Critique of Pebble Limited Partnership's Seismic Hazard Assessment

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Executive Summary

The seismic hazard assessment presented in Pebble Limited Partnership's Environmental Baseline Document (PLP 2012 Ch 6) is flawed. It draws strong, optimistic conclusions from weak evidence, and relies on geologic arguments inconsistent with observed evidence. It misrepresents existing research and fails to use key data sets that PLP has in-hand to inform the analysis. A major fault, the Lake Clark Fault, passes near the Pebble prospect. No published studies establish this fault's location or seismic activity near the prospect, and the hazard assessment presents no effort to positively determine its location. The hazard assessment fails to consider minor faults or induced seismicity. Without further study, the hazard posed by earthquakes is impossible to determine.

Introduction

Mineral exploration and mining claims have recently expanded a great deal in the Bristol Bay area. Of these, the Pebble prospect is the most advanced exploration project. This world-class copper, gold, and molybdenum ore body contains an estimated 10.8 billion tons of ore (Wardrop-NDM 2011) and will leave behind billions of tons of waste material that will require reliable containment in perpetuity, withstanding natural hazards such as floods and earthquakes. Tailings will likely be stored behind a network of earthen dams, some possibly over 700 feet tall (DNR 2006, Wardrop-NDM 2011).

Future earthquake risk at the Pebble prospect is unknown. Similar facilities are usually engineered to withstand the strongest earthquake likely in 10,000 years (ICOLD, 2008), although even larger earthquakes may be relevant to engineering perpetual storage facilities. Because of the long time frames involved, hazard assessment must include faults that produce earthquakes only very infrequently, where fault activity is more difficult to study. These studies have not been conducted in the Pebble area. The proposed open pit mine, buildings, pipeline and port (Wardrop-NDM 2011) would all be vulnerable to a potential earthquake. Their failure could cause loss of life and environmental harm. However, the greatest potential threat to the region would be failure of a tailings dam. A dam failure could release a plume of acidic, metal-laden water and mine tailings into downstream waterways, threatening drinking supplies and fisheries resources (TNC 2010).

The severity of shaking during an earthquake depends both on the size and proximity of the earthquake. If the possibility of a large earthquake close to mine facilities cannot be ruled out, there is a threat of exceptionally strong shaking and dam failure. Therefore, it is critical to locate all the faults in the area and assess their activity so that structures can be engineered for the actual threat. Lacking accurate data, the conservative assumption must be that a large active fault passes directly beneath mine facilities.

Regional Geology

Alaska is the most seismically active state in the nation. The Pacific Plate is diving beneath Alaska, driving frequent earthquakes and feeding volcanoes in Southcentral Alaska, along the Alaska Peninsula and through the Aleutian Islands. The North America tectonic plate is fragmented in Alaska, with one block of crust in Southcentral Alaska (Haeussler, 2008) and another in the Bering Sea (Makey et al., 1997). These blocks appear to be moving independently from the rest of North America, fracturing and deforming the crust between them. The complex relative motion of these crustal fragments drives earthquakes on faults between them.

The region around Pebble sits between these shifting blocks of crust, so stress that could trigger earthquakes is likely accumulating in the region. This is supported by the fact that a few shallow earthquakes have been observed within a few tens of miles Pebble over the past few decades (USGS Earthquake Hazard Program catalog). Though none of these were large, they indicate forces are in place to drive earthquakes.

Environmental Baseline Document (EBD) Seismic Hazard Assessment Methodology

No original work by seismology or neotectonics experts is presented by PLP in this baseline document. PLP's (2012 Ch 6) seismic hazard assessment methodology consists almost entirely of reviewing existing research, most of which relates to the tectonics and seismicity of Southern Alaska and Cook Inlet, but not to the mine area or Lake Iliamna. The analysis focuses on the location and possible activity of the Lake Clark Fault. It does not analyze the potential hazard posed by smaller faults such as those PLP (2012 Ch 3.7.3) has already identified near and beneath proposed facilities, nor does it address the significant induced seismicity hazard.

PLP does not analyze or mention the LiDAR (high-resolution laser altimetry). In a 2011 publication (Wardrop-NDM 2011) PLP mentions results from a geophysical study they conducted, "The location of [the Lake Clark] fault has been identified as part of a geophysical survey of the region." but they do not mention the results or existence of this study in the EBD.

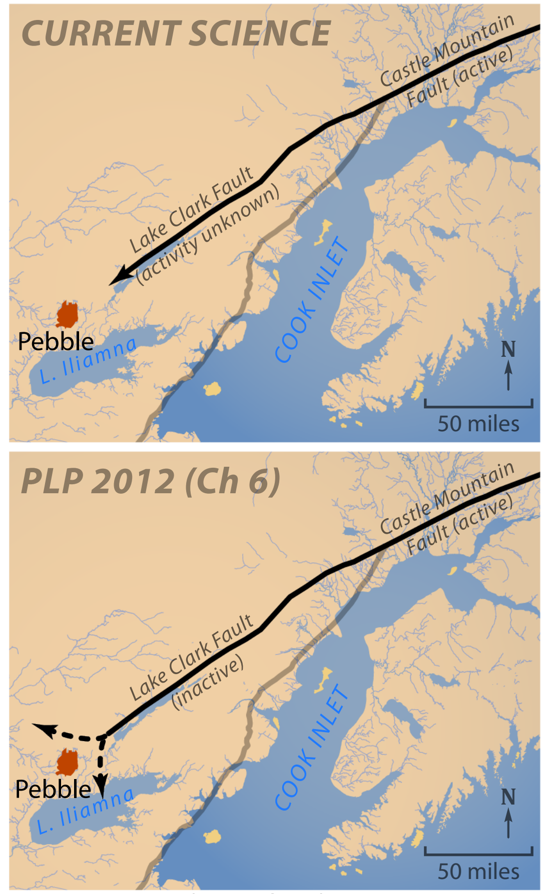

Figure 1: PLP (2012 Ch 6) concludes that the Lake Clark Fault is inactive, and veers away from the mine site. This conclusion is not supported by either PLP's work, or existing literature - the fault's location near Pebble, and its activity, are unknown.

Discussion of EBD Results

One major local fault, the Lake Clark Fault, runs near the Pebble prospect. The PLP (2012 Ch 6) seismic hazard assessment focuses on the potential risk posed by this fault and asserts that there is no significant earthquake risk.

This hazard assessment is flawed. It draws strong conclusions from weak evidence, and relies on geologic arguments inconsistent with observed evidence.

The document contains some 30,800 pages, but the section dealing with seismic hazard assessment is only four pages long. It is found in Section 6.6.2 (summary and conclusions in 6.7) of the EBD. It refers to three figures (Figures 6-51 through 6-53).

The assessment suffers from the following flaws:

1. PLP (2012 Ch6) concludes the Lake Clark Fault cannot pass near the mine site. This conclusion is drawn from several flawed lines of reasoning:

    a. The Lake Clark fault may end northwest of the mine prospect.

    b. If the fault continues, it is assumed to follow glacial flow.

    c. Bedrock near the prospect is assumed to be too strong for a major fault to break it.

2. Lack of evidence of activity is confused with evidence of inactivity.

3. Key data are not examined.

4. Local faults and induced seismicity are not considered.

1. Where is the Lake Clark Fault?

PLP (2012 Ch 6) concludes: *"The seismic hazard associated with crustal faults in the mine study area is not considered to be significant as the ground accelerations generated by earthquakes decrease the farther the distance from the epicenter."*

Since PLP (2012 Ch 6) identifies the Lake Clark Fault as the major seismic hazard in the area, PLP must be assuming that the Lake Clark Fault is far from the Pebble prospect, though this is not explicitly stated. Several flawed lines of reasoning presented in the EBD appear to support this conclusion.

1a. Where Does the Lake Clark Fault End?

The Lake Clark Fault is a major fault connected to the well-known Castle Mountain fault in south-central Alaska. It trends northeast to southwest, from near Beluga, through the Tlikakila River valley, and then along Lake Clark (Nelson et al., 1983). The fault has not been mapped further southwest than this. Taking the simplest assumption, that the fault continues on its mapped course, it would pass through or near the Pebble prospect (Figure 1).

PLP (2012 Ch 6): *" Published information indicates that the Lake Clark fault terminates at the western end of Lake Clark, over 15 miles from the eastern edge of the mine study area. This distance is based on a recent study by Haeussler and Saltus (2004) who used aeromagnetic data to refine the position of the western end of the fault."*

This is inaccurate. Haeussler & Saltus (2004) stopped mapping the fault where their survey data ended. They did not suggest that the fault ended at this point. PLP (2012 Ch6) acknowledges the fault may continue, but implications are not discussed. Haeussler & Saltus (2004) show the Lake Clark Fault has moved 16 miles at Lake Clark. This motion on the fault (offset) cannot simply end – the fault must either extend further, or transition into some other fault.

1b. Do Faults Follow Glaciers?

PLP (2012 Ch 6): *"The mapped direction of primary glacial advance, shown on Figure 6-53, suggests that any potential extension of the Lake Clark fault may pass north and/or east of the mine study area, and would not cross the mine study area."*

PLP (2012 Ch 6) infers this from Hamilton and Klieforth's (2010) surficial geology study of the area, which mentions that Pleistocene glaciers followed the Lake Clark fault along part of its length. Hamilton and Klieforth's work does not imply that faults always follow glacial paths.

Glaciers frequently cross faults, including the Lake Clark Fault further to the northeast. Many active faults are not parallel with landscape features (such as ridges and valleys) that typically control glacial flow (e.g. the Seattle Fault, Sherrod et al. 2008). For the Lake Clark Fault to track with glacial advance, it would have to make an abrupt, unusual turn (Figure 1). PLP presents no evidence that the fault actually makes this turn.

1c. Can Faults Cut Through Volcanic Bedrock?

PLP (2012 Ch 6): *"The mine study area is located on plutonic outcrops (some of batholithic scale) that likely provide resistance to crustal fracture."*

This statement suggests that no large fault (such as the Lake Clark Fault) could pass near the mine because there are large continuous bodies of rock. This is inaccurate. Major faults including the Lake Clark Fault further northeast and the Denali fault in the Alaska Range cut through plutonic volcanic rocks.

Near the Pebble prospect, PLP (2012 3.7.3) mapped a number of faults, demonstrating that the rock is susceptible to faulting. Detailed information on these faults can be found in the EBD, chapter 3. They are depicted in figure 3-6a.

2. Is the Lake Clark Fault Active?

PLP (2012 Ch 6) claims the Lake Clark Fault is inactive. In reality, very little research has been done on Lake Clark Fault's activity.

PLP (2012 Ch 6): *"The Lake Clark fault is considered inactive by the USGS."*

The USGS does not classify Lake Clark Fault as inactive. In fact, the USGS maintains no database of inactive faults. Faults are generally classified based on the most recent evidence of activity on the fault (e.g. Plafker et al. 1994), since it is nearly impossible to establish that a fault is totally inactive and incapable of producing future earthquakes.

In support of this claim that the fault is classified as inactive, PLP (2012 Ch 6) references a USGS publication that reviews information on the Lake Clark Fault, but does no original work on the fault. The USGS publication itself is ambivalent in its conclusion: *"...if further geologic studies find no evidence for surface faulting, it would be difficult to conclude that a significant seismic hazard exists from crustal faults in the area."*

The most recent published research on the activity level of the Lake Clark Fault is by Koehler and Reger (2011). They studied a location 150 miles from the Pebble prospect, on the northeastern section of the fault. This preliminary reconnaissance report suggests no motion in the past ten to sixty thousand years, but possible motion in the last one-hundred thirty thousand years. Tectonic processes change on time-scales of millions to hundreds of millions of years, so any fault active in the past few hundred thousand years is likely active today. The authors explicitly acknowledge the limitations of the work: *"...distributed slip on unrecognized structures and dense vegetation that might obscure tectonic features along the Lake Clark fault could limit assessment of tectonic activity."* They also note: *"The paleoseismic history of the western part of the Lake Clark fault remains unknown."* This part with no known history or activity is the section of the fault that passes near or through the Pebble prospect.

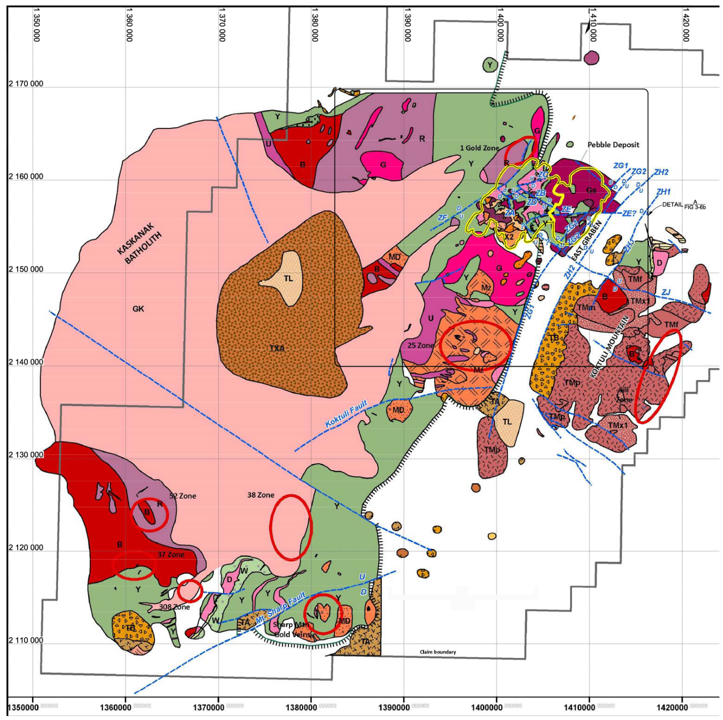

Figure 2 (PLP 2012 3.7.3, figure 3-6a): PLP maps the bedrock near Pebble Prospect. Blue lines are small faults in the area. The deposit is outlined in yellow near the northeast corner of the map.

Studying multiple areas on a fault, and choosing study sites near an area of concern, is important. Evidence of major earthquakes can be missed, leading active faults to appear inactive. Some earthquakes don't rupture the ground surface at all, and therefore don't leave obvious surface evidence. Many earthquakes leave surface evidence that is very subtle and can be missed even in detailed study. For example, in 1999 an "inactive" fault in southern California produced a magnitude 7.1 earthquake and ruptured the desert ground surface for 25 miles (Rymer et al., 2002). Recently another fault in California, the Kern Canyon Fault, long thought inactive, was shown to have produced large earthquakes in the past few thousand years (Nadin and Saleeby, 2010).

Existing research does not provide adequate evidence to estimate the activity level of the Lake Clark Fault at the Pebble prospect, where the fault has not been mapped or studied.

3. Key Data are Not Examined

Some of these questions regarding the Lake Clark Fault could potentially be addressed using data PLP has in-hand. PLP has collected LiDAR (high resolution topographic data) and aeromagnetic surveys in the area of the mine site. Both are useful for seismic hazard investigation. Aeromagnetic surveys sometimes show the location of faults, and were used to map the portion of the Lake Clark Fault immediately to the northeast of the area in question (Haeussler and Saltus, 2004). LiDAR data has often proven critical for identifying subtle deformation of the ground surface caused by past earthquakes (e.g. Sherrod et al. 2004, Kelsey et al. 2008). Despite collecting that data, PLP (2012 Ch 6) did not present a tectonic analysis of either data set in the EBD, and this data is not available for independent review.

4. Minor Faults are Not Considered

PLP's (2012 3.7.3) geologic map (Fig. 2) shows a number of small faults cutting bedrock in the vicinity of the mine. These faults are not discussed in the PLP (2012 Ch 6) seismic hazard assessment.

Minor faults are unlikely to create very strong earthquakes, but if an earthquake happened on a fault located directly underneath tailings dams or other structures, it could be damaging.

In addition to natural earthquakes on these faults, there is the possibility that increased weight and groundwater pressure imposed by a tailings impoundment or waste rock storage could change the stress field in the earth enough to cause a local earthquake. An analysis of past man-made earthquakes (McGarr et al. 2002) shows that structures spanning multiple kilometers, like those proposed at Pebble (DNR 2006, Wardrop-Northern Dynasty, 2011), can result in earthquakes over magnitude 5. These earthquakes are most likely in cases where the force exerted by human activities lines up with geologic stresses and existing faults (McGarr et al. 2002).

PLP (2012 3.7.3) maps several parallel small faults that have allowed a wedge of bedrock to shift downward, a "graben," within the mine area. In their 2006 mine plan (DNR, 2006), a tailings dam is planned directly over this graben. This is a scenario where a fault might be activated by a human activity. Grabens form where the earth stretches, and large blocks of bedrock sink downwards along faults. Since the weight of a tailings facility would apply increased downward pressure to this graben, it has an increased chance of triggering an earthquake (McGarr et al. 2002).

Conclusions

The seismic hazard assessment contained in the PLP EBD misrepresents existing work and relies on faulty arguments. The Lake Clark Fault is a major crustal fault that is likely to pass near or through the Pebble Mine prospect. Both the location and activity of this fault are little studied. Without further study, the likelihood of an earthquake and the potential intensity of shaking are impossible to determine. Due to the nature of the proposed project, the seismic hazard assessment must consider earthquakes that are rare, and without precedent in the immediate past.

PLP's (2012 Ch 6) assessment provides no new research on this issue. It does not analyze relevant existing data. The conclusions consistently downplay potential seismic hazards, and they do not provide convincing evidence in support of those conclusions. Original work is necessary to accurately assess seismic risk at the prospect.

Annotated Bibliography

Referenced publications plus additional publications that specifically bear on seismicity in the Pebble area.

Publication	Referenced in Seismic Hazards section of EBD*	Notes
R. L. Detterman, B. L. Reed, 1980: Stratigraphy, Structure, and Economic Geology of the Iliamna Quadrangle, Alaska; Geological Survey Bulletin 1368-B.	No	Maps several faults of unknown significance near the Pebble Prospect. No information on the location of the Lake Clark Fault.
DNR (Dept. of Natural Resources), 2006: Pebble project initial application for certificate of approval to construct a dam. Tailings impoundment A and Tailings impoundment G. http://www.dnr.state.ak.us/mlw/mining/largemine/pebble/water-right-apps/index.cfm	N/A	Provides specific engineering diagrams of dams from Northern Dynasty's 2006 mine plan. Includes 3 dams, with heights of about 400 feet (impoundment G), and two over 600 feet (impoundment A).
P. J. Haeussler, 2008: An Overview of the Neotectonics of Interior Alaska: Far-Field Deformation From the Yakutat Microplate Collision; Geophysical monograph vol. 179, p. 83-108.	No	Outlines a model for southern Alaska tectonics wherein southcentral Alaska rotates counterclockwise, driven by subduction of the Yakutat Microplate.
P. J. Haeussler, R. W. Saltus, 2004: 26 km of Offset on the Lake Clark Fault Since Late Eocene Time; U.S. Geological Survey Professional Paper 1709–A.	Yes	Maps the Lake Clark Fault based on Aeromagnetic data, showing 26 km (16 mi.) offset.
P. J. Haeussler and C. F. Waythomas, 2011: Review of the Origin of the Braid Scarp near the Pebble Prospect, Southwestern Alaska; USGS Open-file Report 2011-1028.	Yes	Primarily presents evidence that a single trench near on the Braid Scarp does not show evidence of an active fault. Also presents a review of existing literature on the Lake Clark Fault.
T.D. Hamilton, R.F. Klieforth, 2010: Surficial Geologic Map of parts of the Iliamna D-6 and D-7 Quadranagles, Pebble Project Area, Southwestern Alaska, DNR DGGS Report of Investigations 2009-4.	Yes	Maps surficial geology near Pebble, including several lineaments interpreted as unrelated to seismic activity.
ICOLD (International Commission on Large Dams), M. Wieland, 2008: Large Dams the First Structures Designed Systematically Against Earthquakes, 2008 World Conference on Earthquake Engineering.	N/A	Reviews history and criteria for designing dams against earthquakes. States that typically the "Maximum Credible Earthquake" is defined as having a statistical return period of 10,000 years. Note this is looking at all dams – it may be that higher standards would apply to tailings facilities that must stand for longer than 10,000 years.

D. S. Kaufman, K. B. Stilwell, 1997: Preliminary evaluation of emergent postglacial shorelines, Naknek and Iliamna lakes, Southwestern Alaska; J. A. Dumoulin and J. E. Gray Eds., Geological studies in Alaska by the US Geological Survey, 1995: USGS Professional Paper 1574, p. 73-81.	No	Studies elevated shorelines along L. Iliamna at two points and finds no evidence of isostatic or tectnoic deformation.
H.M. Kelsey, B.L. Sherrod, A.R. Nelson, T.M. Brocher, 2008: Earthquakes generated from bedding plane-parallel reverse faults above an active wedge thrus, Seattle fault zone, GSA Bulletin 120 no. 11-12, pp 1581-1597.	N/A	Presents detailed geomorphic, LiDAR, and seismic data depicting the complex deformation on the Seattle Fault.
R. D. Koehler, R. D. Reger, 2011: Reconnaissance Evaluation of the Lake Clark Fault, Tyonek Area, Alaska; DGGS Preliminary Interpretive Report 2011-1.	Yes (2009 draft)	Documents study of the Lake Clark Fault 150 miles northeast of Pebble near Tyonek. No evidence for offset of late Pleistocene moraines.
K. G. Mackey, K. Fujita, L. V. Gunbina, V. N. Kovalev, V. S. Imaev, B. M. Koz'min, L. P. Imaeva, 1997: Seismicity of the Bering Strait region: Evidence for a Bering block; Geology vol. 25, no. 11, p. 979-982.	No	Provides evidence for rotation of the continental crust underlying the Bering Sea.
E.S. Nadin, J.B. Saleeby, 2010: Quaternary reactivation of the Kern Canyon fault system, southern Sierra Nevada, California, Geologic Society of America Bulletin 122 (9-10) pp 1671-1685.	N/A	Presents paleoseismological and seismological evidence of normal earthquakes on the Kern Canyon Fault.
W.H. Nelson, C. Carlson, J.E. Case, 1983: Geologic Map of the Lake Clark Quadrangle, Alaska, USGS Miscellaneous Field Studies Map 1114-A.	No	Shows the Lake Clark Fault as inferred, splaying along both NW and SE shores of Lake Clark. Maps a splay joining the main fault from the north.
PLP (Pebble Limited Partnership), 2012, (3.7.3): Bedrock Geology in the Mine Study Area, Pebble Project Environmental Baseline Document 2004-2008, Chapter 3.7.3. http://www.pebbleresearch.com/download/	N/A	Describes the bedrock geology near the Pebble Prospect, including major rock units, faults, and mineralized areas.
PLP (Pebble Limited Partnership), 2012, (Ch 6): Geotechnical Studies, Seismicity, and Volcanism, Bristol Bay Drainages, Pebble Project Environmental Baseline Document 2004-2008, Chapter 6. http://www.pebbleresearch.com/download/	N/A	Sections 6.6.2 and 6.7 Describe PLP's assessment of the faults in the region surrounding the Pebble Prospect.
G. Plafker, L. M. Gilpin, J. C. Lahr, 1994: Neotectonic Map of Alaska, from Geology of Alaska – Vol G-1 of the Geology of North America (GNA-G1).	No	Overview of Alaska tectonics that includes notes on tectonic status of mapped faults. Notes offset on the Lake Clark Fault in the neogene, but no more recent evidence.
M.J. Rymer, G.G. Seitz, K.D. Weaver, A. Orgil, G. Faneros, J.C. Hamilton, C. Goetz, 2002: Geologic and Peleoseismic Study of the Lavic Lake Fault at Lavic Lake Playa, Mojave Desert, Southern California, Bulletin of the Seismological Society of America 92 (4) pp. 1577-1591.	N/A	Describes post-earthquake study of Lavic Lake Fault, showing that there is evidence of a past earthquake, though it was missed prior to the 1999 earthquake.

B.L. Sherrod, T.M. Brocher, C.S. Weaver, R.C. Bucknam, R.J. Blakely, H.M. Kelsey, A.R. Nelson, R. Haugerud, 2004: Holocene fault scarps near Tacoma, Washington, USA.	N/A	Uses LiDAR and aeromagnetic data to identify an active fault, then presents results of trenching that fault.
W.C. Steele, 1985: Map Showing Interpretations of Landsat Imagery of the Lake Clark Quadrangle, Alaska, USGS Miscellaneous Field Studies Map 1114-F.	No	Maps lineaments and other features interpreted as faults in the Lake Clark quadrangle. Shows lineaments parallel to the Lake Clark structure further to the northwest.
TNC (The Nature Conservancy), 2010: An Assessment of Ecological Risk to Wild Salmon Systems from Large-scale Mining in the Nushagak and Kvichak Watersheds of the Bristol Bay Basin. http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/alaska/explore/ecological-risk-assessment-nushagak-kvichak.pdf	N/A	Extensive analysis of potential impacts of mine development. Includes modeling of tailings dam failure.
Wardrop-NDM (Northern Dynasty Minerals), 2011: Preliminary Assessment of the Pebble Project, Southwest Alaska. Web version: http://www.northerndynastyminerals.com/ndm/Prelim_A.asp	N/A	Provides an economic analysis of several mine scenarios. It includes a 25 year mine plan with a version of tailings impoundment G with two dams, the taller of which is about 675 feet tall.

*Only papers that directly bear on seismicity at the Pebble site are marked Yes/No. Other referenced papers are marked N/A.