Seismic Hazard Considerations for Carbon Sequestration in Alaska

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BACKGROUND

Tectonic deformation in Alaska is driven by the subduction of the Pacific plate beneath the North American plate at the Alaska-Aleutian subduction zone (fig. 1). The Yakutat microplate, an accreted terrane (cross-hatched region in map view), complicates subduction by impinging on the North American plate and creating uplift and counterclockwise rotation of Southcentral Alaska. This tectonic regime gives rise to three main types of earthquakes (visible in cartoon cross-section): 1) interplate earthquakes at the subduction zone boundary, potential for great (M>8) earthquakes and tsunamigenesis; 2) intraplate outer rise and downgoing slab earthquakes within the subducting plate; 3) intraplate upper crustal, potentially surface-rupturing earthquakes. The A-A’ cross section from the Alaska Earthquake Center (AEC) shows the distribution of seismicity into earth’s interior (section line location is approximate).

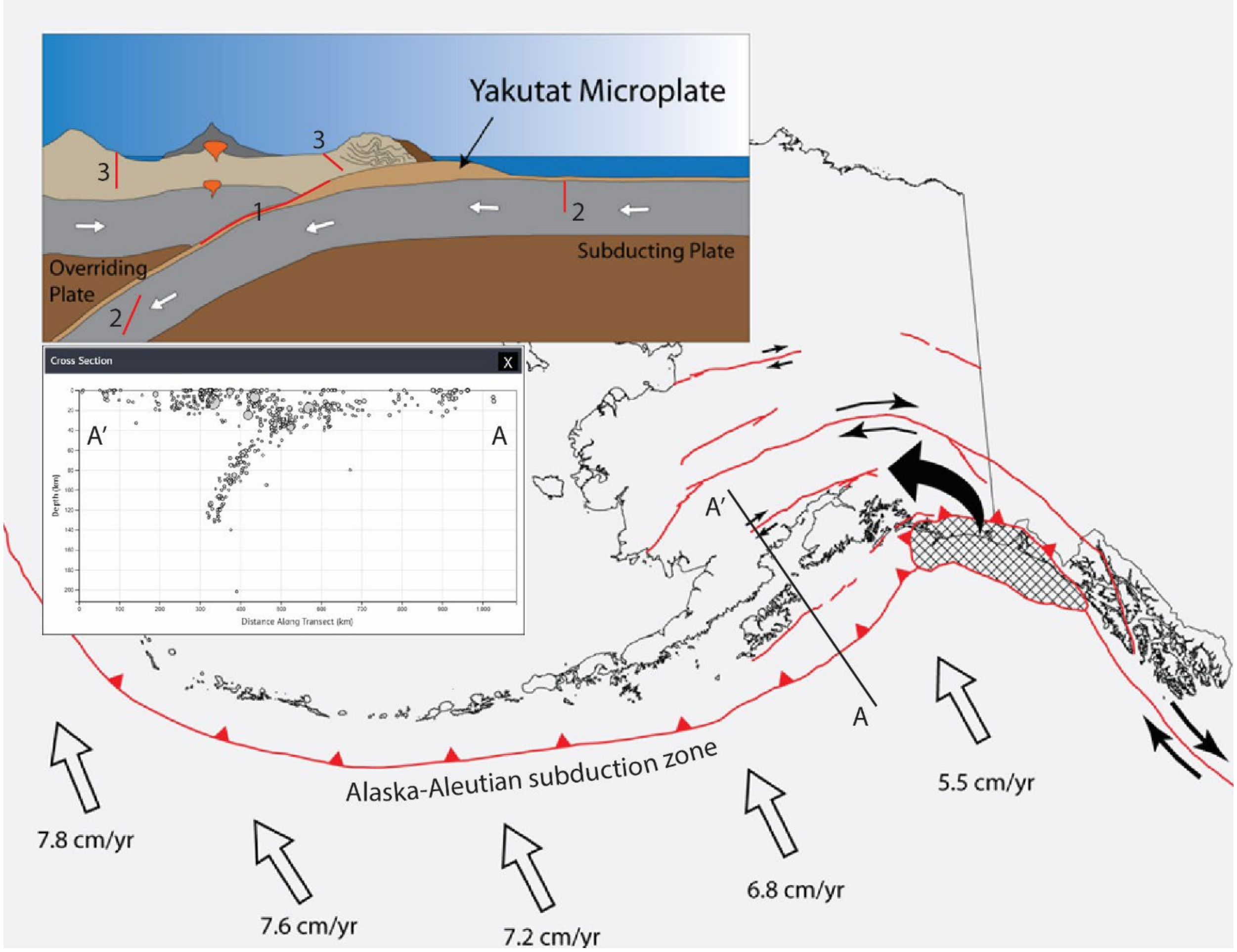


Figure 1 – Map view of major active faults in Alaska, including the Alaska-Aleutian subduction zone at the boundary between the Pacific and North American tectonic plates. The cartoon subduction zone cross section shows approximate source locations of the three types of earthquakes in Alaska. Pacific plate rates assume the North American plate is fixed.

Most of the Alaska-Aleutian subduction zone ruptured in a sequence of great earthquakes in the mid-20th century, the largest of which was the 1964 Mw 9.2 Great Alaska Earthquake. This earthquake ruptured ~800 km of the plate interface from the southwest edge of Kodiak Island to Cape Yakataga and is the second largest instrumentally recorded earthquake worldwide. Significant displacement on the megathrust caused severe shaking that lasted for more than 4 minutes, seafloor deformation that generated a trans-Pacific tsunami, multiple submarine and sub-aerial landslides that generated local tsunami events, and displacement on several upper crustal faults across the region.

True seismic hazard analyses include site-specific investigations and consider a wide range of factors including (but not limited to) the magnitude of an earthquake (including the hypocentral depth, sense of movement, fault orientation, amount of slip, and fault rupture propagation direction), the distance to the causative fault (including the nature of Earth's crust between the fault and site of interest), local soil conditions and hydrology, topography, proximity to water bodies that could sustain a tsunami or seiche, and the proximity to slopes that are prone to earthquake-triggered failure. As we are not able to predict the time and location of any earthquake, we rely on a probabilistic approach to classify statewide seismic hazards. Probabilistic seismic hazard assessments (PSHAs) are based on regional deformation rates and slip rates for individual faults (fig. 2), historical seismicity and effects of historical earthquakes (fig. 3), and paleoseismic data (the timing/recurrence of past earthquakes). All these data are combined to generate a model of all potential future earthquakes and the PSHA maps (fig. 4) depict the expectation for damaging shaking from all possible earthquakes in the next 10,000 years.

Figure 2 depicts the known, Quaternary-active earthquake-producing faults in Alaska. For engineering geologic applications, a fault is classified as “active” and is interpreted to have the potential to generate future earthquakes if it has ruptured during the Holocene (the last 11,000 years). However, for some critical infrastructure (e.g., nuclear power plants) longer timeframes are used to define whether a fault is active. Known Quaternary-active faults in the current database are colored by recency of movement.

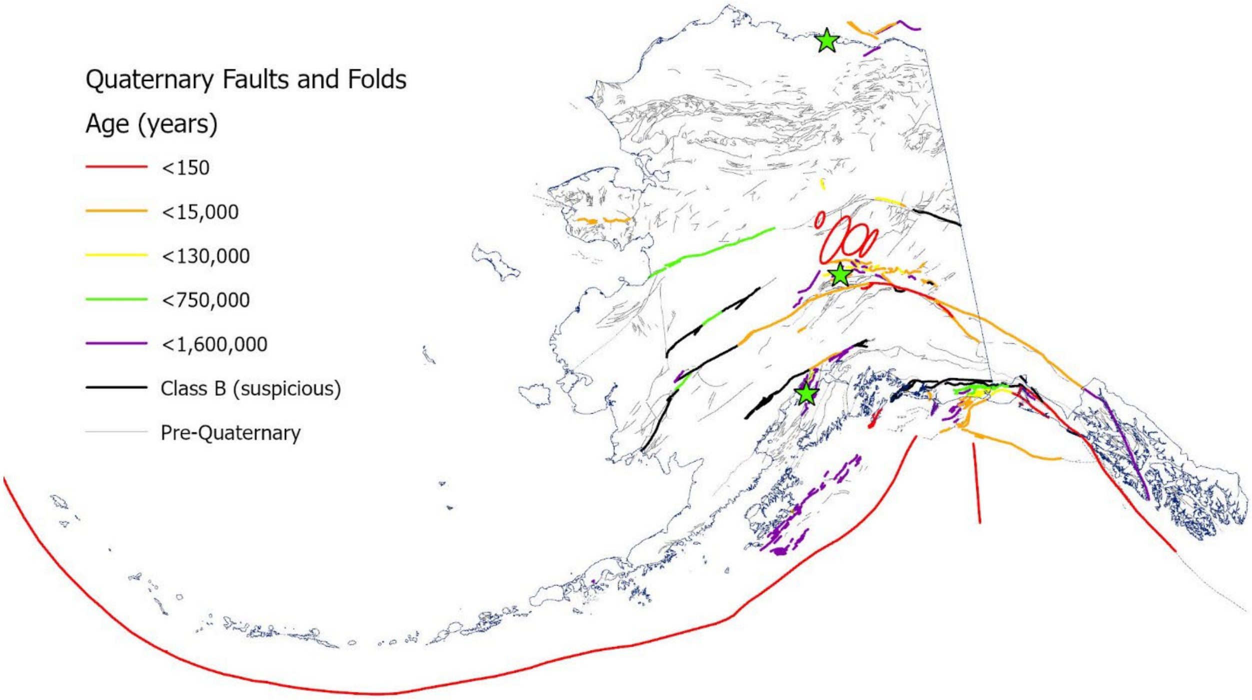


Figure 2 – Quaternary Fault and Fold database from the AK Div. of Geological & Geophysical Surveys, including both Quaternary and Pre-Quaternary faults, from: Koehler, R.D., 2013, Quaternary Faults and Folds (QFF): Alaska Division of Geological & Geophysical Surveys Digital Data Series 3, https://doi.org/10.14509/24956, a digitized version of the Neotectonic map of Alaska from Plafker and others, 1994. Green stars indicate potential carbon sequestration sites.

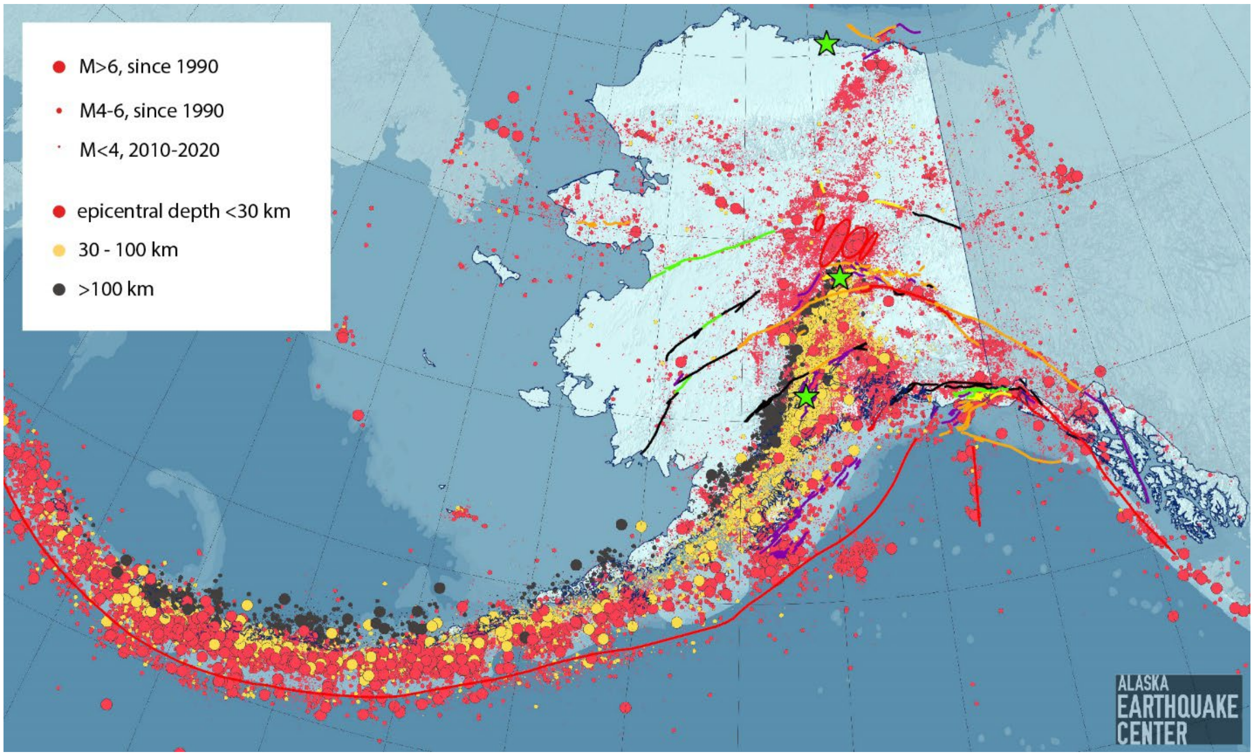


Figure 3 – Historical statewide seismicity from the Alaska Earthquake Center, University of Alaska, Fairbanks. Epicenters are depicted according to earthquake magnitude (circle size) and hypocentral depth (circle color). The increasing hypocentral depths from south to north across the Alaska-Aleutian subduction zone represent earthquakes within the downgoing Pacific plate as it subducts beneath the North American plate. Refer to figure 1 for a cross section.

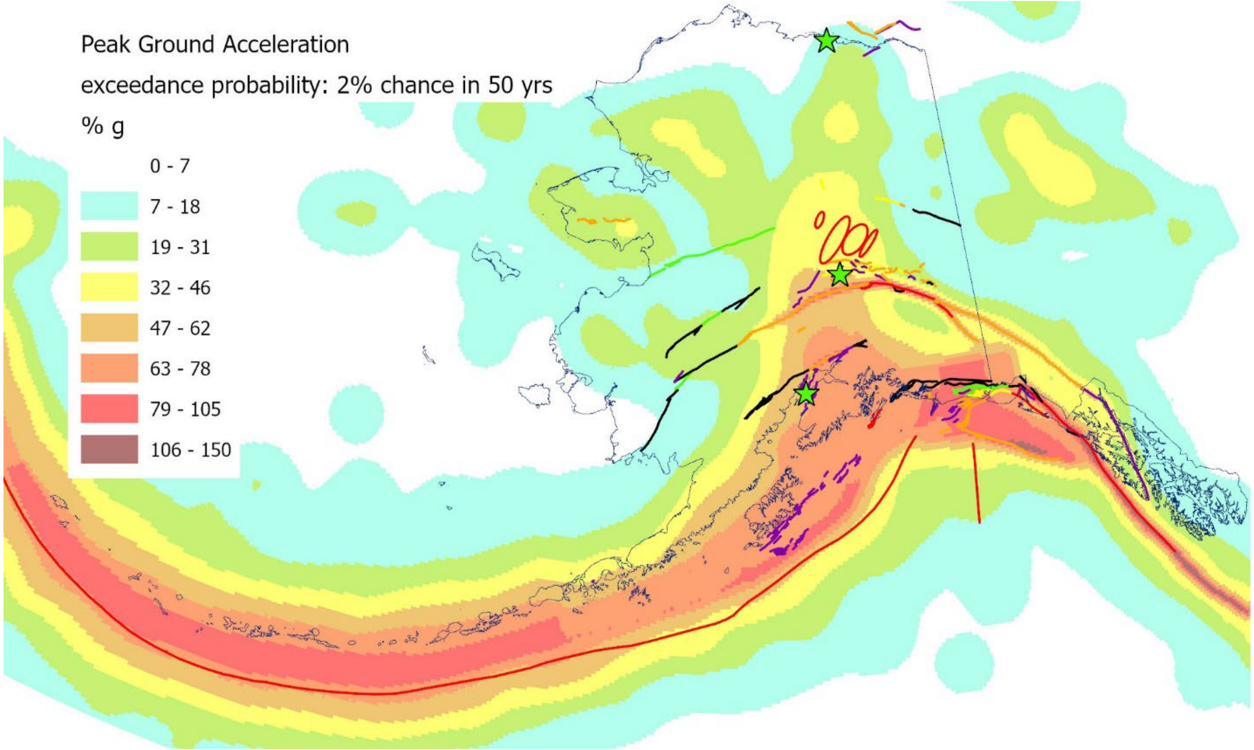
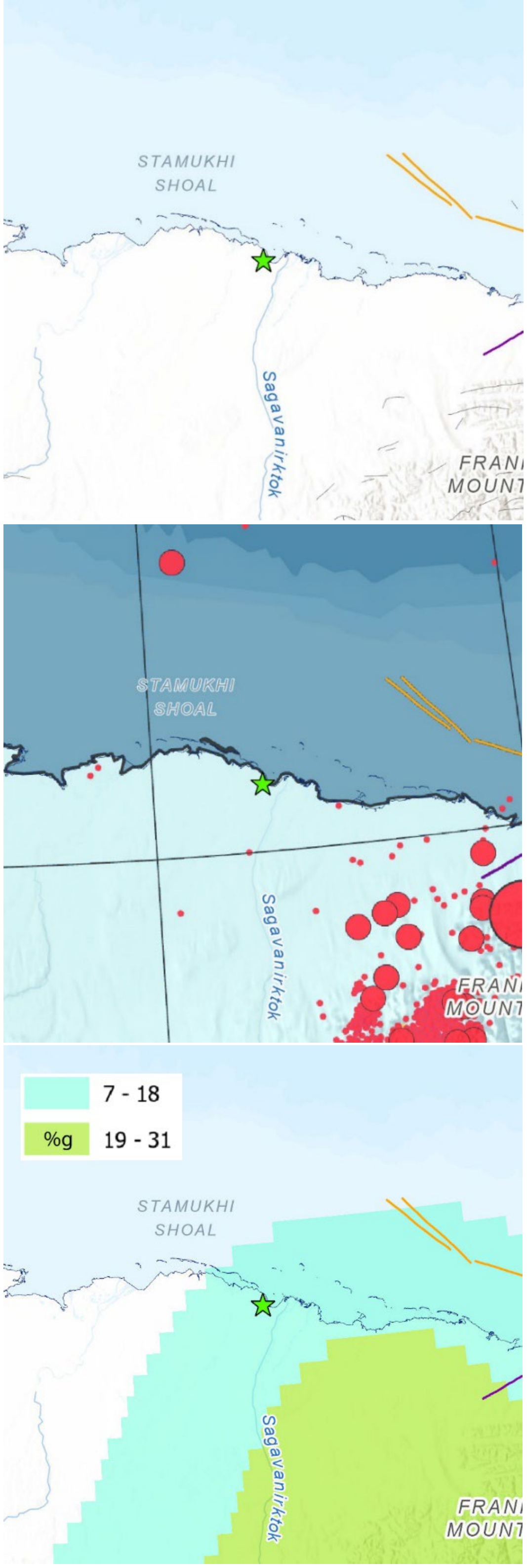


Figure 4 – Time-independent statewide Probabilistic Seismic Hazard Assessment from the United States Geological Survey (10.3133/ofr20071043). Colors represent the ground shaking intensity (in this case peak ground acceleration) measured as a percentage of the acceleration due to gravity with a 2% chance of being exceeded in the next 50 years. A 2% chance in 50 years is an annual probability of 0.0404%, or an earthquake with a return period of roughly 2,500 years. For reference, the 2018 M7.1 Anchorage earthquake produced peak ground accelerations in Anchorage between 20 and 30 %g, with the highest PGA value of 47.4 %g in the midtown section of Anchorage.

The peak anticipated ground accelerations shown in Figure 4 are just one of many data products produced by PSHAs. Importantly, though, these maps show the general earthquake hazard in an area, but they are not depictions of earthquake risk (where risk is the potential that exposure to an earthquake hazard will lead to a loss of life or economic loss). To understand risk in an area, information about buildings, infrastructure, site-specific conditions, and/or people is also needed.

The subsequent three sections will focus on the three proposed carbon sequestration sites, each with a neotectonic summary and three figures that show site: 1) proximity to known active faults/folds from the Quaternary Fault and Fold Database (QFF); 2) regional historical seismicity where red = shallow, yellow = intermediate, and black = deep earthquake source regions; and 3) peak ground acceleration with an exceedance probability of 2% in 50 years. The final page provides more generalized summaries of earthquake hazards in each region.

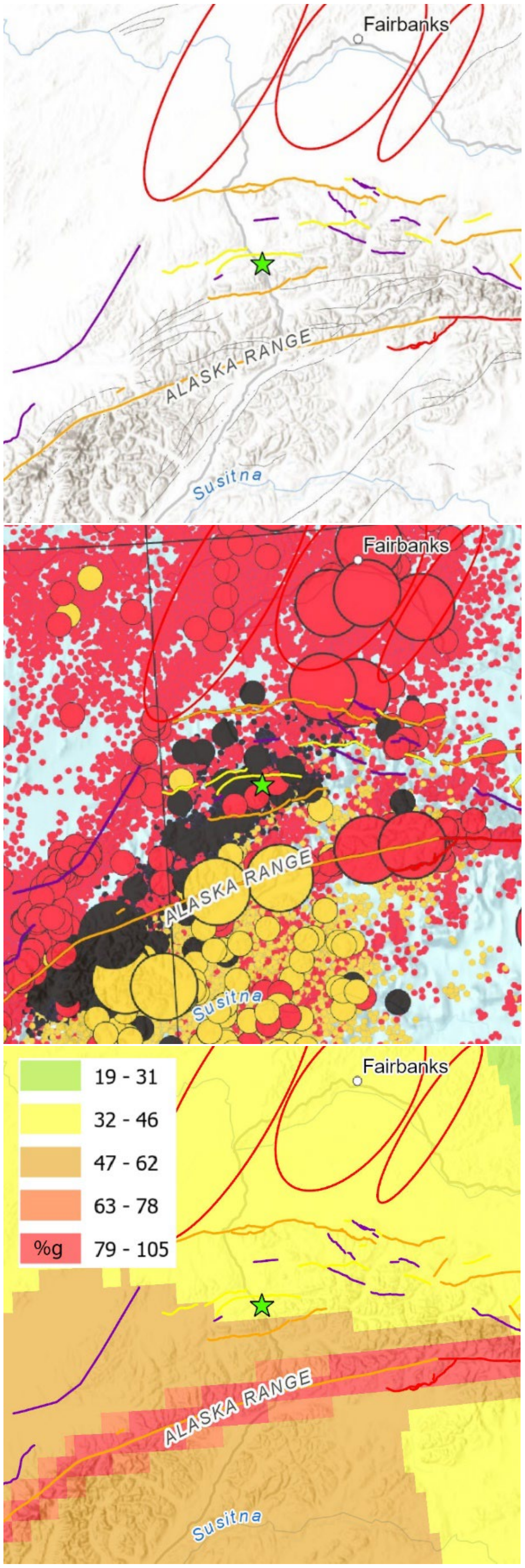


NEOTECTONIC SUMMARIES

Italicized text is paraphrased from Koehler, R.D., Carver, G.A., and Alaska Seismic Hazards Safety Commission, 2018, Active faults and seismic hazards in Alaska: Alaska Division of Geological & Geophysical Surveys Miscellaneous Publication 160, 59p. https://doi.org/10.14509/29705

NORTHERN ALASKA AND BROOKS RANGE SOURCE REGION

Intraplate earthquakes in the northern Alaska and Brooks Range source region are associated with the Brooks Range orogen, gravitational deformation of thick sedimentary sequences, and crustal reorganization. The northwestern part of this source region is relatively aseismic, however the general lack of detectable earthquakes is likely a product of minimal instrumentation and does not necessarily indicate an absence of active faults. The northeastern part of the source region contains a broad earthquake band, extending from the Brooks Range toward the Beaufort Sea, which has been associated with more than 20 historical earthquakes of M 4.0–5.3 with focal mechanisms that indicate strike-slip and normal faulting events indicative of north–northwest compression and northeast extension. In the Brooks Range itself, more than 70 moderate earthquakes of M 4.0–5.7 and four M > 5.0 shallow earthquakes have occurred over the last 60 years. Earthquake swarms along the southern margin of the Brooks Range, which include more than 20 moderate earthquakes ~M 4 in 1989 (AEC, 2016) and four moderate events in October 1980 (Gedney and Marshall, 1981), suggest that this region may be capable of generating a larger earthquake. No major or great earthquakes have been recorded in northern Alaska. Even with this seismic activity, only the Kobuk fault along the south side of the Brooks Range northwest of Bettles, faults in the Camden Bay area, and the Marsh Creek anticline have been inferred to be active in the Quaternary Period (Plafker and others, 1994).



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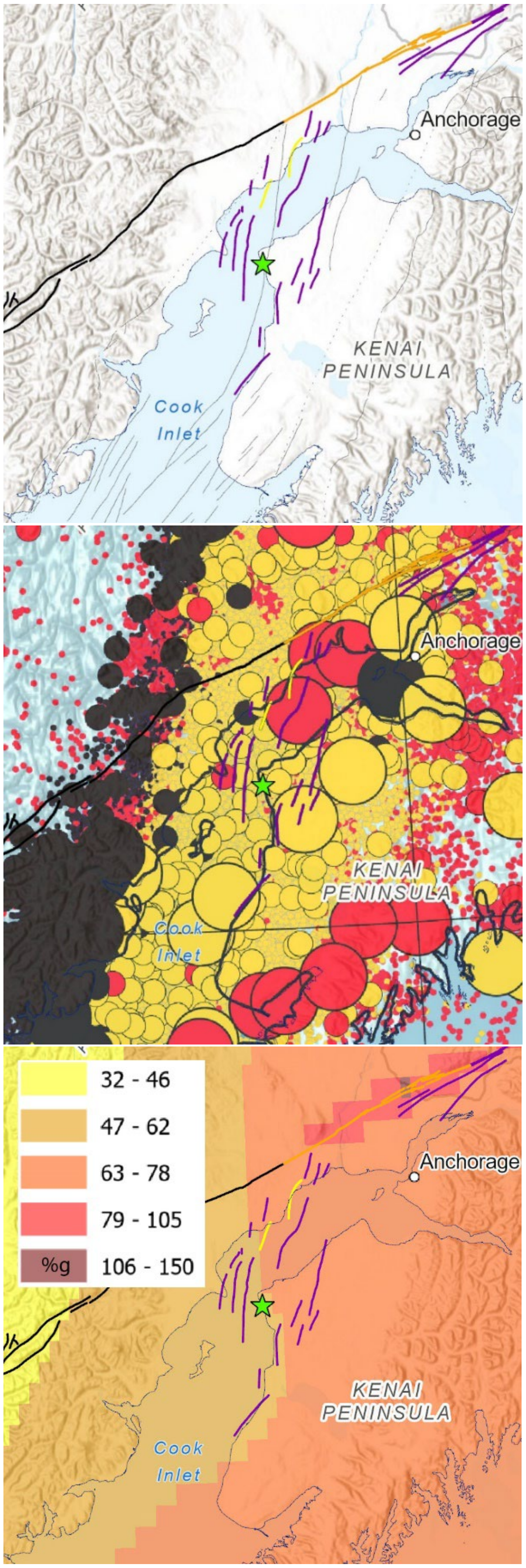
DENALI AND NORTHERN ALASKA RANGE SOURCE REGION

The transpressional right-lateral Denali fault system extends over 2,000 km (~1,250 mi) in a northward convex arc from Goodnews Bay on the Bering Sea to Chatham Strait in southeastern Alaska, including ~500 km (310 mi) along the arcuate southern margin of the Alaska Range (St. Amand, 1957; Grantz, 1966; Richter and Matson, 1971; Plafker and others, 1977, 1994). The fault was the source of the 2002 Mw 7.9 Denali fault earthquake, one of the seven largest continental strike-slip earthquakes since 1900 (Schwartz, 2006), which ruptured 340 km (211 mi) along the Susitna Glacier thrust, Denali fault, and Totschunda fault with average displacements of 4–5 m (13–16 ft) (Eberhart-Phillips and others, 2003; Haeussler and others, 2004).

Along the northern flank of the Alaska Range north of the Denali fault, a system of imbricate thrust faults, the Northern Foothills fold-and-thrust belt (NFFTB), extends over 500 km (310 mi) from Denali to the Tok River valley. These faults have uplifted and warped the Plio–Pleistocene Nenana Gravel and glacial deposits, forming a series of anticlines and synclines along the northern foothills of the Alaska Range (Péwé and others, 1966; Wahrhaftig, 1958). Geomatrix Consultants (1997) and Hanson and others (2002) interpreted the system as a fold-and-thrust belt and Bemis and others (2012) divided it into the Kantishna Hills, western, and eastern sections based on differences in structural style (Bemis and others, 2012). A M 7.2 event occurred in 1947 at the front edge of the northern foothills of the Alaska Range. Although the source mechanism of this event is poorly constrained, observations from modern seismicity are consistent with ongoing thrust deformation on the north side of the central Alaska Range.

In the general vicinity of Fairbanks, a series of north–northeast-trending left-lateral strike-slip seismic zones including the Dall City, Rampart, Minto Flats, Fairbanks, and Salcha seismic zones have been the source of numerous felt earthquakes and all have produced M ≥ 6 shocks.



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COOK INLET SOURCE REGION

Seismic sources within the Cook Inlet forearc basin are associated with the Cook Inlet fold belt and include numerous north–northeast-trending, discontinuous, asymmetric folds that are cored by blind reverse faults (purple lines at left). The location and extent of these structures has been interpreted primarily from proprietary seismic reflection data, structure contour maps, cross sections, and aeromagnetic data (Haeussler and Saltus, 2011, Haeussler and others, 2000; Magoon and others, 1976; fig. 9 in Magoon, 1994; Boss and others, 1976; Kirschner and Lyon, 1973). Numerous structures that have displaced Tertiary sediments are present in the southern part of the inlet in the vicinity of Homer and Augustine Volcano (Haeussler and Saltus, 2011); however, their Quaternary activity and seismic potential is poorly constrained.

Quaternary activity is inferred for many of the anticlines in the northern part of the basin based on deformed Plio– Pleistocene sediments offshore and deflection of rivers around topographic highs on land (Haeussler and others, 2000; Kelley, 1961). These structures range in length from 3 to 85 km (2–53 mi), and are optimally oriented in the modern stress field to generate moderate to large (M 6–7) earthquakes (Haeussler and others, 2000; Haeussler, 2008; Bruhn and Haeussler, 2006).

Due to the location of the structures on the sea floor and the poor resolution of Holocene sediments in seismic reflection and well data, earthquake timing and recurrence data do not exist for the Cook Inlet fold belt and slip rate data are only available for several structures. Given the evidence for Quaternary motion and diffuse low-level seismicity, Koehler and others (2012) assigned a poorly constrained slip rate of <0.2 mm/yr (<0.01 in/yr) for the majority of the Cook Inlet structures.

PLAIN LANGUAGE SUMMARIES

North Slope

The North Slope site is the least instrumented and least studied of the three. The nearest known Quaternary-active faults and folds are the Camden Bay faults (~80 km to the east-northeast) and the Marsh Creek Anticline (~120 km east-southeast), though this is likely due to the remote, uninhabited, (and until recently) uninstrumented nature of the North Slope. Ongoing earthquakes in the region are intraplate, upper crustal earthquakes that are likely driven by deformation associated with subduction of the Pacific plate at the Alaska-Aleutian subduction zone. The Alaska Earthquake Center detects a magnitude 5 earthquake in this region every ~8 years, but by far the largest event in the region was the 2018 M6.4 Kaktovik earthquake—an event that was nearly large enough to rupture to the surface. The biggest concern here is a rare, surface-rupturing earthquake (M>6.5) that would not only cause strong ground shaking, but potentially discrete offsets in the uppermost ~10 km of earth's crust. It is reasonable that this type of event could occur on a previously unmapped fault. Relatively speaking, deformation rates here are slow and the probabilistic seismic hazard is low (peak ground accelerations of 7-18 %g expected with a 2% in 50-year exceedance probability).

Healy

The Healy site is in an area of moderately high seismic activity, directly within the Northern Foothills Fold and Thrust Belt (NFFTB). These shallow, overlapping thrust faults can produce M6-7, surface rupturing events. Though individual fault slip rates are only millimeters per year, the area is poorly studied, and we have relatively little understanding of earthquake histories in the area. The closest Quaternary-active structure is the Healy fault, with surface expression ~500 m from the proposed sequestration site. In addition to many other thrust structures in this belt, the Denali fault, which produced a M7.9 strike-slip rupture in 2002, is only 45 km to the south. Ongoing earthquakes in the area are associated with the upper crustal, potentially surface-rupturing thrust faults of the NFFTB (including a notable M7.2 in 1947), potential surface-rupture of the Denali fault, intermediate-depth earthquakes occurring within the downgoing Pacific plate, and rupture of previously unrecognized surficial faults. Probabilistic seismic hazard here is moderately high, with peak ground accelerations of 30-60 %g at 2% chance in 50 years.

Cook Inlet

The Cook Inlet site has the highest probabilistic seismic hazard of all proposed locations, located within the Cook Inlet forearc fold belt above the Alaska-Aleutian subduction zone. The nearest Quaternary-active structures are multiple north-northeast striking fault-cored folds capable of producing M6-7 earthquakes. However, rupture of these fault cores would likely be blind, meaning that they do not rupture through to the surface but rather cause growth of existing anticlines in the form of broad warping of the seafloor. The surface-rupturing Castle Mountain fault is ~75 km to the northeast, the Alaska-Aleutian subduction zone trench is 350 km to the southeast, and intraplate earthquakes in the downgoing Pacific Plate all contribute to seismic hazard in the region. Probabilistic seismic hazard here is relatively extreme given the proximity to the subduction zone. Potential peak ground accelerations (2% chance in 50 years) exceed 100% g.

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