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by

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INTRODUCTION

The Alaska Peninsula study area occupies onshore and state offshore areas in southwestern Alaska from Nushagak Bay to Moffet Point along Bristol Bay, and inland to Becharof Lake and the crest of the Aleutian Range (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 hazards present in the area.

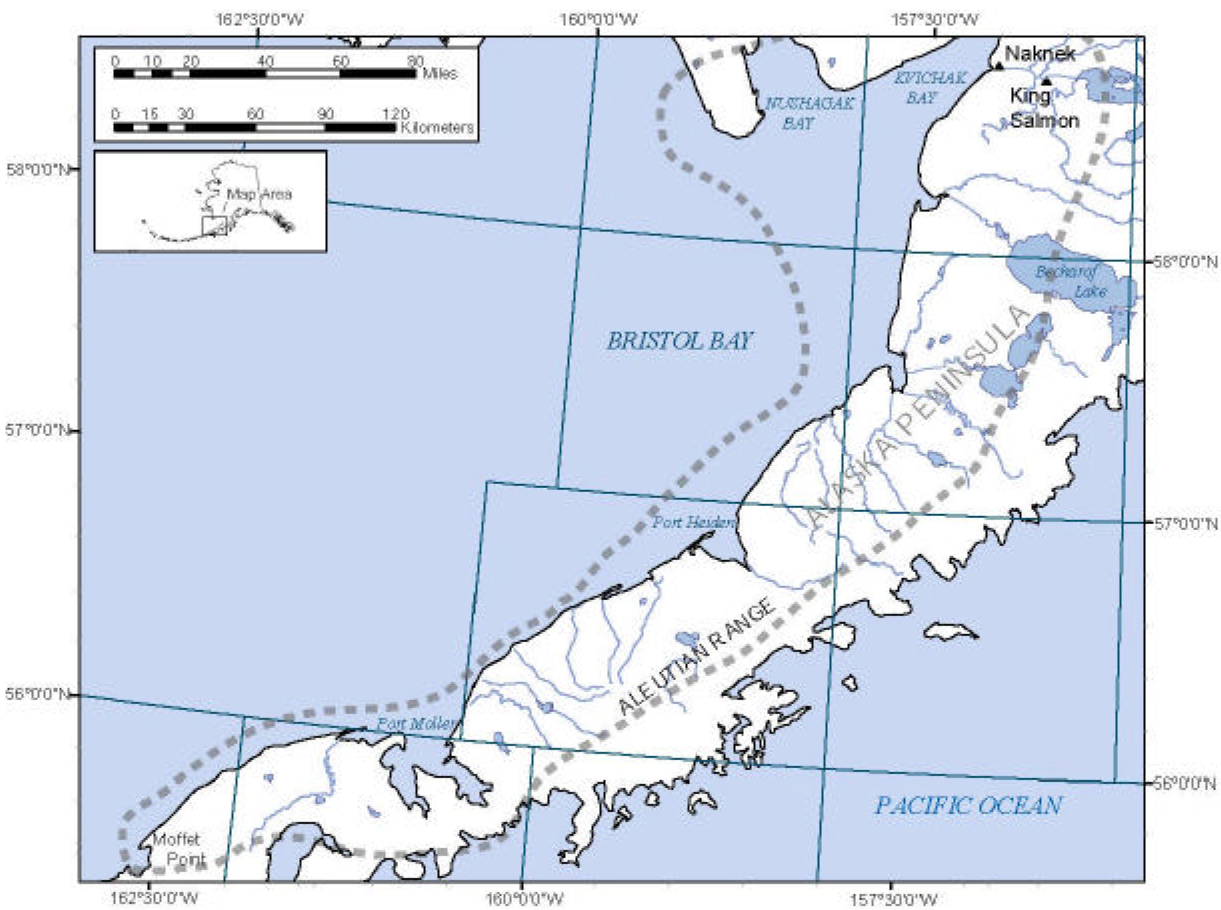

Figure 1. *Alaska Peninsula, study area delineated by dashed line.*

Primary hazards in the study area include: Earthquakes associated with the Aleutian megathrust and Togiak–Tikchik, Bruin Bay, Hallo Creek, Takayofo Creek, Chignik, Port Moller, Emmons Lake, Chirikof Island, Sitkinak Dome, Kodiak Shelf, Kodiak Island, and Border Ranges faults; volcano hazards, including volcanogenic tsunamis; floods; seafloor instability; sea ice; snow avalanches near steep terrain; localized permafrost; and stream icings. Geologic maps by Detterman and Reed (1964, 1973, 1980), Detterman and others (1981a, 1981b), DuBois and others (1989), McLean and others (1978), Riehle and Detterman (1993), Riehle and others (1987, 1993), Waldron (1961), and Wilson and others (1991, 1995, 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 Aleutian seismic zone to the south of the Alaska Peninsula is one of the most active seismic zones in the world. Great earthquakes are common along its length, and violent ground motion is a major potential hazard. The study area on the northwest side of the Alaska Peninsula is almost entirely in seismic zone 3 of the Uniform Building Code, on a scale of 0 to 4 where 4 represents highest seismic hazard (International Congress of Building Officials, 1997). The recently adopted International Building Code specifies maximum considered ground motion ranges from about 25 to 125% g (gravitational acceleration) for 0.2 second spectral response acceleration, and from about 12 to 50% g for 1.0 second spectral response acceleration (International Code Council, 2000). In and near the study area, 15 earthquakes of magnitude >6.0 were reported between 1899 and 2003 (fig. 2). Of these, five were less than 30 km deep and ten were deeper than 30 km. Most seismicity in the area is deep (more than 30 km or 20 mi). Two great earthquakes (magnitude 7.8 or greater) have occurred near this area since 1899. These were a magnitude 7.9 event southeast of Sand Point on May 31, 1917, and a magnitude 8.3 event due east of Sand Point on November 10, 1938 (fig. 2).

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 Aleutian megathrust 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. Many other scientists predict that this Shumagin seismic gap is due for a great earthquake in the next few decades (Boyd and others, 1988; Bruns and others, 1985; Bufe and others, 1994; Davies and House, 1979; Davies and others, 1981; McCann and others, 1979; Nishenko and Jacob, 1986; Sykes, 1971; Sykes and others, 1980, 1981). However, Lisowski and others (1988) report that measurements of deformation of a trilateral network in the gap during the interval 1980-1987 failed to detect any strain accumulation, suggesting that the

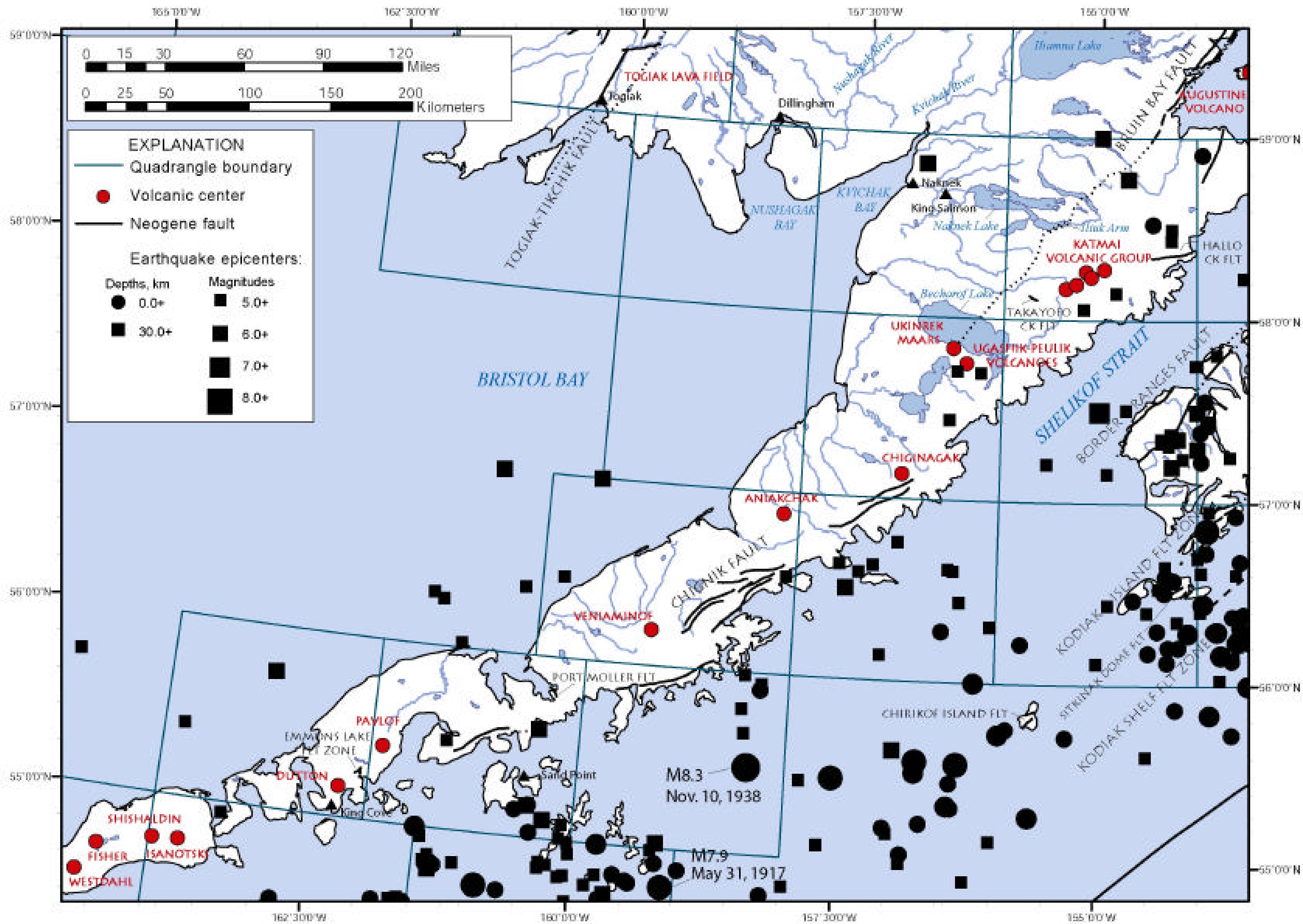

Figure 2. *Volcanic centers, faults, and epicenters of earthquakes with magnitudes > 5.0 in the Alaska Peninsula region. Epicenters from the Alaska Earthquake Information Center.*

entire plate interface in this segment is slipping freely. Recent work by Freymueller and Beavan (1999) using GPS measurements to record surface deformation seems to confirm that no significant strain is present. 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 0.30 g during the next 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 tanks (Hays and Gori, 1986). The severity of these earthquake-induced hazards depends largely on local site conditions, such as slope, soil properties, soil thickness, and saturation.

Because marine portions of the study area in Bristol Bay 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 probably low to moderate. Modeling of tsunami travel-time contours from a major earthquake predicted to occur in the Shumagin seismic gap indicates that tsunami effects on the north coast of the Alaska Peninsula could occur within 3-5 hours of the rupture (Kowalik and Murty, 1984, 1989). Distribution of maximum tsunami amplitude showed a considerable amount of energy directed towards the southern coasts of the Alaska Peninsula and Aleutian Islands (Kowalik and Murty, 1989). Modeling of a tsunami generated by a large earthquake that struck the northwestern United States in 1700 shows that tsunami waves can pass around the Alaska Peninsula and between islands in the Aleutians to impact Bristol Bay (Satake and others, 2003). In 1946, a magnitude 7.4 earthquake that ruptured seaward of Unimak Island generated one of the most destructive tsunamis recorded in the Pacific Ocean (Okal and others, 2002, 2003; Shepard and others, 1950; Sokolowski and Whitmore, 1994; Sykes, 1971). The tsunami wave was directed primarily to the open ocean to the south, but directivity diagrams for far-field tsunami waves centered on the epicenter for a 200 km bilateral rupture indicate that some of the energy also impacted the shores of Bristol Bay on the north side of the Alaska Peninsula (Ben-Menahem and Rosenman, 1972; Okal and others, 2002). Runup reached 42 m on the south side of Unimak Island, where the Scotch Cap lighthouse was destroyed, and the tsunami killed 162 people in California, the Marquesas, and Hawaii (Okal and others, 2002, 2003). This tsunami was the impetus for creating the Tsunami Warning System in the Pacific (Sokolowski and Whitmore, 1994). Recent modeling has suggested that, rather than the earthquake itself solely causing the tsunami, the earthquake may have triggered one or more submarine landslides that contributed energy and southward directionality to the tsunami (Okal and others, 2003).

Togiak–Tikchik Fault

Togiak–Tikchik fault (fig. 2) is the westernmost extension of the Denali fault system, which is the largest in Alaska. 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; Grantz, 1966; Hoare, 1961; Hoare and Coonrad, 1961a, 1961b; Woodward-Clyde Consultants, 1978).

The Denali fault system west of the Denali–Mt McKinley area, including 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 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; Grantz, 1966; Hoare, 1961; Hoare and Coonrad, 1961a; Woodward-Clyde Consultants, 1978). A source characterization study by Woodward-Clyde Consultants (1978) yielded a potential earthquake magnitude range of 5–6.25 on Togiak–Tikchik fault.

Bruin Bay Fault

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 Bruin Bay fault or related structures during late Pleistocene or Holocene time (the last ~120,000 years), Woodward-Clyde Consultants (1978) note that Bruin Bay fault has had a small number of epicenters associated with it, the largest of which had a magnitude 7.3 earthquake on November 3, 1943. While this epicenter was located far from the study area, the effects of a similar rupture on 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 Bruin Bay fault.

Border Ranges Fault

The Border Ranges fault system is one of the major structural features in south-central Alaska. It cuts through the center of the Nelchina–King Mountain region and separates the trench-slope and trench-fill deposits of the Chugach terrane from the plutonic and volcanic rocks of the Peninsular terrane (Burns and others, 1991). The fault trace forms a steep, sharp contact easily visible in oblique aerial photography (MacKevett and Plafker, 1974). Cowan and Boss (1978) and MacKevett and Plafker (1974) mapped Border Ranges fault at somewhat different locations on Kodiak Island. Based on magnetic data and regional geologic considerations, Fisher (1981) suggested that Border Ranges fault extends from the Copper River basin to Sutwik Island, farther south than the previously assumed termination at Kodiak Island. Bradley and others (1999) show Border Ranges fault in cross section in the Seldovia Quadrangle. The cross section shows the fault offsetting pre-Tertiary strata and terminating upward at the base of the Tertiary rocks. MacKevett and Plafker (1974) suggest that Border Ranges fault marks a plate boundary that developed near the end of Mesozoic or in early Tertiary time.

The fault system is associated with a broad, steep gravity gradient along the eastern portions of Cook Inlet basin that lies parallel to the Kenai Mountain front (MacKevett and Plafker, 1974). Saltus and others (2001) discuss the "Knik arm anomaly" (originally named by Grantz and others in 1963) as a discontinuous magnetic anomaly that can be traced for more than 1,000 km along Border Ranges fault (Burns and others, 1983; Case and others, 1966; Griscom and Case, 1983). This wide and relatively steep gravity-gradient zone extends across the Kenai Peninsula and along the Kenai Mountain front. The zone borders the eastern flank of the Cook Inlet basin and is interpreted as being caused by extensive basement faulting. Reconnaissance aeromagnetic data (Grantz and others, 1963) indicate northeast-trending basement discontinuities along this part of the Kenai Peninsula. The width and extent of the gravity and magnetic gradients imply considerable regional stratigraphic truncation of the Tertiary sediments along the eastern margin of the Cook Inlet basin (Hackett, 1977).

The level of activity on Border Ranges fault is the subject of much controversy. Investigations by Updike (1984) in the Twin Peaks area northeast of Anchorage suggest that movement on the Border Ranges fault system has occurred during the past several thousand years, but Plafker and others (1994) assign an age of Neogene (less than 24 million years without younger record of activity) to the fault. Extensive ground breakage in surficial deposits along a northeast-striking zone in the northwestern part of the Kenai Peninsula developed during the 1964 earthquake (Foster and Karlstrom, 1967). MacKevett and Plafker (1974) suggested that the reported ground breakage may have been related to movement on a buried fault. Furthermore, they suggested that although the ground breakage occurred northwest of the inferred trace of Border Ranges fault, it may have been related to the fault or a splay of it. Two faults that have been interpreted to be active and associated with Border Ranges fault have been mapped in the Anchorage area. One of the faults is Matanuska Glacier fault, shown on maps by Plafker and others (1994) and Burns and others (1983), 25 km north of Anchorage. The other is Twin Peaks fault, mapped by Updike and Ulery (1983), 50 km northeast of Anchorage. Updike (1984) refers to the Twin Peaks segment of the Border Ranges as the active segment of the Border Ranges fault system. Yehle and Schmoll (1987) did not map Twin Peaks fault in the area. Haeussler and Anderson (1997) dismiss Twin Peaks fault as a coincidental alignment of bedrock structural fabric, a headscarp related to landsliding within an inactive rock glacier, and swales related to sackungen and landsliding. They then assert that if the Twin Peaks fault has no seismogenic potential, then there is no evidence for Holocene activity on or near Border Ranges fault near Anchorage. Furthermore, Haeussler cites Little and Naeser (1989) and Plafker and others (1994) suggesting that geologic evidence indicates a lack of Quaternary faulting on the Border Ranges fault. MacKevett and Plafker (1974) describe Border Ranges fault as covered by surficial deposits near Anchorage and in the northeastern Kenai Peninsula. Page and others (1991) suggest that seismicity is not directly associated with the Border Ranges fault.

Activity on Border Ranges fault where it crosses northern Kodiak Island within about 150 km of the study area has not been evaluated, but a source characterization study of the Bristol Bay area by Woodward-Clyde Consultants (1978) yielded a potential earthquake magnitude range of 5–7 on the fault.

Hallo Creek Fault

The postulated Hallo Creek fault is in the active Aleutian volcanic arc (Riehle and others, 1993). It is west of Mt. Katmai on the south side of Hallo Creek where it drains into Hallo Bay, and was originally mapped by Keller and Reiser (1959) as displacing Quaternary and Tertiary units. The fault is expressed as a northward facing scarp that forms the divide between Kukak and Hallo bays (Keller and Reiser, 1959). Riehle and others (1993), however, mapped a stratigraphic contact rather than a fault contact, and an unfaulted late Tertiary intrusive unit across the location of Keller and Reiser's (1959) fault trace. Plafker and others (1994) assigned an age of Neogene (less than 24 million years without younger record of activity) to Hallo Creek fault.

Other Faults

There are several other faults that may be of concern to development in the Alaska Peninsula area. Little is known about these features but there is evidence to suggest comparatively recent activity and thus potential for geologic hazard, primarily to structures located on or very near the faults.

Takayofo Creek fault: Takayofo Creek fault is located in the southern Mt. Katmai Quadrangle at the headwaters of Takayofo Creek (Riehle and others, 1993). The fault is not mentioned in text accompanying the 1:250,000-scale map by Riehle and others (1993), but it is shown crossing undifferentiated Holocene and Pleistocene surficial deposits. The fault passes within 25 km of the Bruin Bay fault on this map. Plafker and others (1994) assign an age of Late Pleistocene (approximately 500,000 to 11,000 years) for Takayofo Creek fault.

Port Moller fault: Wilson (1994) and Wilson and others (1995) used stratigraphic and geomorphic evidence in the vicinity of Left Head of Port Moller to infer the presence of a Quaternary high-angle fault with significant vertical offset and a trend parallel to the Alaska Peninsula.

Emmons Lake fault zone: The faults near Emmons Lake were first mapped by Kennedy and Waldron (1955). They did not name these faults, which they inferred in Quaternary basalt flows. Plafker and others (1994) named the structures and assigned an age of Quaternary (approximately 2 million to 11,000 years old) for the fault zone.

Chignik fault: Knappen's 1929 report describes a great fault offsetting Tertiary deposits along the northwest side of Chignik Lagoon, and shows faults near Chignik on his map. None of these structures are shown offsetting Quaternary deposits. Plafker and others (1994) assign an age of Neogene (less than 24 million years without younger record of activity) to Chignik fault.

Chirikof Island fault: Plafker and others (1994) assign an age of Historic (1796 to present) for Chirikof Island fault. Stover and Coffman (1993) examined historical records and report that a vertical displacement of 2 m took place along this fault in conjunction with a large earthquake in 1880, which was accompanied by aftershocks, numerous deep fissures, strong shaking, sea waves that traveled about 55 m onshore, and permanent changes in sea level.

Sitkinak Dome fault: Plafker and others (1994) assign an age of Neogene (less than 24 million years without Quaternary record of activity) to Sitkinak Dome fault.

Kodiak Shelf fault zone: Plafker and others (1994) assign ages ranging from Holocene to Neogene for faults within the Kodiak Shelf fault zone.

Kodiak Island fault zone: Plafker and others (1994) were unable to determine an age for the Kodiak Island fault zone, but its inclusion in their neotectonic map of Alaska indicates that there is evidence for Neogene activity. A source characterization study by Woodward-Clyde Consultants (1978) yielded a potential earthquake magnitude range of 5–7 on the Kodiak Island fault zone, which they refer to as the "deformed zone."

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. Fourteen active volcanic centers lie within 110 miles (185 km) of the study area. These are, from north to southwest: The Togiak lava field, Augustine Volcano, the Katmai volcanic group, Ukinrek maars, Ugashik–Peulik volcanoes, Mount Chiginagak, Aniakchak caldera, Mount Veniaminof, Pavlof and Pavlof Sister, Mount Dutton, Isanotski Volcano, Shishaldin Volcano, the Fisher volcanic center, and Westdahl–Pogromni volcanoes (fig. 2). Eruptions have occurred at eight of these centers in the last century (Augustine, Katmai, Ukinrek, Aniakchak, Veniaminof, Pavlof, Shishaldin, and Westdahl), 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 (Begét and Nye, 1994; Begét and others, 1994; Stihler, 1991; Stihler and others, 1992). 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). 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). There are no known tephra beds on the ground surface near Mount Chiginagak, so the poorly documented historic activity in 1929 and 1972 is believed to be merely fumarolic in nature; thermal springs are present downslope from the fumarole (Wood and Kienle, 1990). Aniakchak caldera was formed about 3,400 years ago by collapse of a stratovolcano and catastrophic eruption of more than 50 km^3 of material that was deposited as far as 50 km away; the only historic eruption documented for Aniakchak occurred in 1931 and resulted in the emplacement of a dome (Wood and Kienle, 1990; Neal and others, 2001).

Mount Veniaminof is one of the most voluminous centers on the Aleutian volcanic arc, with deposits from its climactic caldera-forming eruption 3,700 years ago extending from coast to coast across the Alaska Peninsula (Wood and Kienle, 1990). Known historic eruptions took place in 1830–38, 1892, 1939, 1944, 1956, and 1983–84, and possible eruptions in 1852 and 1874 (Coats, 1950; Wood and Kienle, 1990; Yount and others, 1985). Mount Veniaminof is currently in a state of elevated activity. Pavlof and Pavlof Sister are a prominent pair of twin stratovolcanoes. Pavlof is the most consistently active volcano in the Aleutian arc, with 39 eruptions from 1790 to 1986–87, while Pavlof Sister has only one reported historic eruption in 1762 (Wood and Kienle, 1990). Mount Dutton is a little-studied Quaternary volcano that has not had any historic eruptive activity but was the site of earthquake swarms in 1984–85 and 1988 (Wood and Kienle, 1990). Virtually nothing is known about Isanotski Volcano, which had a major eruption in 1825 that blasted away a large part of the volcano and has not erupted since the 1840s (Wood and Kienle, 1990). Shishaldin volcano has been in a nearly constant state of mild activity throughout local recorded history, with steam or smoke continuously rising from its summit, lava extruded in 1830 and 1932, and lahar formation in 1976 and 1999 (Wood and Kienle, 1990;

Begét and others, 2002). Shishaldin volcano is currently in a state of elevated activity. The only historic activity reported for Fisher volcano was an ash eruption in 1826 (Wood and Kienle, 1990). Westdahl and Pogromni are poorly studied volcanoes on Unimak Island. Pogromni erupted in 1795, 1796, 1826, 1827, and 1830, and Westdahl erupted in 1964–65 and 1978 (Wood and Kienle, 1990). Seventeen satellite vents located southeast and northwest of Westdahl summit are all post glacial in age (6,700–8,400 years ago) (Wood and Kienle, 1990).

The study area is within range of such proximal volcanic hazards as lava flows, block-and-ash flows, pyroclastic flows, hot gas surges, lahars (volcano-induced mudflows), volcanic gases, and volcanogenic floods, including jokulhlaups (glacial outburst floods). As noted above, Mount Veniaminof caldera-forming deposits extend from coast to coast across the Alaska Peninsula (Wood and Kienle, 1990). Pyroclastic flows from the Aniakchak caldera-forming eruption crossed topographic barriers 500 m high at distances of 30 km from the caldera rim, and were deposited up to 50 km from the vent (Wood and Kienle, 1990; Neal and others, 2001). Neal and others (2001) also indicate there is a potential for significant flooding along Aniakchak River during a large eruption, as well as on most of the other major drainages radiating from the caldera. While no point sources of toxic gases are currently known to exist at Aniakchak, at least one warm spring emits magma-derived carbon dioxide and helium, leading Neal and others (2001) to suggest that new mama rising to the surface may release potentially lethal concentrations of gases. The poorly-studied Fisher volcanic center formed a caldera 9,100 years ago that was accompanied by pyroclastic flows that traveled 15 km and climbed at least 500 m over a ridge before descending into the Bering Sea (Wood and Kienle, 1990). The 1978 Westdahl eruption sent ash 11 km into the atmosphere, deposited ash thicknesses up to 18 cm within 15 km of the crater, and produced a lahar that extended 12 km (Wood and Kienle, 1990). As noted above, Shishaldin Volcano produced lahars in 1976 and 1999 (Wood and Kienle, 1990; Begét and others, 2002). 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. One of the principal potential hazards from an eruption of Mount Veniaminof is a jokulhlaup resulting from melting of the extensive intracaldera and radiating alpine glaciers that together comprise 280 km^2 of ice (Waythomas, 1994; Wood and Kienle, 1990). During the 1983–84 eruption approximately 0.15 km^2 of glacial ice melted and the subglacially impounded water was in danger of being catastrophically released from the caldera (Wood and Kienle, 1990; Yount and others, 1985). Geologic evidence indicates that a catastrophic flood was caused by drainage of the caldera lake at Aniakchak caldera sometime after 3,400 years ago, and that floods from lake-filled calderas may be particularly large and constitute significant hazards (McGimsey and others, 1994; Waythomas and others, 1996).

The most common volcanic hazards to distant sites 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. Ashfall tephra up to 7 cm thick from the Aniakchak caldera-forming eruption has been found 1,100 km away (Wood and Kienle, 1990), and Neal and others (2001) include the eastern portion of the study area within the area likely to be affected by fallout during future eruptions. The Ukinrek maars sent ash at least 160 km north and east of the vent and covered an area of about 25,000 km^2 (Wood and Kienle, 1990). 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 has been documented throughout the Bristol Bay region (Allen, 1994; Armes, 1996; Lea, 1989; Waythomas and Neal, 1998; Waythomas and Watts, 2003; Waythomas and others, 1995; Neal and others, 2001). A rapidly moving, voluminous pyroclastic flow generated a tsunami wave up to 7.8 m high (Waythomas and Neal, 1998; Neal and others, 2001) 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). While Neal and others (2001) indicate that there is unlikely to be a future eruption that is of sufficient magnitude to send such large volumes of material to the Pacific Ocean or Bering Sea, Lea (1989) notes that there are deposits preserved in older material in the region that are similar to the deposits associated with the caldera-forming event, and that these 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, oral communication, 2003). High-rainfall floods can occur on any stream under the requisite meteorological conditions. The most recent 25-year flood events on Nushagak and Kvichak rivers occurred in 1990 and 1980, respectively (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 the Alaska Peninsula in the study area may be subject to coastal flooding under certain meteorological conditions (Fathauer, 1975, 1978; Sallenger and others, 1977; R. Thoman, National Weather Service, oral 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 and others, 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, oral 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 and others, 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). The Meshik storm of October 27–28, 1976, resulted when a low pressure center moved southeast from Nunivak Island to Kodiak and a flow of cold, unstable air brought heavy surf into the Port Heiden village of Meshik (Fathauer, 1978). Peak winds during this storm reached 30 to 45 knots over a 300-mile ice-free fetch that persisted for about 36 hours, and Meshik sustained moderate damage (Fathauer, 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).

SEAFLOOR HAZARDS

Current measurements, video scans, and seismic reflection profiles show that scouring and sediment transport is actively taking place in the Bristol Bay region along the north coast of the Alaska Peninsula (Hoose and Ashenfelter, 1983; Molnia and others, 1982; Molnia and Schwab, 1985). The seafloor is characterized by thousands of parallel, linear scours that are found in groups at water depths to 90 m or more (Marlow and Cooper, 1984; Molnia and others, 1982, 1983; Molnia and Schwab, 1985). The scours are up to 5 m deep, more than 300 m long, and range in width from a few meters to more than 250 m (Marlow and Cooper, 1984; Molnia and others, 1982, 1983; Molnia and Schwab, 1985). Hoose and Aschenfelter (1983) produced a Holocene isopach map revealing that the sediment distribution is current-controlled and that the current-related features, including ripple marks, sediment waves, and scour zones, generally occurred within 60 km of shore and in water depths of less than 70 m. Sediment transport in the basin area north of Port Moller has generated areas of mega-ripples and dunes that cover more than 1,500 km^2 (Molnia and Schwab, 1985). Wind-induced waves can move sediment in water depths of up to 100 m in the Bering Sea, where storms are frequent and the probability of storm waves several meters in height can exceed 20 percent in a year (Lisitsyn, 1969). The redistribution of large volumes of sediment in a short time by wave action presents a potential hazard to man-made structures in coastal areas and on the sea floor. Geophysical data examined by Molnia and others (1983) showed no evidence of submarine sliding or slumping, or surface pockmarks or craters.

Gas hydrates and gas-charged sediments are potential unevaluated hazards in the study area. Gas charged sediment has been reported in the Kodiak region and the Bering Sea (Cooper and others, 1980, 1984; Hampton and others, 1981; Marlow and others, 1976; 1979; 1980; Molnia and Schwab, 1985; von Huene and others, 1976), and gas hydrates are reported on the continental slope (MacLeod, 1982). Molnia and others (1983), however, saw no evidence in the geophysical data of the north Aleutian shelf for the existence of either. Potential hazards arising from gas hydrates and gas charged sediments are the reduction of strength and bearing capacity of seafloor sediments (Bruns and others, 1985).

SEA ICE

With more than 650 km of coastline in the study area, sea ice is a concern to coastal development. The southern Bering Sea has ice cover during 10–50 percent of the year, with maximum ice development in March and April (Lisitsyn, 1969; Marlow and Cooper, 1984; Marlow and others, 1980; McRoy and Goering, 1974). During this time the average ice thicknesses range from 1–1.5 m (Marlow and others, 1980). Both shorefast and mobile sea ice are present, with stationary shoreline ice up to 2 m thick extending as far as 80 km from land (Marlow and others, 1980). Ice gouging has been documented near shorelines where ice is thickest (Marlow and Cooper, 1984; Marlow and others, 1980), but the geophysical data set examined by Molnia and others (1983) showed no evidence of ice-related erosional features on the sea floor. An additional potential hazard to man-made structures is ice-ramming.

SNOW AVALANCHES

The northeastern part of the study area, approximately from Port Heiden east, 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). The snow pack is generally shallow to moderately deep (0.5–3.0 m) and is controlled by seasonal variation in solar input, leading to ice lenses and depth hoar near the ground-snow interface (Hackett and Santeford, 1980). The southwestern part of the study area is in the south-central snow-avalanche region. Predominant avalanche activity in this zone is characterized by major direct- and indirect-action loose snow and slabs, with highly dynamic dry and wet snow throughout the winter and spring and climax cycles in early spring (Hackett and Santeford, 1980). The snow pack is typically deep (1.0–5.0 m) and is controlled by noticeable variations of solar input, resulting in pervasive snow metamorphism throughout the snow season, much layering and variability with large vertical and horizontal changes, and thus a snow pack that is highly dynamic and generally unstable (Hackett and Santeford, 1980). Snow avalanche potential is moderate to high in the mountainous regions of the Aleutian Range, and limited in low-lying coastal areas (Hackett and Santeford, 1980). As defined by Hackett and Santeford (1980): Regions of high avalanche potential are where snow avalanches occur seasonally, and elevations above 3,000 m can expect potential activity throughout the year; regions of moderate potential have snow avalanches that occur less than once every 1–5 years or during winters with unseasonably heavy snowfall; and regions of limited potential contain no known snow-avalanche activity. Snow-avalanche risks can be mitigated by careful evaluation and avoidance of susceptible slopes, or appropriate engineering of structures that must be placed in avalanche zones. Avalanching from roofs in developed areas is an additional consideration.

PERMAFROST

Perennially frozen ground, or permafrost, exists where the ground temperature remains at or below freezing (32ºF or 0ºC) 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 45ºN in the northern hemisphere (Brown and others, 1997; Péwé, 1975, 1982). The northeastern part of 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, but the visible ground-ice content in the upper 10–20 m is considered low to medium, ranging from 0–20 percent by volume (Brown and others, 1997; Harris, 1986). 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 and others, 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.

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 are typically braided streams and include, from northeast to southwest: Naknek River above King Salmon; parts of upper and lower–middle King Salmon River draining into Egegik Bay; below Mother Goose Lake on another King Salmon River, this one draining into Ugashik Bay; Mud Creek on the flats north of Aniakchak volcano; Barabara, Birthday, and Reindeer creeks near the Port Heiden village of Meshik; the middle reach of Plenty Bear Creek on the northwestern slope of Aniakchak volcano; Fog Creek, Ocean River, lower Muddy River, along Sandy River, along Milky River, and along an unnamed tributary to Bear River on the northwest slope of Veniaminof volcano; and upper David River near Big Fish Lake, north-northeast of Pavlof volcano (Dean, 1984). These hazards are highly localized, however, and can be mitigated by careful evaluation and avoidance of susceptible areas.

CONCLUSIONS

Development on the northern coast of the Alaska Peninsula will be subject to potentially severe geologic hazards, including earthquake shaking, earthquake-induced ground failures, volcanic ash fall, volcanic flows, volcanogenic tsunamis, river and coastal floods, seafloor instability, sea ice, and snow avalanches. Additional hazards may include localized permafrost effects and minor stream icings. All structures should be built to exceed minimum requirements of the 1997 Uniform Building Code for seismic zone 3 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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