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P. Haussler
USGS

W. Leith
USGS

D. Wald
USGS

J. Filson
USGS

C. Wolf
USGS

See next page for additional authors

Authors

P. Haussler, W. Leith, D. Wald, J. Filson, C. Wolf, and D. Applegate

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A little more than 50 years ago, on 27 March 1964, the Great Alaska earthquake and tsunami struck. At moment magnitude 9.2, this earthquake is notable as the largest in U.S. written history and as the second-largest ever recorded by instruments worldwide. But what resonates today are its impacts on the understanding of plate tectonics, tsunami generation, and earthquake history as well as on the development of national programs to reduce risk from earthquakes and tsunamis.

The Earthquake and Its Effects

The 1964 Alaska earthquake resulted from rupture along the thrust fault boundary between the downgoing Pacific Plate and the overriding North American Plate, causing widespread shaking and tectonic deformation. During the earthquake, an 800-kilometer by 250-kilometer area (see Figure 1) moved with a maximum horizontal displacement of 20 meters to the southeast, and earthquake-triggered submarine landslides produced deadly local tsunamis that came ashore as quickly as 90 seconds after the shaking began. Coseismic displacement of the ocean floor generated a tsunami that took lives in Alaska, Oregon, and California. Tsunamis accounted for 122 of the 131 fatalities, and 85 deaths were attributed to submarine landslide-generated tsunamis.

The earthquake was felt throughout much of mainland Alaska. Most of the population of Alaska and its major transportation routes, ports, and infrastructure lay within or near the earthquake rupture zone (Figure 2, left). Property losses from the earthquake and ensuing tsunamis totaled approximately $300 million in 1964 dollars ($2.3 billion in 2014 dollars). The shaking in Anchorage lasted about 4.5 minutes and produced heavy damage, particularly from induced landslides (Figure 2, right). Farther afield, the seismic waves swayed Seattle's Space Needle, sloshed water bodies as far away as Florida, and perturbed aquifers in the eastern United States.

Plate Tectonics in Action

The 1964 earthquake occurred at a pivotal time in Earth science history. *Wegener* [1912] first proposed continental drift, and later paleomagnetic studies by *Irving* [1956] and *Runcorn* [1956] seemed to confirm the movement of continents. *Hess*'s [1962] "geopoetry" paper on the history of the ocean basins finally provided a plausible mechanism for motion of tectonic plates by seafloor spreading, but the notion of a convergent plate margin remained controversial.

Benioff [1955] examined the pattern of deep earthquakes of all the circum-Pacific margins. He noted that earthquakes occurred along dipping planes beneath the continents or volcanic arcs and proposed that the oceanic side was being thrust beneath the continent or island arc side, as indicated by *Honda and Masatsuka*'s [1952] first-motion studies. But after Benioff's paper, some seismologists incorrectly concluded that great circum-Pacific earthquakes had strike-slip motion [e.g., *Hodgson*, 1957].

Focal mechanism analysis of the 1964 earthquake offered the choice of either a near-vertical or horizontal slip plane for the rupture. Within 2 weeks of the 1964 earthquake, it was clear that there was a landward belt of subsidence and a seaward belt of uplift. In a landmark 1965 paper, U.S. Geological Survey (USGS) geologist George Plafker [*Plafker*, 1965] convincingly showed that the only fault configuration consistent with the pattern of deformation was a "megathrust" on the low-angle fault plane. Analysis of the aftershock sequence supported this interpretation [*Stauder and Bollinger*, 1966]. Plafker's

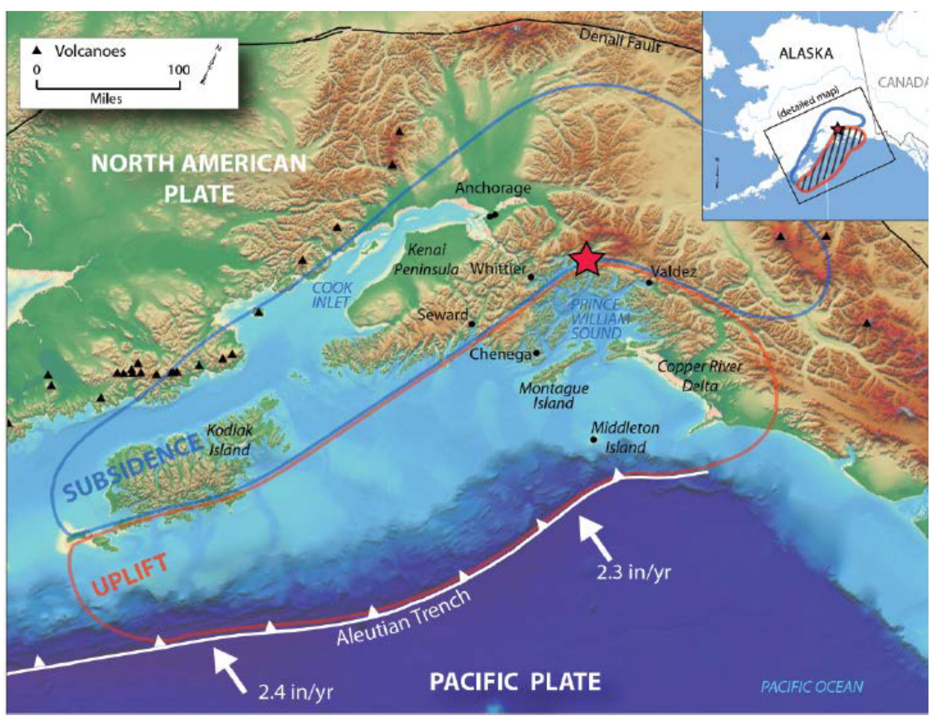

Fig. 1. Rupture area of 1964 M9.2 *earthquake showing areas of uplift, subsidence, epicenter (red star), relative plate motions (white arrows), and volcanoes (black triangles).*

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Fig. 2. (left) A photo of Alaska governor William Egan viewing earthquake damage in 1964 in Valdez (courtesy of Dennis Egan) and (right) front page of the Anchorage Daily Times *the day after the 1964 earthquake (photo credit: U.S. Geological Survey).*

work provided the geologic field evidence that helped to explain where oceanic crust, initially created at mid-ocean ridges, is eventually consumed.

After his Alaska work, Plafker investigated the world's largest earthquake—the 1960 *M*9.5 Great Chile earthquake. He found a similar pattern of a seaward belt of uplift and a landward belt of subsidence [*Plafker and Savage*, 1970]. The pair of papers on the two largest earthquakes in the world convinced skeptics that convergent plate boundaries produce megathrust earthquakes. Moreover, the great size of both earthquakes was more fully appreciated after *Kanamori* [1977] developed a magnitude scale based on moment to measure the energy of large earthquakes.

Tsunami Generation

The 1964 earthquake also advanced understanding of tsunami generation. Scientists had long recognized that ocean floor displacement generates tsunamis, but the exact mechanism was unclear without a plate tectonics framework. The 1964 earthquake provided, for the first time, a clear picture of two parallel belts of vertical coseismic displacement, with uplift mostly offshore and subsidence mostly onshore. These belts appear today as the initial condition in tsunami simulations for subduction zones.

Understanding of earthquake-generated tsunamis was further enhanced by the discovery of the first splay fault system branching off the megathrust, also mapped by *Plafker* [1967, 1969] after the 1964 earthquake. Plafker discovered that these faults produced local uplift of island coastlines of up to 9 meters. Using the velocity of tsunami waves, Plafker showed that tsunami arrival times at several locations on the nearby coastline were consistent with a tsunami generated along these splay faults.

Fingerprinting Megathrust Earthquakes

Paleoseismology is an important tool for extending earthquake histories thousands of years into the past to spur and guide risk reduction efforts. For subduction zones, a number of paleoseismic methods in use today are based in part on Alaskan analogs. For example, tectonic uplift during the 1964 earthquake added a new step to a flight of marine terraces at Middleton Island, Alaska. The entire flight, six steps in all, outlines a great-earthquake history for the past 4000–5000 years [*Plafker and Rubin*, 1978].

Tectonic subsidence during the 1964 earthquake provided clues that sparked another discovery a quarter century later. Along the Cascadia subduction zone, no great earthquake was known from 200 years of written history, but geophysicists nevertheless recognized the potential for great earthquakes. Guided by Alaskan examples, geologists in the 1980s found stratigraphic evidence of great earthquakes. They proceeded to reconstruct thousands of years of Cascadia earthquake history by studying the buried remains of subsided forests and marshes at Pacific coast estuaries [*Atwater et al.*, 2005] and offshore turbidite deposits.

Geophysical Monitoring for Rapid Tsunami Warnings

Rapid tsunami warnings are a direct result of the 1964 earthquake. U.S. tsunami warning capability was developed after Hawaii was devastated from the tsunami associated with the 1946 Aleutians earthquake. However, after the 1964 earthquake, it took about 1.5 hours to issue an alert, which was far too long for effective emergency response. As a result, the U.S. government established the Palmer Observatory (now the National Oceanic and Atmospheric Administration (NOAA) National Tsunami Warning Center in Palmer, Alaska). Today most tsunami warnings are issued within about 5 minutes of an earthquake.

The 1964 tsunami devastation caused Alaskan coastal communities to be particularly receptive to tsunami inundation mapping. Early mapping efforts paved the way for public awareness and education campaigns, currently run through state-federal partnerships like NOAA's National Tsunami Hazard Mitigation Program, which help people on the coast know what to do and where to go when tsunami warnings are issued. Currently, 11 communities in Alaska have received "tsunami ready" status. The 1964 earthquake also motivated increased regional seismic monitoring in Alaska, now centered at the University of Alaska Fairbanks.

Earthquake Safety Policy

The 1964 Alaska earthquake had three lasting effects on national earthquake safety policy. First, it showed how disruptive a major earthquake is to modern society and its infrastructure. Second, it showed the complexity of earthquake effects (e.g., ground failures, tsunamis, and ground shaking) that need to be addressed in a national mitigation policy. Third, in the iconic scenes of houses broken apart by landsliding at Anchorage's Turnagain Heights, the 1964 disaster demonstrated the importance of considering earthquake effects in engineering, urban planning, and development.

Another important earthquake in 1964 was centered in Niigata, Japan, where earthquake-induced liquefaction caused some apartment complexes to tilt at varying angles of repose. The combination of the 1964 Alaska and Japan earthquakes prompted government-funded research in both countries to better understand the physics of liquefaction and the implications for structural stability.

California's 1971 San Fernando earthquake gave further impetus to earthquake research in the United States through the estalishment by Congress of the multiagency National Earthquake Hazards Reduction Program (NEHRP). The 1964 Alaska earthquake laid the groundwork for NEHRP by forcing recognition that earthquake risk is a national issue and by promoting earthquake-related research within USGS and the U.S. Coast and Geodetic Survey, efforts that were merged into USGS in 1972.

Subsequent Progress Toward Risk Reduction

The 1964 earthquake showed plate tectonics in action, facilitated subduction zone paleoseismology, clarified tsunami generation, contributed to establishing national research programs and hazard assessments, and exposed the need for greatly increased monitoring capabilities. Successes in earthquake engineering, societal readiness, and

tsunami modeling all connect to the 1964 earthquake in various ways.

On that day a half-century ago—besides those immediately impacted by shaking or a tsunami—only a select few scientists at seismographic stations around the world knew that a mammoth earthquake had struck. Today, rapidly characterizing an earthquake's magnitude and its causative fault and slip extent—both of which improve estimates of anticipated shaking and tsunami potential—is practically taken for granted. Moreover, rapid mapping of the shaking distribution (via USGS ShakeMaps), applied to population and building construction data, now leads to rapid impact assessments (via the USGS Prompt Assessment of Global Earthquakes for Response system), allowing alerts to be sent within minutes to help prioritize and mobilize a disaster response.

Earthquake early warning systems, which in favorable circumstances can provide many tens of seconds of warning before strong ground shaking arrives, are already in place in Japan, Taiwan, Mexico, and elsewhere. An early warning system now being tested in California and the Pacific Northwest will soon integrate geodetic data with the seismic data streams. To ensure that warnings are effectively used, earthquake scientists are now engaging social scientists to develop clear, actionable warning messages.

Scientists accept the inevitability of earthquakes but have learned that their disastrous impacts can be greatly reduced. Disruption to society can be mitigated, and recovery hastened, through strong and well-enforced building codes and critical infrastructure standards, made possible by advances in earthquake engineering and increasingly accurate hazard mapping. Robust monitoring networks and rapid data analysis can deliver effective situational awareness for emergency response, including actionable tsunami and earthquake early warnings that reach those in harm's way. The 1964 Great Alaskan earthquake showed that all of these elements are needed, and need to be applied, to reduce global earthquake and tsunami risk.

For more information and resources on the 1964 earthquake, see http://earthquake.usgs.gov/earthquakes/events/alaska1964/.

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Author Information

—Peter Haeussler, U.S. Geological Survey (USGS), Anchorage, Alaska; email: pheuslr@usgs.gov; William Leith, USGS, Reston, Va.; David Wald, USGS, Golden, Colo.; and John Filson, Cecily Wolfe, and David Applegate, USGS, Reston, Va.