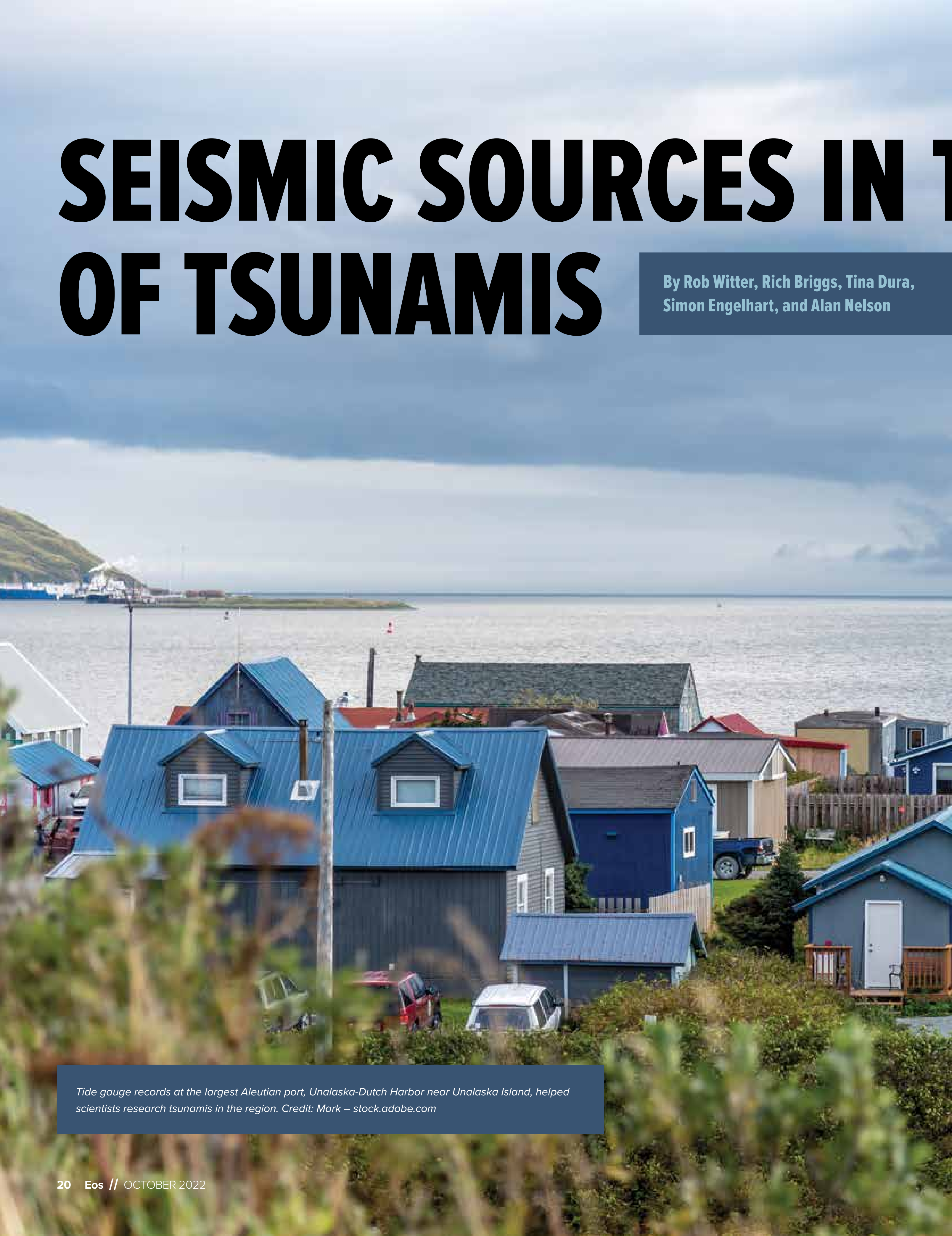
SEISMIC SOURCES IN T
OF TSUNAMIS

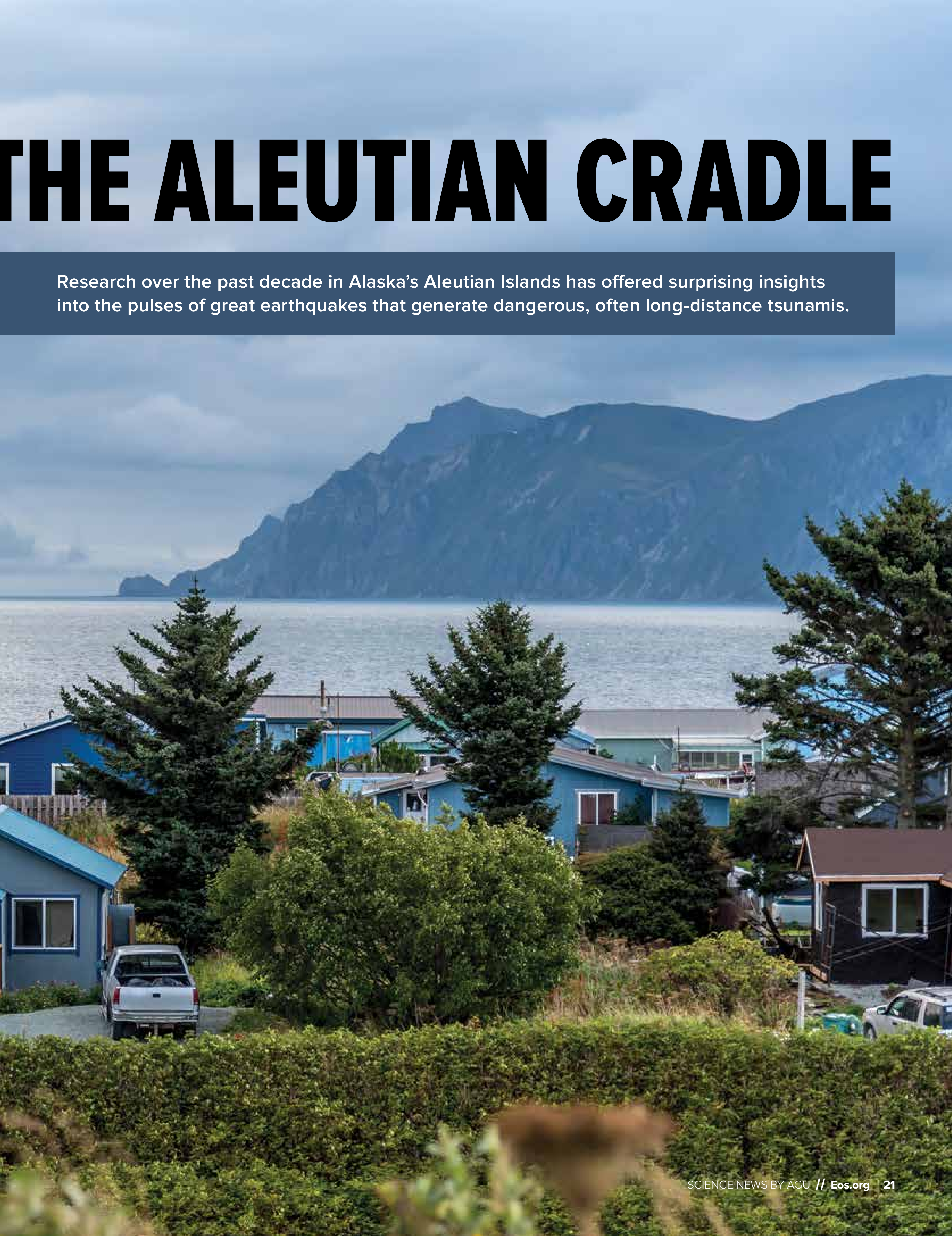
By Rob Witter, Rich Briggs, Tina Dura, Simon Engelhart, and Alan Nelson



Tide gauge records at the largest Aleutian port, Unalaska-Dutch Harbor near Unalaska Island, helped scientists research tsunamis in the region. Credit: Mark – stock.adobe.com

THE ALEUTIAN CRADLE

Research over the past decade in Alaska's Aleutian Islands has offered surprising insights into the pulses of great earthquakes that generate dangerous, often long-distance tsunamis.



Between 1938 and 1965, nearly the entire 3,300-kilometer length of the Alaska-Aleutian subduction zone ruptured in a sequence of powerful, tsunami-generating earthquakes. For example, the moment magnitude (M_w) 8.6 Unimak Island earthquake in 1946 heaved up the seafloor, generating a tsunami that reached 42 meters in height. This wave destroyed the Scotch Cap lighthouse on nearby Unimak Island, Alaska, and killed 159 people in Hawaii, 3,750 kilometers away. The unexpectedly distant and fatal consequences of the 1946 tsunami instigated the formation of the U.S. Tsunami Warning System.

PROVIDING HAZARD FORECASTS IS CRUCIAL CONSIDERING THAT ALASKAN TSUNAMIS ENDANGER COASTAL COMMUNITIES AROUND THE PACIFIC RIM, INCLUDING DENSELY POPULATED PARTS OF SOUTHERN CALIFORNIA AND THE SHORELINES OF HAWAII.

Subduction zones around the world continue to surprise: For example, the 2010 M_w 7.8 Mentawai earthquake caught the world off guard because it broke the shallow portion of the Sunda megathrust fault directly above a larger rupture in 2007 and because it triggered an unexpectedly large tsunami for the size of the earthquake. A year later came an even bigger surprise: Japanese officials did not anticipate the scale and devastating impacts of the 2011 M_w 9.1 Tōhoku earthquake, or of the resulting tsunami and meltdowns at the Fukushima nuclear power plant, which together constitute the most financially costly disaster in human history. At the time, earthquake and tsunami hazard assessments in Japan relied primarily on instrumental records and written documents from time spans far shorter than the recurrence intervals (time elapsed between major events) of extreme earthquakes and tsunamis, which can span several centuries [*Sawai*, 2020]. The 2011 earthquake illustrated starkly that brief historical records alone are inadequate indicators of potential future fault behavior.

Similarly, the single century of instrumentally recorded great ($M_w > 8$) Alaska-Aleutian earthquakes is too short a period on which to base forecasts of these earthquakes and their accompanying tsunamis in the future. Yet providing hazard forecasts is crucial considering that Alaskan tsunamis endanger coastal communities around the Pacific Rim, including densely populated parts of Southern California and the shorelines of Hawaii [*Dura et al.*, 2021; *La Selle et al.*, 2020].

So how can we get better at preventing future disasters by anticipating and mitigating the impacts of tsunamigenic earthquakes? The answer involves digging into the coastal stratigraphic record to extend our knowledge of great earthquakes and tsunamis farther back in time.

CLUES FROM PAST EARTHQUAKES

Subduction megathrusts—huge, gently dipping reverse faults that form where one tectonic plate dives below another—extend from deep-sea trenches to hundreds of kilometers beneath overlying islands or continents. Coastlines along subduction margins above megathrusts are the most accessible places to search for evidence of prehistoric subduction zone earthquakes and tsunamis.

Such evidence includes signs of sudden land uplift or subsidence caused by earthquake deformation, of scoured landforms and layered sand deposits left behind by tsunami inundations, and of landslides or underwater slumps triggered by strong shaking. The timing and pace of past events can be estimated with dating methods, like radiocarbon analyses of spruce needles or fragments of salmon vertebrae. Altogether, paleoseismic observations narrate the history of past earthquakes—their location, size, and recurrence—and validate geophysical models that simulate earthquake rupture and tsunami inundation.

From 2010 to 2021, we conducted paleoseismic studies by excavating, describing, and sampling Holocene sediments in coastal environments at 16 sites spanning 1,800 kilometers between the Fox Islands and

Clues to a history of eight Aleutian tsunamis in the past 2,000 years lie beneath the coastal lowlands of Driftwood Bay on Umnak Island, part of the Fox Islands of Alaska. Credit: USGS

Prince William Sound (Figure 1). These studies have helped reveal the long-term earthquake and tsunami potential of the eastern Aleutian megathrust. We discovered that great Aleutian earthquakes—and their towering tsunamis—have occurred more frequently than is accounted for in current seismic hazard assessments for Alaska.

Our research suggests that the upper (North American) and lower (Pacific) plates are presently locked at various locations along the megathrust, but earthquake rupture behavior at these locations varies over timescales that greatly exceed the quarter-century-or-shorter duration of space geodetic (i.e., Global Navigation Satellite System (GNSS)) data sets. Our observations also imply a prevalence of shallow megathrust earthquake ruptures near the seafloor that tend to generate high tsunamis, as well as complex, long-term patterns of ruptures whose boundaries vary from one earthquake to the next.

SLEUTHING A CASE FROM 1788

Historical clues about pre-20th-century Aleutian earthquakes and tsunamis are sketchy. For example, anecdotal evidence of a great earthquake and tsunami in 1788 exists in written accounts of flooding at Russian settlements at Sanak Island and at Three Saints Bay on Kodiak Island [*Lander*, 1996]. The accounts describe earthquake shaking that rattled the region between these islands and a tsunami that towered at least 30 meters above

Fig. 1. Paleoseismic sites (colored dots) investigated in the eastern Alaska-Aleutian subduction zone since 2010 are superimposed on aftershock regions (red shading; data from Tape and Lomax *[2022]) showing the spatial extent of a sequence of 20th-century earthquakes that unzipped the megathrust. The arrow indicates the section of the subduction zone discussed in the text and the rate (70 millimeters per year) and direction of Pacific Plate motion.*

HISTORICAL CLUES ABOUT PRE-20TH-CENTURY ALEUTIAN EARTHQUAKES AND TSUNAMIS ARE SKETCHY.

Aleutian shorelines. If the accounts are accurate, the 1788 earthquake would be the largest known event to have affected this stretch of the subduction zone.

Seeking evidence of the 1788 tsunami as well as earlier events, we visited the possible western end of the earthquake rupture at Sanak Island (Figure 1), where Russian church books recount a terrible flood that year [*Lander*, 1996]. However, our investigations of the geology at the coastal sites indicated in the accounts did not confirm evidence of tsunami flooding in 1788. Instead, we found evidence on Sanak of the 1946 Unimak Island earthquake and tsunami, along with four older sand sheets deposited between 2,000 and 4,200 years ago. Despite a continuous sedimentary record, the 2,000-year hiatus in tsunamis prior to the 1946 event casts doubt on the veracity of the written accounts of the 1788 tsunami near Sanak Island. The discrepancy between the geologic record on Sanak and accounts of the 1788 tsunami remains a mystery.

Northeast of Sanak, in the Shumagin Islands, Russian documents recount "a terrible inundation on Unga Island in which many Aleuts perished but God spared the Russians." We investigated three islands in the Shumagins (Figure 1). On one island, we identified a few thin (<1-centimeter-thick) sand sheets in coastal deposits below high tide that probably record storms or low tsunamis that occurred within the past few thousand years. These waves were likely similar to the small (<1.2-meter) tsunamis generated by the July–October 2020 earthquake sequence, which saw moment magnitudes of up to 7.8. Otherwise, we found no evidence for high tsunamis or earthquake-related land level changes, casting further doubt on the idea that the Sanak-Shumagin region marked the western terminus of a great 1788 rupture as suggested by the historical accounts [*Witter et al.*, 2014].

GAPS IN THE SEISMIC GAP HYPOTHESIS

Until the 2020 M_w 7.8 Simeonof earthquake, the Shumagin section of the Aleutian megathrust, unlike adjacent sections of the subduction zone, had not ruptured historically. The Shumagin seismic gap, labeled by seismologists in the 1970s (Figure 1), has been expected to release its accumulated strain and break in a great earthquake similar to the 1938 M_w 8.2 and 1946 M_w 8.6 ruptures. To date, however, no M_w 8 or larger earthquake,

Researchers (nearest to furthest) Simon Engelhart, Peter Haeussler, Tina Dura, Rich Koehler, and Rich Briggs climb a slope above Larsen Bay on Nagai Island in the Shumagin Archipelago, Alaska, during a field expedition to explore for evidence of past great earthquakes and high tsunamis. Credit: USGS

not even the Simeonof event, has filled the gap. What about in the geologic past?

GNSS measurements of the movement of the Alaska Peninsula and adjacent islands indicate that both large earthquakes (M_W 7–8) and gradual creep accommodate substantial plate convergence in the Shumagin gap. Creep describes the process in which converging plates slide past each other without locking, thereby reducing the buildup of elastic strain. Even though creep is considered an aseismic process, it is usually accompanied by moderate-magnitude earthquakes.

We found that great earthquakes and high tsunamis have not occurred in the Shumagin seismic gap over the past 3,400 years, suggesting, surprisingly, that great earthquakes may be extremely rare in the Shumagin gap, where creep has persisted for thousands of years [*Witter et al.*, 2014].

RUPTURING HISTORIC BARRIERS

Farther east, the Semidi Islands and Kodiak sections of the megathrust behave very differently than those from the creeping Shumagin section do. The Semidi section is firmly locked: Stress builds on the fault until an earthquake releases it. Here, our paleoseismic work (Figure 1) corroborated Russian accounts of the 1788 earthquake and tsunami. For example, on Chirikof Island, a stack of thin sand beds within 3–4 meters of radiocarbon-dated peat implies a recurrence interval for high tsunamis of just 180–270 years over the past 3,500 years, including the 1788 event [*Nelson et al.*, 2015]. And at Sitkinak Island, located at the southern end of Kodiak Island, we found stratigraphic evidence of sudden uplift of the island and tsunami inundation, consistent with Russian accounts of an earthquake and tsunami in 1788 [*Briggs et al.*, 2014].

Sitkinak Island also preserves clues that help define the western end of the 1964 M_W 9.2 Great Alaska Earthquake. Here, we investigated tidal exposures of peat and mud beds that contain evidence, in the form of fossil organisms too small to see with the naked eye, for five episodes of land level change accompanying earthquakes in the past 1,050 years [*Briggs et al.*, 2014]. We also tracked six continuous sand beds between 0.9 and 1.5 kilometers inland and described sedimentary properties consistent with tsunami deposits. Our field and lab findings add to a growing paleoseismic data set showing that the Kodiak section of the megathrust ruptures every 300–380 years, on average, about twice as frequently as the Prince William Sound section to the east, although both sections failed in the 1964 earthquake.

Sitkinak Island's prehistoric record suggests that the western boundary of the 1964 rupture has not been a persistent feature of the megathrust over time. The fossil organisms we studied on Sitkinak indicate that in 1964, parts of the island that had been high marsh environments suddenly subsided and became low marsh or tidal flat environments, consistent with the island's location near the western rupture boundary. However, they also indicated that the island jerked upward in the 1788 event and in older earthquakes, which implies that during these earlier events the megathrust ruptured through the 1964 boundary. Our findings, which could portend how future earthquakes will behave, will be incorporated into the 2023 update of the National Seismic Hazard Map for Alaska, which will be used, among other purposes, to improve seismic building codes.

DANGEROUS AND DIFFICULT TO DECIPHER

Some earthquakes generate much larger tsunamis than would be expected from their magnitude. Shallow earthquakes (<15-kilometer depth) with slow rupture speeds along the uppermost part of a megathrust typically produce large tsunamis because they cause large seafloor displacements in deep water. The 1946 Unimak Island earthquake is a prime example of a tsunami earthquake [*Okal and Hébert*, 2007]. Have similar earthquakes occurred elsewhere in the Aleutians?

We investigated two bays in the Fox Islands (Figure 1), located directly west of the rupture area of the 1946 earthquake, where evidence of frequent great earthquakes and unusually high tsunamis is recorded [*Witter et al.*, 2016, 2019]. Both bays face the Aleutian trench, like baseball catcher's mitts, at the eastern end of the rupture of the 1957 M_W 8.6 Andreanof Islands earthquake. Drift logs stranded inland 18–23 meters above sea level on these treeless islands, along with sheets of nearshore marine sand, record the 1957 tsunami at both sites.

Earthquake and tsunami computer simulations help us explore the nature and variability of past Aleutian tsunamis. But tsunami modeling using initial estimates of the megathrust slip that occurred in the 1957 earthquake failed to re-create conditions that account for two important observations: tide gauge records at the largest Aleutian port, Dutch Harbor, and the stranded drift logs along the islands' Pacific coasts [*Nicolsky et al.*, 2016].

Further testing demonstrated that the tsunami model that best matched the constraints posed by tide gauge records and drift log locations required a shallow (5- to 15-kilometer-depth) rupture with 20 meters of average slip and a M_w approaching 9 [*Nicolsky et al.*, 2016]. The long-term tsunami record we gleaned from the Fox Islands points to previous tsunami earthquakes that affected the area, but not all of the events mimicked the 1957 rupture. Together the Fox Island sites record nine tsunamis over the past 2,200 years with a 160- to 260-year recurrence interval—much shorter than recurrence estimates used in previous Aleutian seismic hazard assessments.

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PACIFIC-WIDE IMPACTS OF RECURRING WAVES

Underestimating the frequency of tsunamis that originate in the Aleutian Islands raises concerns about safety, not only for Alaskans but also for coastal communities thousands of kilometers away. The far reach of Aleutian tsunamis was seen during the 1964 Great Alaska Earthquake, which caused deaths and damage as far away as Crescent City, Calif. And it is evident in coastal wetlands and lagoons of Hawaii, which archive marine sand sheets deposited by Alaska-sourced tsunami waves in historic and prehistoric times [*La Selle et al.*, 2020]. Sand sheets on the islands of Hawaii, Oahu, and Kauai, dated by cesium and radiocarbon methods, chronicle inundation by Aleutian tsunamis in 1957 and 1946 and during a larger event sometime between 1350 and 1450.

Climate change may exacerbate Aleutian tsunami hazards. For example, the ripple effects of sea level rise over the next century will expose the ports of Los Angeles and Long Beach in Southern California to higher wave heights from tsunamis generated by Alaskan earthquakes [*Dura et al.*, 2021]. Worst-case predictions of sea level rise from the Intergovernmental Panel on Climate Change indicate that by 2100, M_w 8.0 earthquakes along the Alaska-Aleutian subduction zone could produce tsunamis with maximum nearshore heights of more than 1 meter at Southern California ports. Earthquakes of this magnitude are about 6.7 times more likely to occur along the Alaska-Aleutian subduction zone than the M_w 9.1 earthquakes required to produce such tsunamis with present-day sea level.

SEISMIC STUDIES FOR SAFER COMMUNITIES

The long-term record of seismic activity along the Alaska-Aleutian subduction zone that we are helping assemble has shown that this cradle of Pacific tsunamis launches dangerous waves every 60–90 years, on average. The sequence of great earthquakes from 1946 to 1965 alone generated four transpacific tsunamis—and more such ruptures are likely to occur in the 21st century.

The past decade of earthquake and tsunami research along the Alaska-Aleutian subduction zone conducted by us and by others can help bolster societal resilience and reduce losses in future events by providing updated

Researchers (left to right) Andrew Kemp, Peter Haeussler, and Alan Nelson examine salt marsh beds in a tidal outcrop on Sitkinak Island, Alaska. These beds provide evidence of earthquake-induced changes in land level, including coastal uplift during the 1788 earthquake. Credit: USGS input to strengthen hazard assessments, including the U.S. Geological Survey's 2023 National Seismic Hazard Map for Alaska. Seismic safety codes adopted by the state based on earlier seismic hazard assessments likely explain the relative resilience of the built environment to strong ground motions during the 2018 M_w 7.1 Anchorage earthquake. This work also supports more accurate inundation scenarios that aid in delineating tsunami evacuation zones and improve public safety.

There are several as-yet-unexplored frontiers for Alaska-Aleutian paleoseismic research, including the western Aleutians, which have yet to be investigated at all. Our investigation of tsunami evidence related to the 1965 M_w 8.7 Rat Islands earthquake at Kiska Island in the western Aleutians, planned since 2020, has been hampered by logistical challenges and pandemic restrictions, although we intend to pursue this work in the future. Lakes overlying the megathrust offer other targets for ongoing work. In summer 2022, we surveyed Karluk Lake on Kodiak Island for evidence of turbidites in lake sediments that may record strong shaking during past great megathrust earthquakes. Lake sediment studies can provide greater precision for earthquake age estimates and potentially differentiate past megathrust events from earthquakes with shallow crustal or deep slab sources.

By digging into the Holocene stratigraphic record, these and other paleoseismic studies enrich our knowledge of past subduction earthquakes and tsunamis in the Alaska-Aleutian region by allowing us to better understand the range of seismic behavior and better forecast future tsunami hazards to coastal communities around the Pacific rim.

THIS CRADLE OF PACIFIC TSUNAMIS LAUNCHES DANGEROUS WAVES EVERY 60–90 YEARS, ON AVERAGE.

Geologist Rich Koehler examines layers, or sheets, of beach and nearshore sands deposited in a freshwater peat bog on Sitkalidak Island, Alaska, near Kodiak Island. The bog lies beyond the reach of Gulf of Alaska storm waves. Such evidence of marine inundation indicates that large earthquake-generated tsunamis flooded the coast repeatedly in the past millennium. Credit: USGS

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AUTHOR INFORMATION

Rob Witter (rwitter@usgs.gov), U.S. Geological Survey (USGS), Anchorage, Alaska; **Rich Briggs,** USGS, Golden, Colo.; **Tina Dura,** Virginia Polytechnic Institute and State University, Blacksburg; **Simon Engelhart,** Durham University, Durham, U.K.; and **Alan Nelson,** USGS (Ret.), Boulder, Colo.

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