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by

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INTRODUCTION

The northern Bristol Bay basin study area occupies onshore and state offshore areas in southwestern Alaska from Nushagak Bay to Naknek along Bristol Bay, and inland to Mulchatna River and Iliamna Lake (fig. 1). Natural processes will impose some constraints on exploration, production, and transportation activities associated with possible petroleum development, but proper siting, design, and construction practices should accommodate the potential natural hazards present in the area.

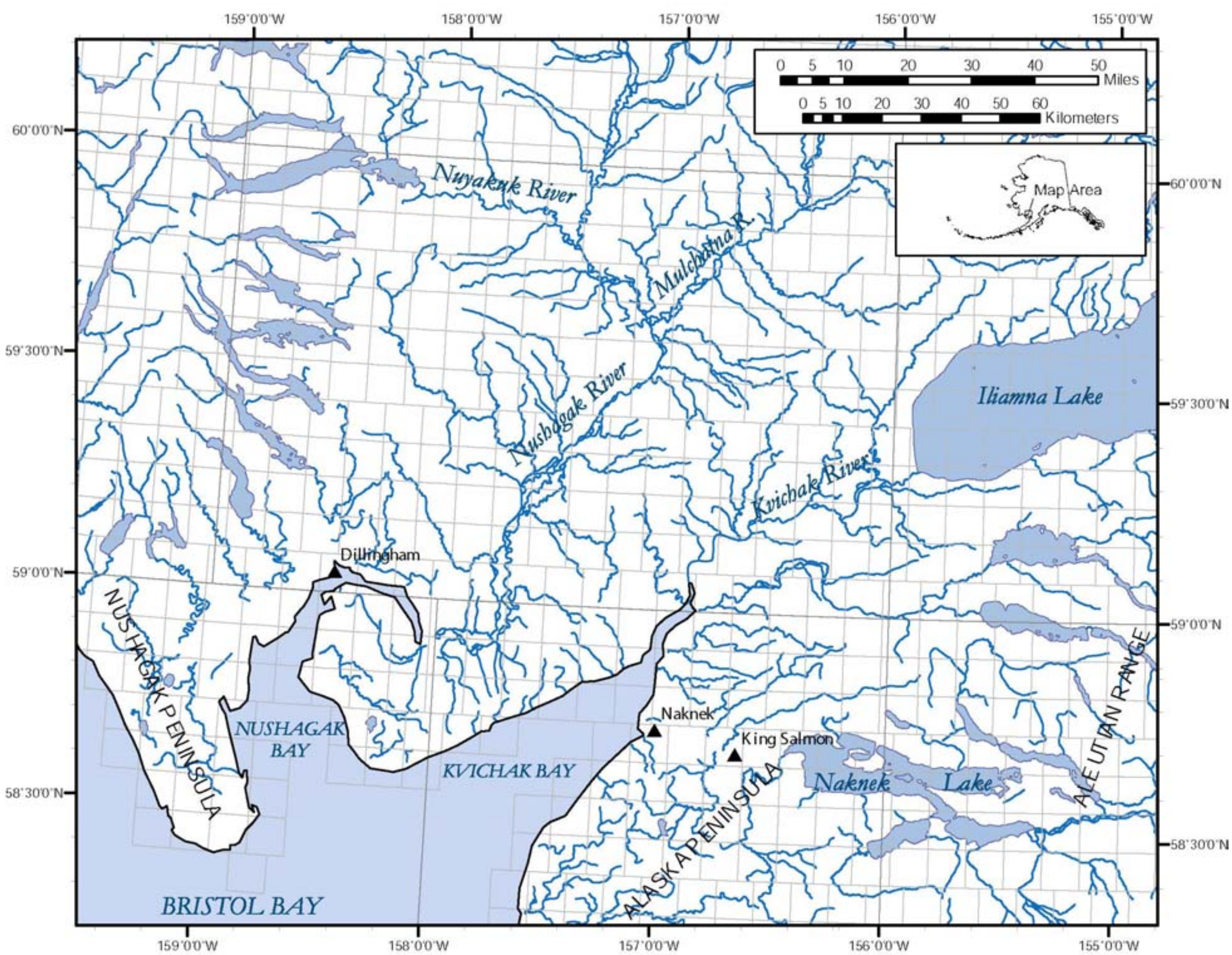

Figure 1. *Northern Bristol Bay basin study area.*

Primary hazards within the study area include: earthquakes associated with the Aleutian megathrust and the Togiak–Tikchik and Bruin Bay faults; volcano hazards, including volcanogenic tsunamis; floods; localized permafrost; snow avalanches near steep terrain; and stream icings. Geologic maps by Detterman and Reed (1964, 1973, 1980), Riehle and others (1987, 1993), Riehle and Detterman (1993), and Wilson and others (2003) show the distribution of bedrock and surficial deposits and faults in parts of the study area, but do not encompass the entire area and do not address all potential geologic hazards. This report provides a brief summary of available information related to these hazards.

EARTHQUAKES AND FAULTING

The study area is almost entirely in seismic zone 2B of the Uniform Building Code, having a moderate seismic hazard risk (International Congress of Building Officials, 1997). The International Building Code specifies maximum considered ground motion ranges from about 25 to 60% g (gravitational acceleration) for 0.2 second spectral response acceleration, and from about 12 to 25% g for 1.0 second spectral response acceleration (International Code Council, 2000). In and near the region of the study area, 2 earthquakes of magnitude >5.0 were reported between 1899 and 2003 (fig. 2). These were a magnitude 6.2 event near Kulik Lake on August 14, 1944, and a magnitude 6.1 event northeast of Naknek on May 1, 1990. Recent small earthquakes (less than magnitude 5.0) recorded in the region around the study area tend to cluster near Naknek Lake. Most seismicity in the area is deep (more than 30 km or 20 mi).

Although no great earthquakes (magnitude 7.8 or greater) have occurred in this zone since 1899, a seismic event characterization study carried out by Woodward-Clyde Consultants (1978) indicated that earthquakes in the magnitude range 5–8.5 could be generated from the shallow-dipping Benioff zone where the North Pacific plate is being subducted beneath the North American plate, in addition to smaller earthquakes in the magnitude range 5–6.25 from distant offshore and outer shelf faults as well as the Aleutian volcanoes. Nishenko and Jacob (1990) calculated conditional probabilities for future large and great earthquakes in the Queen Charlotte-Alaska-Aleutian seismic zone and determined that the Kodiak Island-Alaska Peninsula segments of the megathrust have an 11-37 percent conditional probability of having a magnitude range 7.7-8.2 event between 1988 and 2008. They also calculated that the Shumagin segment of the seismic zone, located along the southwest part of the Alaska Peninsula, has a 74-84 percent conditional probability of having a magnitude 7.4 event during that period. This is largely based on the absence of recent large-magnitude seismic events in this segment, suggesting that the fault may be locked and is building strain. Recent work by Freymueller and Beavan (1999) using GPS measurements to record surface deformation show that no significant strain is present, suggesting that the entire plate interface in this segment is slipping freely. This significantly reduces the probability of a large-magnitude megathrust event in this area. Probabilistic seismic maps of Alaska prepared by Wesson and others (1999) indicate that there is a 10 percent probability that peak ground acceleration during an earthquake in parts of the study area will exceed 0.25 g during 50 years.

Potential physical effects resulting from earthquakes include foundation settlement, foundation failure, structural failure, lurching, soil liquefaction, landslides, compaction, and seiches, which can include not only sloshing of water in lakes but also the contents of storage

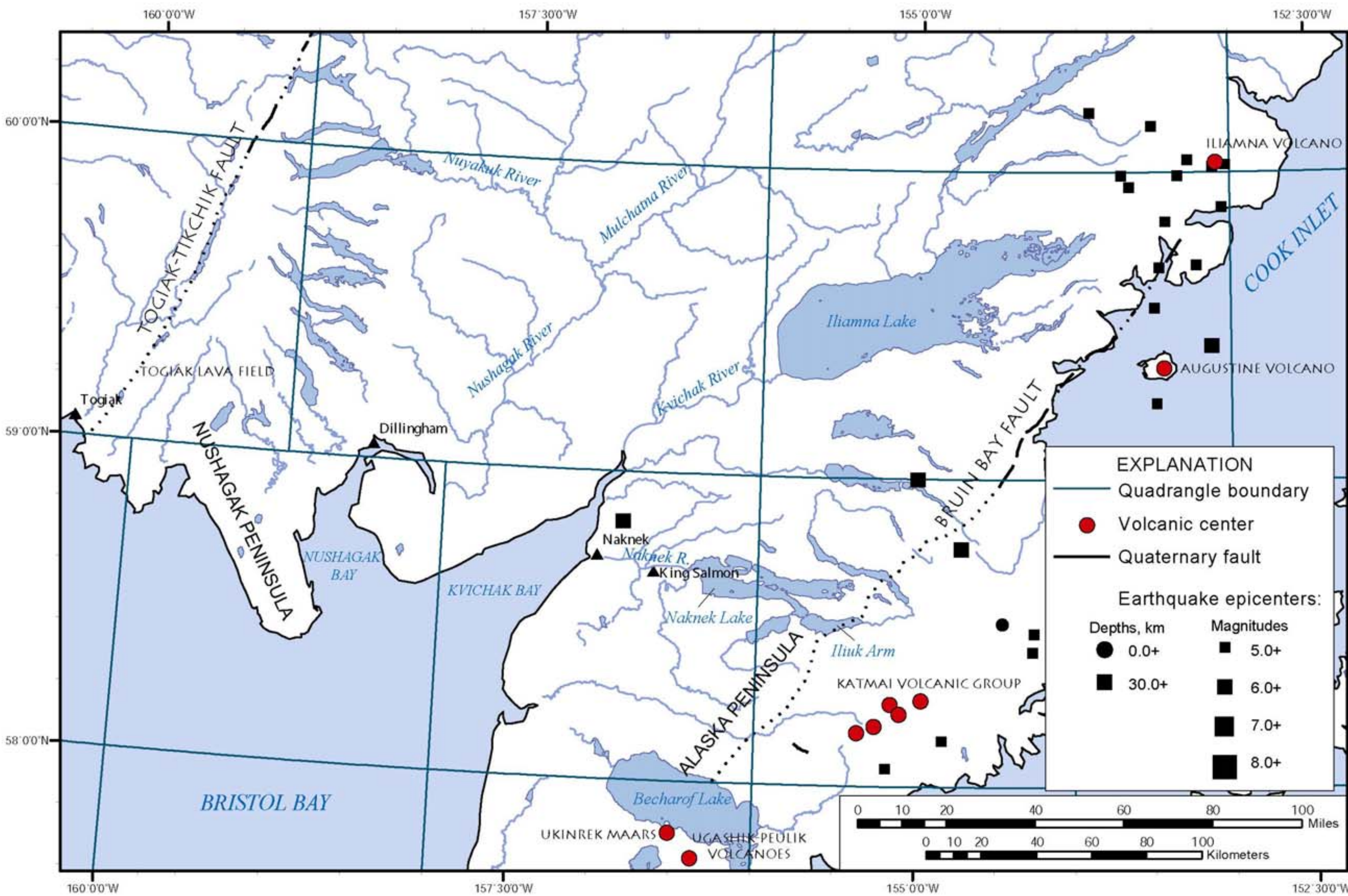

Figure 2. *Volcanic centers, faults, and epicenters of earthquakes with magnitudes > 5.0 in the Bristol Bay region. Epicenters from the Alaska Earthquake Information Center.*

tanks (Hays and Gory, 1986). Because marine portions of the study area are not near the megathrust, being separated from the Aleutian trench by the Alaska Peninsula, the hazard from seismic tsunamis (earthquake-generated ocean waves) is low. There is no record of historic tsunamis in this area.

Togiak–Tikchik Fault

The Togiak–Tikchik fault (fig. 2) is the westernmost extension of the Denali fault system, which is the largest in Alaska. The Togiak–Tikchik fault runs from the Gemuk River through the Tikchik region into the Bering Sea near the village of Togiak (St. Amand, 1957). The fault zone trends about N 55 E, approximately parallel to the trend of the Aleutian trench to the southeast. The trace of the fault is marked by offsets in unconsolidated alluvial deposits in the central Kuskokwim region (Cady and others, 1955), as well as by aligned landscape features that can be mapped from air photos (Hoare and Coonrad, 1961a). Geologic evidence suggests that this fault is steeply dipping (ranging from 60-80˚) with dextral offset and highly variable vertical motion (Cady and others, 1955; Hoare, 1961; Hoare and Coonrad, 1961a, 1961b; Grantz, 1966; Woodward-Clyde Consultants, 1978).

The Denali fault system west of the Denali–Mt McKinley area, including the Togiak–Tikchik fault, is poorly studied and the timing and amount of movement are not well constrained (Redfield and Fitzgerald, 1993). While there is some question about the existence of very recent activity on the Togiak–Tikchik fault (Plafker and others, 1977, 1994), geologic evidence indicates that parts of the fault have been active as recently as Quaternary time (younger than 1.6 million years ago) (Cady and others, 1955; Hoare, 1961; Hoare and Coonrad, 1961a; Grantz, 1966; Woodward-Clyde Consultants, 1978). A source characterization study by Woodward-Clyde Consultants (1978) yielded a potential earthquake magnitude range of 5–6.25 on the Togiak–Tikchik fault.

Bruin Bay Fault

The Bruin Bay fault is a major reverse (thrust) fault dipping 45–80° to the northwest (Barnes, 1966; Woodward-Clyde Consultants, 1978; Haeussler and others, 2000). The fault can be mapped for 530 km from Mount Susitna, near Anchorage, to the south shore of Becharof Lake. Based on unpublished aeromagnetic data, Detterman and others (1987) suggest that the fault may continue southwest toward Aniakchak Crater. The fault is buried under Quaternary deposits except where it is exposed in the Beluga and Chuitna River canyons (Barnes, 1966). Although Schmoll and Yehle (1987) found no geologic evidence of activity on the Bruin Bay fault or related structures during late Pleistocene or Holocene time (the last ~120,000 years), Woodward-Clyde Consultants (1978) note that the Bruin Bay fault has had a small number of epicenters associated with it, the largest of which had a magnitude 7.3 on November 3, 1943. While this epicenter was located far from the study area, the effects of a similar rupture on the Bruin Bay fault near the study area, though unlikely, would easily be felt there. The source characterization study by Woodward-Clyde Consultants (1978) yielded a potential earthquake magnitude range of 5–6.75 on the Bruin Bay fault.

VOLCANO HAZARDS

Alaska is extremely volcanically active, containing about 80 percent of all active volcanoes in the United States and about 8 percent of the active volcanoes in the world. Six active volcanic centers lie within 100 miles (175 km) of the study area. These are Iliamna Volcano, Augustine Volcano, the Katmai volcanic group, Ukinrek maars, Ugashik–Peulik volcanoes, and the Togiak lava field (fig. 2). Eruptions have occurred at three of these centers in the last century (Augustine, Katmai, and Ukinrek), and further eruptions are possible in the next few decades.

Study of volcanic-ash layers (tephras) in the Cook Inlet region indicates that eruptions have occurred there every 1 to 200 years (Riehle, 1985). In the 20th century, these events have occurred every 10 to 35 years, and, for the last 500 years, tephras were deposited at least every 50 to 100 years with Augustine Volcano being the most active of the volcanoes close to the study area (Stihler, 1991; Stihler and others, 1992; Begét and Nye, 1994; Begét and others, 1994). Augustine Volcano is one of the most active volcanoes in Alaska, with major eruptions in 1812, 1883, 1935, 1963-4, 1976, and 1986 (Wood and Kienle, 1990; Waythomas and Waitt, 1998). It will be surprising if it does not erupt again in the near future. The Katmai volcanic group includes Snowy Mountain, Mount Griggs, Mount Katmai, Trident Volcano, Novarupta volcano, Mount Mageik, Mount Martin, and Alagogshak volcano. All but Alagogshak have erupted during the last 6,000 years, with a total of at least 15 major eruptive episodes that could have produced ash clouds in the last 10,000 years (Fierstein and Hildreth, 2001). Novarupta produced the world's largest eruption of the 20th century and sent ash around the globe when it was formed in 1912. The Ukinrek maars were formed over the course of ten days in 1977, sending ash at least 160 km north and east of the vent and covering an area of about 25,000 km^2 (Wood and Kienle, 1990). Iliamna Volcano is believed to have formed within the last 1,000,000 years; while it has not erupted historically, two large, continually active, fumarolic areas near the summit attest to its continued potential for eruptive activity (Wood and Kienle, 1990; Motyka *et al.,* 1993; Waythomas and Miller, 1999). Ugashik caldera formed explosively more than 30,000 years ago, and Peulik volcano grew as a parasitic cone on its northern flank in a series of eruptions during 1814 and 1852 (Wood and Kienle, 1990). The Togiak lava field was erupted from vents along the Togiak–Tikchik fault and is believed to be less than 750,000 years old (Wood and Kienle, 1990).

The study area is far enough from the volcanic centers to be considered out of range of such proximal volcanic hazards as lava flows, block-and-ash flows, pyroclastic flows, and hot gas surges, but lahars (volcano-induced mudflows) and volcanogenic floods may be a concern. Fierstein and Hildreth (2001) include many of the major rivers draining into Iliuk Arm of Naknek Lake as drainages at risk for lahars and floods, which can inundate waterways with pumice and ash. This inundation could affect Naknek River and the major settlements of King Salmon and Naknek, impacting the exploration, production, and transportation activities associated with possible petroleum development in the study area.

Distal hazards are caused by volcanic eruptions that impact distant sites. The most common of these is ashfall, where explosive eruptions blast volcanic ash (finely ground volcanic rock) into the atmosphere and stratosphere and it then drifts downwind and falls to the ground.

There have been scores of such events from Cook Inlet and Alaska Peninsula volcanoes in the last century. These ash clouds can drift thousands of kilometers from their source volcanoes and are a severe hazard to mechanical and electronic equipment such as computers, transformers, and engines if they ingest ash past the air filter, causing electrical shorts and fusing jet engines. Fine ash is a nuisance and can cause respiratory problems, and heavy ashfall can disrupt activities by interfering with power generation and impairing visibility. Resuspension of dry ash by wind can cause the effects of ash fallout to persist well beyond the eruption. Ash fallout from historical eruptions of Augustine Volcano has measured several millimeters thick or more on the mainland (Waythomas and Waitt, 1998). Fallout thick enough to collapse buildings, such as fell in Kodiak after the 1912 eruption at Katmai, is possible but rare. The study area is included within the area described by Waythomas and Waitt (1998) as likely to be affected by ashfall similar to the 1976 and 1986 eruptions of Augustine Volcano; it is outside the expected ashfall-hazard zone of small to moderate eruptions of Iliamna Volcano (Waythomas and Miller, 1999). The possible extent of ashfall from a major eruption of Iliamna Volcano is not known. Ash clouds from a Novarupta-style eruption in the Katmai area would dwarf those of all other more recent Alaska eruptions of Cook Inlet and Alaska Peninsula volcanoes (Fierstein and Hildreth, 2001) and would pose a significant hazard in the study area.

Another possible distal hazard is posed by volcanogenic tsunamis. These can occur when volcanoes cause debris avalanching due to gravitational instability or erupt large-volume pyroclastic flows. When this rapidly flowing material suddenly enters water it can generate large waves that can travel quickly for long distances. Evidence of a prehistoric volcanogenic tsunami related to the 3,430-year-old eruption of Aniakchak caldera, more than 200 km away on the Alaska Peninsula, has been documented throughout the Bristol Bay region (Lea, 1989; Allen, 1994; Waythomas *et al.,* 1995; Armes, 1996; Waythomas and Neal, 1998; Waythomas and Watts, 2003). A rapidly moving, voluminous pyroclastic flow generated a tsunami wave up to 7.8 m high (Waythomas and Neal, 1998) when it hit Bristol Bay, and deposited as much as 70 cm of wave-carried material 18.4 m above mean high tide on the shores of Nushagak Bay (Allen, 1994; Armes, 1996). Lea (1989) notes that there are similar deposits preserved in older material in the region that may record additional tsunami or storm-surge events. The potential clearly exists for the generation of future but infrequent volcanogenic tsunamis in the Bristol Bay area.

FLOOD HAZARDS

Besides possible volcanogenic flooding of Nushagak and Kvichak bays, flood hazards in the study area can result from ice jams, high rainfall, and storm surges. Only a few rivers are monitored in the area, but ice-jam flooding is a known concern on Nushagak River (R. Page, National Weather Service, personal communication, 2003). High-rainfall floods can occur on any stream under the requisite meteorological conditions. Nushagak and Kvichak rivers experienced their most recent 25-year flood events in 1990 and 1980, respectively, and Nuyakuk River experienced a 50-year flood event in 1977 (Jones and Fahl, 1994). In addition to hazards caused by high water levels, the primary hazards to facilities from river flooding are bank erosion, increased sediment deposition at the river mouth, high bedload transport, and channel modification.

Severe storms can cause coastal flooding when the sea is driven above high tide level onto what is normally dry land via a combination of tide levels, wind-driven transport of sea water, and atmospheric pressure (Fathauer, 1978). Coastal areas of Bristol Bay in the study area may be subject to coastal flooding under certain meteorological conditions (Fathauer, 1975, 1978; Sallenger *et al.,* 1977; R. Thoman, National Weather Service, personal communication, 2003). Not only do the funnel-shaped embayments of Nushagak and Kvichak bays amplify the tidal bulge to create extremely large tidal ranges (Sallenger *et al.,* 1977), but sea water driven directly into these embayments by winds around low pressure systems in the eastern Bering Sea can be similarly funneled and amplified (R. Thoman and E.L. Stevens, National Weather Service, personal communication, 2003). The great Bering Sea storm of November 9–12, 1974, moved north–northeast from the central Aleutians through Bering Strait and had winds of 50 to 75 knots (Fathauer, 1975, 1978; Sallenger *et al.,* 1977). The storm coincided with the highest tides of the month and raised the water level 5 feet (1.5 m) at Naknek and 12 feet (3.65 m) at Nome, causing moderate to major flood damage from Bristol Bay to Kotzebue Sound (Fathauer, 1975, 1978). High water levels combined with powerful and destructive surf make coastal floods one of the leading causes of property damage in Alaska (Fathauer, 1978).

PERMAFROST

Perennially frozen ground, or permafrost, exists where the ground temperature remains at or below freezing (32˚ F or 0˚C) for at least two years (Muller, 1943; Péwé, 1975, 1982). While permafrost is primarily a feature of polar and subpolar regions, patches extend as far south as latitude 45˚N in the northern hemisphere (Péwé, 1975, 1982; Brown *et al.,* 1997). Although the study area lies within the zone of sporadic permafrost, with potentially as much as 10-50 percent of the area being underlain by perennially frozen ground, the visible ground-ice content in the upper 10-20m is considered low to medium, ranging from 0-20 percent by volume (Harris, 1985; Brown *et al.,* 1997). The most severe permafrost hazards result from the thawing of massive ground ice, including pore ice, segregated ice, ice-wedge ice, pingo ice, and buried ice. Comparatively warm mean annual air-temperature conditions suggest that it is highly unlikely that ice wedges and pingos can exist in the study area (Péwé, 1975, 1982), and no large bodies of ground ice (massive segregated ice, ice wedges, pingos, buried ice) have been recognized there (Péwé, 1975, 1982; Brown *et al.,* 1997). Potential hazards resulting from permafrost include: thawing of ground ice with subsequent surface subsidence; intensified frost action, such as heaving and ground cracking; and freezing of buried sewer, water, and oil lines (Péwé, 1982). These hazards would be highly localized and limited in the study area, however, and can be mitigated by careful evaluation, proper engineering, or avoidance of susceptible areas.

SNOW AVALANCHES

The study area is in the western snow-avalanche region of Alaska, in which the predominant avalanche activity in mountainous areas may be characterized by dry, hard wind slabs on bimodal lee slopes with some wet loose snow and slush-flow avalanches in spring (Hackett and Santeford, 1980). However, because mountainous terrain is virtually absent in the study area there is limited snow-avalanche potential, and that only in localized areas of steeper slope. Hazard mitigation can be accomplished by careful evaluation and avoidance of susceptible slopes. Avalanching from roofs in developed areas is an additional consideration.

STREAM ICINGS

Stream icings (also called naleds or aufeis) are seasonal flood phenomena that develop where spring, surface, or seepage water flows over the surface during freezing temperatures and forms accretions of ice layers that may be several meters thick and extend for many kilometers (Dean, 1984; Harris, 1986). Icings can present difficult engineering problems for the construction of bridges, roads, and other structures, and construction may exacerbate the conditions leading to icing development (Péwé, 1982; Harris, 1986). Streams that may host icings in the study area include: upper Kvichak River; Alagnak River; eastern tributaries of Mulchatna River draining Stuyakok Hills; northern tributaries of Kokwok River; and upper Iowithla River where it drains Muklung Hills (Dean, 1984). These hazards are highly localized, however, and can be mitigated by careful evaluation and avoidance of susceptible areas.

CONCLUSIONS

Development in the northern portion of the Bristol Bay basin will be subject to potentially severe geologic hazards, including earthquake shaking, earthquake-induced ground failures, volcanic ash fall, volcanogenic tsunamis, and river and coastal floods. Additional hazards may include localized permafrost effects, snow avalanches, and minor stream icings. All structures should be built to exceed minimum requirements of the 1997 Uniform Building Code for seismic zone 2B and/or the minimum requirements of the 2000 International Building Code, which is currently being adopted by the State of Alaska. Additional precautions should be taken to identify and accommodate special site-specific conditions such as unstable ground, flooding, erosion, and other localized hazards. Proper siting and engineering will minimize the detrimental effects of these natural processes.

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