill would increase from 78 million cubic yards (yd^3) to 124 million yd^3, and the impoundment footprint area would increase by 119 acres (PLP 2018-RFI 075a). This would result in increased impacts on other resources such as material sites, substrate, and wetlands (Section 4.13, Geology; Section 4.18, Water and Sediment Quality; and Section 4.22, Wetlands and Other Waters/Special Aquatic Sites), but would not change the global stability of the embankment.

Summer-Only Ferry Operations Variant

There would be no difference in geohazard-related impacts under this variant for this component.

4.15.3.2 Transportation Corridor

Mine and Port Access Roads

Earthquakes. Referring to Chapter 2, Alternatives, Figure 2-49, Figure 2-50, and Section 3.15, Geohazards, Figure 3.15-1, the access roads under Alternative 2 would not cross any known active faults. The magnitude, extent, and duration of potential impacts related to ground shaking for the roads would be similar to those described above under Alternative 1. Even though the access road from Williamsport to Diamond Point would be adjacent to the shoreline of Iliamna Bay, as described below for the Diamond Point port site, potential tsunami-related impacts in Iliamna Bay would be expected to be less severe than at the Amakdedori port site because Iliamna Bay is more protected and shallower than Amakdedori.

Unstable Slopes. Several areas of unstable solifluction, colluvium, and landslide deposits have been mapped in the area northwest of Eagle Bay on the flanks of Roadhouse Mountain and along the mine access road west of Newhalen River (Section 3.15, Geohazards) (Detterman and Reed 1973; Hamilton and Klieforth 2010). Steep alluvial fan and talus deposits occur in incised valleys crossed by the eastern portion of the route east of Pile Bay (Detterman and Reed 1973). RRockfall hazards could also occur in this area of exposed bedrock where rock cuts would be likely. Steep unstable slopes and rockfall hazards would also be expected along the Diamond Point-Williamsburg waterfront section of the road.

Typical engineering and construction practices such as engineered cuts, benching, and drainage controls, as well as road maintenance, would be used to manage unstable slopes, to reduce the potential for landslide impacts on the roads during construction and disruption of truck haulage. Several locations along the existing Williamsport-Pile Bay Road would be rerouted under this alternative to avoid steep slopes, including approximately the eastern third of this area, and a shorter road segment close to Pile Bay. Unstable slopes could also lead to an increase in the likelihood of spills (Section 4.27, Spill Risk, provides an analysis of spill impacts from a truck spill scenario). The likelihood of such effects occurring would be expected to be greater for Alternative 2 as compared to Alternative 1, because there would be more areas of unstable slopes associated with the transportation corridors under Alternative 2. However, in terms of duration and extent, with appropriate designed engineering controls in place during construction and operations, impacts on the project and related effects on environmental resources would be easily repairable over the short term, and limited to the immediate vicinity of the road footprint.

The potential exists for avalanches to occur for portions of the road alignment between Williamsport and Pile Bay. However, the avalanches would be preventable using relevant best management practices (BMPs) such as hazard mapping, forecasting, and blasting if necessary. In terms of duration and extent, if avalanches were to occur, they would temporarily impact a local portion of the road until the snow could be removed.

Eagle Bay to Pile Bay Ferry

The magnitude, duration, and extent of potential impacts on the ferry terminals related to ground shaking would be similar to those described above under Alternative 1. Although the eastern end of the lake is narrower and deeper compared to the Alternative 1 ferry route—factors that can increase earthquake-generated seiche potential—the potential for occurrence would still be considered unlikely (AECOM 2018j). This analysis assumes that the risk of major landslide-generated seiches at the eastern end of the lake would be low, and there is little evidence of past major landslides in the lake bottom, assumptions that would be further investigated through collection of more detailed bathymetric survey data as design progresses.

Summer-Only Ferry Operations Variant

Under the Summer-Only Ferry Operations Variant, road traffic would be concentrated during the 6-month transportation season, which would include rainy months. Because heavy rain is often a trigger for slope failure, the potential for these impacts on road traffic and spill potential could be slightly greater under this variant, but would be balanced by fewer avalanche impacts due to lack of winter season traffic. Lake ice hazards are discussed under Section 4.16, Surface Water Hydrology.

4.15.3.3 Diamond Point Port

Referring to Chapter 2, Alternatives, Figure 2-52 and Figure 2-53, the Diamond Point port facility would use the same design concept as the Amakdedori port under Alternative 1[10], although with a footprint about four times bigger than at Amakdedori (PLP 2018-RFI 071).

As discussed in Appendix K4.15, in terms of magnitude and extent of impacts, ground shaking potential in the Diamond Point area is slightly greater than at Amakdedori. The Bruin Bay Fault extends along the western shore of Cook Inlet near the Diamond Point port site. Although there is no evidence for Holocene offset at the surface, this fault is associated with several small to moderate earthquakes up to M7.3 in 1943 (Stevens and Craw 2003).

Stability of Dock Structure

Sheet Pile Dock. The proposed sheet-pile dock would be the same potential to result in adverse impacts to the environment during construction and operations as discussed for the Amakdedori port site (see "Amakdedori Port," section above, and Appendix K4.15). As with Amakdedori port, the Diamond Point port facilities would be closed and undergo reclamation after the off-site transport of concentrate was completed at Year 20. All structures and related earthfill would be removed, and the site reclaimed (PLP 2018-RFI 024). The duration of potential geohazards-related impacts would therefore be long-term, and the extent would generally be limited to the close vicinity of the dock footprint. With additional geotechnical investigation and stability analyses, dock design would be refined to address the potential for failure that could lead to adverse impacts on the environment.

The magnitude of potential impacts for Alternative 2 could be greater than Alternative 1 due to the larger footprint and fill volume required for the Alternative 2 dock, and possible higher likelihood of boulders in the subsurface with related risk of short embedment or sheet-pile damage. As described in Section 4.18, Water and Sediment Quality, substrate conditions are generally finer-grained in Iliamna Bay than in Kamishak Bay. Because dock fill would partly consist of dredged material, in the event that potential geohazard-related impacts cause a release of fill to the marine environment, the extent of redeposition could be greater than under Alternative 1, and could range widely depending on season, tides, and wave conditions (e.g., from the close vicinity of the dock structure to the mouth of Iliamna Bay).

Pile-Supported Dock Variant

The Pile-Supported Dock Variant for the Diamond Point port would have potential geohazard-related impacts similar in magnitude, extent and duration as the Pile-Supported Dock Variant at the Amakdedori port under Alternative 1. The off-shore foundation conditions would likely be different than the Amakdedori site, which would affect the overall performance of the pile-supported system. If this variant is chosen, field conditions would be further investigated in support of final design.

Tsunamis

The magnitude, extent, duration, and potential for tsunami impacts at the Diamond Point port site would be similar or slightly less than those at the Amakdedori port site under Alternative 1. The predicted run-up elevation for the 2,500-year event is slightly less for Diamond Point (36 to 39 feet MLLW) than at Amakdedori (42 feet MLLW) (see Section 3.15, Geohazards), and would exceed the proposed terminal elevation by 1 to 4 feet (assuming the terminal and causeway/dock elevations would be the same as at Amakdedori [35 feet MLLW]). The potential for landslide-generated tsunamis affecting the port site and lightering locations would be

[10] A causeway constructed of earthfill embankment, and barge berth and wharf constructed of a sheet-pile wall wharf structure filled with earthfill.

considered similar to Amakdedori, because historic events have occurred radially around Augustine Volcano (Figure 3.15-5). The proposed engineering analyses and mitigation in final design that would occur at Amakdedori based on ASCE (2017a) industry standards (PLP 2018-RFI 112) would be expected to be the same for Diamond Point, assuming additional infrastructure (dredge material storage area and roads) would be included.

Volcanoes

The proposed Diamond Point port location would be approximately the same distance from volcanoes in the area, including Augustine Volcano, as the Amakdedori port under Alternative 1. Therefore, the potential for impacts would be similar to Alternative 1, with the magnitude, duration, and extent of impacts dependent on the severity of an ash cloud and the wind direction at the time of an eruption. However, in winter, the magnitude, extent, and duration of potential impacts from Augustine Volcano on the Alternative 2 port site could be greater than Alternative 1 due to dominant northwesterly winds in this area (Knight Piésold 2018g).

4.15.3.4 Natural Gas Pipeline Corridor

Referring to Figure 2-54, natural gas pipeline construction under Alternative 2 would follow a different corridor route west of Cook Inlet, and would therefore encounter different geology and related potential geohazards than Alternative 1 (Section 3.13, Geology and Section 3.15, Geohazards).

Earthquakes and Surface Faults

In western Cook Inlet, the Alternative 2 pipeline would be routed to Ursus Cove to avoid known boulders and reefs at the mouth of Iliamna Bay (PLP 2018-RFI 063). At about 3 miles before making landfall, the pipeline would cross a mapped fault trace of the potentially active Bruin Bay fault (Section 3.13, Geology, Figure 3.13-1 and Figure 3.15-1). Additional field investigation prior to final design (e.g., an offshore geophysical survey or onshore fault study at Ursus Head where the fault is mapped as having an upland component), would be needed to identify whether the fault is active and whether potential displacement mitigation in design would be necessary, if this alternative were to be selected.

Unstable Slopes

Steep unstable slopes are a known hazard to pipeline integrity, and have been known to cause operation interruptions and ruptures in other mountainous areas of the world (e.g., the Andes, Eastern Europe, and Sakhalin Island) (Lee et al. 2016). Unstable slopes mapped between Ursus Cove and Pile Bay, and for the Alternative 2 route west of Eagle Bay, are discussed above under the Alternative 2 transportation corridor. The pipeline segment between Pile Bay and Eagle Bay crosses areas of exposed steep bedrock with the potential for rock instability, and alluvial fan and talus deposits, which could be unstable on steeper slopes. The corridor would avoid mapped landslide deposits on the flanks of Knutson and Roadhouse mountains.

Typical engineering and construction practices such as engineered cuts, rock stabilization, benching, and drainage controls would likely be used at these locations to reduce the potential for rockslide and landslide impacts to the pipeline. Additional mitigation, such as long-term slope monitoring, may be necessary in select areas. With these controls, the likelihood of slope failures occurring during the construction and operation that would affect pipeline integrity would be expected to be minimal. In terms of potential, duration, and extent, related effects on environmental resources would also be expected to be minimal, repairable in the short-term, and limited to the immediate vicinity of the pipeline right-of-way (ROW).

Coastal Hazards

The depth of the pipeline as it approaches Ursus Cove from Cook Inlet, as well as the underwater crossing of the bay to Diamond Point, would be sufficient to ensure that the top of the pipeline lies below the mudline. The minimum depth of cover above the 12-foot water depth would be 3 feet, which would be expected to reduce potential effects from coastal hazards, such as shoreline drift or ice-rafting of surface boulders.

4.15.4 Alternative 3 – North Road Only

Under Alternative 3 and its variants, the magnitude, extent, duration, and likelihood of impacts at the mine site (including concentrate pumphouse) and natural gas pipeline corridor would be the same as those described under Alternative 2. The following section describes impacts for the transportation corridor and port that would be different under Alternative 3 and its variants.

4.15.4.1 Transportation Corridor

All Road Routes, Mine Site to Port

Geohazards-related impacts resulting from construction and operation of the Alternative 3 north access road from Diamond Point to the mine site would be generally the same as the combination of road and natural gas pipeline corridors described under Alternative 2. However, the likelihood of slope stability issues occurring along the all-road route would be higher between Eagle Bay and Pile Bay than under Alternative 2, due to the wider road ROW (compared to the Alternative 2 pipeline-only in this area) and greater need for engineering controls (such as wider cut and fills) to mitigate potential slope impacts. There would also be a slightly higher likelihood of spills due to the longer road route through steep terrain (Section 4.27, Spill Risk provides an analysis of spill impacts from a truck spill scenario), and greater potential for avalanches to occur that would be preventable using relevant BMPs described above for Alternative 2.

Appropriate engineering controls and BMPs described in Chapter 5, Mitigation, would reduce the likelihood of slope failures occurring along the all-road route. In terms of duration and extent, related effects on environmental resources would also be expected to be repairable over the short-term (days or weeks), and of limited to the immediate vicinity of the access road ROW footprint.

Concentrate Pipeline Variant

Because the concentrate pipeline would be installed in the same trench as the natural gas pipeline, the magnitude, extent, duration, and likelihood of impacts from geohazards, such as unstable slopes would be similar to the Alternative 2 natural gas pipeline corridor and Alternative 3 all-road route. There would also be a slightly higher likelihood of minor spills due to the additional potential contaminant source from the concentrate pipeline along steep terrain, which would be partially mitigated through leak detection systems (Section 4.27, Spill Risk, provides analysis of spill impacts from a concentrate spill scenario).

4.15.4.2 Diamond Point Port

Geohazard-related impacts would have the same magnitude, extent, duration, and likelihood as those described for Alternative 2, except for the concentrate storage and bulk handling described below.

Concentrate Pipeline Variant

Due to the mapped presence of alluvial fan deposits in the proposed footprint of the concentrate storage facility and steep slopes above the facility, the potential for unstable slopes would exist during the construction and operation (Detterman and Reed 1973). If this variant were selected, the final design would include a geotechnical investigation to confirm foundation and slope conditions to ensure the facility construction and operation would avoid or mitigate unstable slopes.

As noted under Alternative 2, the impacts from a tsunami at the Diamond Point port site would be similar or less severe than at the Amakdedori port under Alternative 1. However, if a tsunami were to occur, it would have a higher potential to result in a contaminant release to the marine environment under this variant; this is because this variant includes bulk storage of concentrate and the others do not. Section 4.27, Spill Risk, provides analysis of spill impacts from a concentrate spill scenario. Effects would be unlikely to occur, and the duration of impacts could range from hours to months (in the event repairs would be required). Typical mitigation might include a vulnerability analysis of equipment and facilities, incorporation of flooding into design (e.g., tie-downs), emergency action planning with tsunami escape routes, or consideration of design changes to facility armoring and elevation (Chapter 5, Mitigation).

4.15.5 Summary of Key Issues

Table 4.15-1 provides a summary of the key impact-related issues for geohazards.

Table 4.15-1: Summary of Key Issues for Geohazards

Impact Causing Project Component	Alternative 1 and Variants	Alternative 2 and Variants	Alternative 3 and Variants
	Mine Site		
TSF and WMP Embankment Stability	Low probability of embankment instability with static stability analysis (FoS 1.7-2.0), foundation preparation, seepage design, and flood controls incorporated into design. Temporary repairable damage in OBE, and 4 to 5-foot displacement/ settlement in MCE, would not result in effects on the environment outside of the footprint. Duration long-term with removal of pyritic TSF and WMPs at closure and dry closure of bulk TSF.	Design provides marginal additional stability over Alternative 1 design (FoS 1.9-2.0 for both).	Same as Alternative 1.
Open Pit Slope Stability	Low to medium likelihood of localized unstable slopes in lower pit in early closure, to be mitigated through targeted groundwater depressurization while lake rises.	Same as Alternative 1.	Same as Alternative 1.
Container Storage and Pumphouse	*Summer-Only Ferry Operations Variant:* Low likelihood of earthquake toppling effects at container storage area with foundation preparation.	Same as Alternative 1.	*Concentrate Pipeline Variant*: Impacts at pumphouse similar to Alternative 1.

Table 4.15-1: Summary of Key Issues for Geohazards

Impact Causing Project Component	Alternative 1 and Variants	Alternative 2 and Variants	Alternative 3 and Variants
	Transportation Corridor		
Road Construction and Operations	Low likelihood of unstable slope impacts on roads. *Summer-Only Ferry Operations Variant and Kokhanok East Ferry Terminal Variant:* Similar impacts to Alternative 1.	Low to medium likelihood of unstable slope impacts along road corridor; effects temporary and localized with engineering controls and maintenance. *Summer-Only Ferry Operations Variant:* Similar impacts to Alternative 2.	Slightly higher likelihood of unstable slope effects than Alternative 2 due to longer route in steep terrain; effects similar to Alternative 2 with engineering controls and maintenance. *Concentrate Pipeline Variant*: Low likelihood of minor spills due to unstable slopes.
Ferry Terminals and Operations	Earthquakes: Low likelihood of temporary ground-shaking effects such as cracking, spreading, and settlement of terminals. Low likelihood of seiches and unstable slope effects. *Summer-Only Ferry Operations Variant and Kokhanok East Ferry Terminal Variant:* Similar impacts to Alternative 1.	Similar impacts to Alternative 1.	Similar impacts to Alternative 1.
	Ports		
Dock Construction and Operations	*Proposed Sheet-Pile Dock:* Low to medium likelihood of stability effects on dock, and potential for fill escaping sheet-pile into marine environment. Tsunamis: low likelihood of temporary (repairable) effects such as dock or fuel tank damage. Volcanic ash from Augustine: low likelihood of port operations interruption. *Pile-Supported Dock Variant*: Lower likelihood of stability effects than sheet pile dock.	*Proposed Sheet-Pile Dock:* Slightly higher likelihood and extent of stability effects than Alternative 1, due to 4x larger structure and finer fill material. Tsunamis: slightly lower intensity than Alternative 1 due to lower predicted run-up elevation. Volcanic ash from Augustine: slightly higher likelihood of effects during winter due to prevailing winds. *Pile-Supported Dock Variant*: Lower likelihood of stability effects than Alternative 2 proposed sheet-pile dock.	*Proposed Sheet-Pile Dock:* Impacts same as Alternative 2. *Concentrate Pipeline Variant*: Low likelihood of unstable slope effects on storage facility. Tsunamis: Same likelihood as Alternative 2, but with slightly higher risk of contaminant release.

Table 4.15-1: Summary of Key Issues for Geohazards

Impact Causing Project Component	Alternative 1 and Variants	Alternative 2 and Variants	Alternative 3 and Variants
Natural Gas Pipeline Corridor			
Construction and Operations – Cook Inlet	Low likelihood of pipe damage form liquefaction. No active fault crossing effects.	Liquefaction impacts similar to Alternative 1. Low likelihood of active fault crossing (Bruin Bay fault) and displacement effects.	Liquefaction impacts similar to Alternative 1. Surface faults: same as Alternative 2.
Construction and Operations – Upland Areas	Low likelihood of unstable slope effects on pipeline.	Low-medium likelihood of unstable slope effects (such as operations interruption or rupture) between Diamond Point and Roadhouse Mountain; expected to be mitigated through typical engineering controls and monitoring.	Same as Alternative 2.

4.15.6 Cumulative Effects

The cumulative effects analysis area for geologic hazards encompasses the footprint of the proposed project, including alternatives and variants. In this area, a nexus may exist between the project and other past, present, and reasonably foreseeable future actions (RFFAs) that could contribute cumulatively to geologic hazards-related impacts. Section 4.1, Introduction to Environmental Consequences, details the comprehensive set of past, present, and RFFAs considered for evaluation as applicable. A number of the actions identified in Section 4.1, Introduction to Environmental Consequences, are considered to have no potential of contributing to cumulative geologic hazard effects in the analysis area. These include offshore-based developments, activities that may occur in the analysis area but are unlikely to result in any appreciable cumulative effect with regard to geohazards, or actions outside of the geologic hazards cumulative effects analysis area (e.g., Donlin Gold, Alaska Liquefied Natural Gas [LNG]). RFFAs that are in the analysis area and would involve earthworks resulting in possible geohazard-related impacts would be considered to have potential cumulative effects. Past, present, and RFFAs that could contribute cumulatively to geologic hazard impacts, and are therefore considered in this analysis, include:

- Pebble Project buildout – development of 55 percent of the resource over a 78-year period.
- Pebble South/PEB mineral prospect exploration.
- Groundhog mineral prospect exploration.
- Diamond Point rock quarry.
- Lake and Peninsula transportation, infrastructure and energy projects.

4.15.6.1 Past and Present Actions

Past and present actions in the analysis area would not be expected to contribute cumulatively to geologic hazards. While past or current actions in the analysis area have included some minor earthworks, the effects are minor both in magnitude and extent, and are not expected to be a significant factor in increased geologic hazards. Similarly, while there have been past volcanic and earthquake events in the region, they have not contributed to any increased geologic hazard risk in current conditions.

4.15.6.2 Reasonably Foreseeable Future Actions

No Action Alternative

The No Action Alternative would not contribute to cumulative geologic hazard effects.

Alternative 1 – Applicants Proposed Alternative

Pebble Mine Expanded Development Scenario. An expanded development scenario for this project, as detailed in Introduction to Environmental Consequences, Table 4.1-2, would include an additional 58 years of mining and 20 years of milling (for a total of 98 years) over a substantially larger mine site footprint, and would include increases in port and transportation corridor infrastructure. The mine site footprint would have a larger open pit and new facilities to store tailings and waste rock (Introduction to Environmental Consequences, Figure 4.1-1), which could contribute to cumulative geologic hazard effects.

The Pebble Project buildout would require additional earthworks and mine-related facilities. The magnitude of potential geohazard-related impacts would be similar to the proposed project, with added stability risk and potential cumulative effects on the Upper Talarik Creek (UTC) drainage due to the large waste rock pile that would be required in the buildout scenario. However, because the projects would likely use some of the infrastructure already developed under the proposed project, the net impacted geographic area would likely be less than developing mines at new greenfield sites in terms of geohazards. In addition, additional storage containment improvements such as extended or new tailings dam facilities would require review and approval from the State of Alaska.

The potential for geohazard impacts along the transportation corridor, ports, and pipeline would increase under the expanded mine scenario, as both the north and south access corridors and two ports would be used. This would potentially add the effects of unstable slopes along the north access road to those of Alternative 1. In addition, the development of a port at Iniskin Bay would increase the likelihood of impacts from dock instability, volcanic ashfall, and tsunamis. For example, in the case of tsunamis, the likelihood of a large tsunami with a 2,500-year return period occurring would increase due to the longer life of the project. The probability of this size tsunami occurring at either port over the life of the expanded mine is roughly 1 in 15, assuming the ports would be functioning for approximately 148 years total (98 years operations, plus 50 years of closure activities).

Other Mineral Exploration Projects. Mineral exploration at the Pebble South/PEB and Groundhog prospects could have a minor cumulative effect on geologic hazards, depending on the extent of infrastructure development that were to occur. Under any pre-development exploration scenario, effects on geologic hazards would be expected to be temporary and minor, and limited to potential cumulative effects on infrastructure shared with the Pebble Project.

Road Improvement and Community Development Projects. Road improvement projects could have limited impacts on geologic hazards, and therefore contribute to cumulative effects in the analysis area. Lake and Peninsula Borough (LPB) and State of Alaska transportation, infrastructure, and energy projects include possible upgrades to the Williamsport-Pile Bay Road, which is the same alignment that would be used under Alternatives 2 and 3. If either of these alternatives is selected, the net magnitude and geographic extent of unstable slope effects may be relatively low, because the mine access road would already be rerouted or upgraded for maintaining slopes. If the road were to be further widened as part of a transportation improvement project, there would likely be additional impacts.

Additional RFFAs that have the potential to affect geologic resources in the analysis area are limited to the Diamond Point rock quarry. That RFFA would include the excavation of geologic resources, and could have a cumulative effect on geologic hazards such as slope instability effects, although such these would be expected to be minor and limited to the immediate area around the proposed quarry site.

Alternative 2 – North Road and Ferry with Downstream Dams and Alternative 3 – North Road Only

Pebble Mine Expanded Development Scenario. Mine site expansion would be the same as Alternative 1, but overall cumulative effects under Alternatives 2 and 3 with expanded mine development would be less than that of Alternative 1 with expanded mine development, because the expanded mine scenario under Alternatives 2 and 3 would not use the south access corridor or Amakdedori port site. Under these alternatives, project expansion would use the existing Diamond Point port facility, the same natural gas pipeline, and the constructed portion of the north access road. A concentrate pipeline and a diesel pipeline from the mine site to Iniskin Bay would be constructed, both having potentially limited impacts on geologic hazards due to trenching and other earthworks required.

Other Mineral Exploration Projects, Road Improvement and Community Development Projects. Cumulative effects of these activities on geohazards would be similar to those discussed under Alternative 1. The Diamond Point rock quarry is the same location proposed for the Diamond Point port site under Alternatives 2 and 3; hence, there would likely be a relatively minor net increase in geohazard impacts, such as dock stability effects on the marine environment.

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