The 30 November 2018 Mw7.1 Anchorage Earthquake

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ABSTRACT

The M\textsubscript{w}7.1 47-km deep earthquake that occurred on 30 November 2018 had deep societal impacts across southcentral Alaska and exhibited phenomena of broad scientific interest. We document observations that point to future directions of research and hazard mitigation. The rupture mechanism, aftershocks, and deformation of the mainshock are consistent with extension inside the Pacific plate near the down-dip limit of flat-slab subduction. Peak ground motions exceeding 25% g were observed across more than 8,000 km\textsuperscript{2}, though the most violent near-fault shaking was avoided because the hypocenter was nearly 50 km below the surface. The ground motions show substantial variation highlighting the influence of regional geology and near-surface soil conditions. Aftershock activity was vigorous with roughly 300 felt events in the first six months, including two dozen aftershocks exceeding M4.5. Broad subsidence of up to 5 centimeters across the region is consistent with the rupture mechanism. The passage of seismic waves, and possibly the co-seismic subsidence, mobilized ground waters resulting in temporary increases in stream flow. Though there were many failures of natural slopes and soils, the shaking was insufficient to reactivate many of the failures observed during the 1964 M9.2 earthquake. This is explained by the much shorter duration of shaking as well as the lower amplitude long-period motions in 2018. The majority of observed soil failures were in anthropogenically-placed fill soils. Structural damage is attributed to both the failure of these emplaced soils as well as to the ground motion, which shows some spatial correlation to damage. However, the paucity of instrumental ground motion recordings outside of downtown Anchorage makes these comparisons challenging. The earthquake demonstrated the challenge of issuing tsunami warnings in complex coastal geographies and highlights the need for a targeted tsunami hazard evaluation of the region. The event also demonstrates the challenge of estimating the probabilistic hazard posed by intraslab earthquakes.
INTRODUCTION

On the morning of 30 November 2018, southcentral Alaska experienced the most societally significant earthquake in the region in half a century. The $M_{w}$.7.1 earthquake occurred nearly 50 km beneath Anchorage inside the subducting slab as a result of tensional forces near the transition from flat to steeply-dipping slab. Strong to severe shaking was felt by more than half of Alaska’s population. Because the earthquake impacted so many sectors of society, it is arguably the best earthquake learning experience in Alaska since the $M_{w}$.9.2 Great Alaska earthquake in 1964. The purpose of this paper is to provide an introduction to the observations and impacts across disciplines.

Anchorage and south-central Alaska experience frequent shaking from earthquakes occurring on the Alaska-Aleutian subduction zone interface. But earthquakes inside the subducting slab and in the overlying crust add to the hazard. Magnitude 4 and 5 earthquakes are felt routinely, albeit lightly, by the majority of Alaskans. Even large earthquakes occur with some regularity. More than 80% of the $M_{6+}$ earthquakes in the U.S. occur in Alaska and surrounding waters. Averaged over decades, $M_{7+}$ earthquakes occur somewhere along the arc every other year, though the past few years have exceeded this rate.

From this perspective, the $M_{w}$.7.1 earthquake was not exceptional and did not surprise anyone familiar with the region’s tectonics. What made this earthquake unusual was its proximity to population. The population of Alaska is small compared to other parts of the U.S. and is clustered in a handful of locations separated by hundreds of kilometers. Hence, the vast majority of earthquakes occur at considerable distance from population. The earthquake ground motions felt routinely are nearly always low-frequency rumbles from distant earthquakes or the abrupt modest tremors of small local earthquakes. Even larger recent earthquakes, such as the 2002 $M_{w}$.7.9 Denali Fault earthquake (Eberhart-Phillips et al., 2003), the 2013 $M_{w}$.7.5 Craig earthquake (Yue et al., 2013), the 2014 $M_{w}$.7.9 Little Sitkin earthquake (Macpherson and Ruppert, 2015), and the January 2018 $M_{w}$.7.9 Offshore Kodiak earthquake (Ruppert et al., 2018) had only minor impacts. In each case, the impact of these earthquakes was tempered by distance from population and the absence of significant tsunamis.

The most notable exception for Anchorage is the 1964 $M_{w}$.9.2 Great Alaska earthquake. The 700-km-long rupture generated violent ground motions across southern Alaska and generated a tsunami with fatal impacts from Alaska to California. Though the majority of damage and fatalities resulted from the tsunami (Lander, 1996), which did not extend to Anchorage, the damage from strong ground motion was extensive (Hansen, 1965). The shaking caused widespread damage to buildings and infrastructure that had been constructed with limited regard for seismic resilience. The most significant failures were not caused by the amplitude of the shaking. Instead, the ground motions, which lasted many minutes and were rich in long period energy, triggered widespread ground failures (Hansen, 1965). The repeated strain cycling of wet unconsolidated soils (i.e., loosely arranged, lacking strong bonds) and clays caused slumping, landslides, liquefaction, and in some more notorious cases the complete sloughing of steep bluffs.

The reconstruction in the decade following the 1964 earthquake coincided with a boom in Alaska development tied to the discovery of oil. The rapid growth and optimism about the future—buoyed by statehood in 1958—led the state, and Anchorage in particular, to adopt a proactive
stance toward safe development. With the memories of 1964 still raw, Anchorage adopted notably progressive building codes for the time. Even the state legislature wrote explicit seismic requirements into many of its laws.

Anchorage today is a product of this history. The municipality of Anchorage is home to 300,000 of the state’s 740,000 residents. The greater Anchorage region, including the Matanuska-Susitna (Mat-Su) Valley, adds another 100,000. Anchorage infrastructure, especially in its outlying areas, is generally young. The population of Anchorage has grown more than threefold since 1964. While a portion of the infrastructure predates the worldwide introduction of seismic construction details in the early 1980s, much of the development boom occurred after the introduction of these standards. Oversight and code enforcement vary by location but are good in downtown Anchorage. Taken together, these various factors have led to a city that has made an honest effort at seismic resilience.

The 30 November earthquake represents the first critical test of these efforts. There have been no magnitude 6 or larger earthquakes within 100 km of Anchorage in the past half a century. In 2012, a M5.8 earthquake 30 km north-northwest of Anchorage generated ground motions of ~5% g in the downtown area, and a M6.4 in 1983 caused damage to a school that had previously been flagged for poor construction. In 2016, the Mw7.1 Iniskin earthquake produced ground motions in the 10-15% g range (Grapenthin et al., 2018). Isolated cases of damage were recorded, primarily from secondary influences such as ruptured natural gas lines. However, the earthquake occurred 250 km away from Anchorage and the damage was light enough that no systematic effort was undertaken to compile and assess damages. The Iniskin earthquake highlighted the urban hazard potential of earthquakes generated inside the subducting Pacific plate and the possible effects of nearby sedimentary basins.

Though the Anchorage earthquake was far from a worst-case scenario, its impact was profound. It tested the region’s earthquake preparedness and shortcomings more than any earthquake in recent history. That makes it a rare learning experience. Many of these topics will be examined in detail by later studies. By providing a broad multidisciplinary overview, the authors hope to catalyze subsequent research that is both insightful and societally-relevant.

TECTORIC SETTING AND EARTHQUAKE SOURCE

This earthquake occurred at the northeastern end of the Alaska-Aleutian subduction zone, where the subducting Pacific plate is moving to the north-northwest at about 5.1 cm/yr (Figure 1). The tectonics of the region include the collision and subduction of the Yakutat terrane, which has characteristics of an oceanic plateau (Christeson et al., 2010). The subduction zone has a very shallow dip, which is attributed to the high buoyancy and thickness of the subducted Yakutat slab compared to a typical oceanic slab (Ferris et al., 2003; Eberhart-Phillips et al., 2006; Abers, 2008; Haeussler, 2008). Seismicity follows the slab to a depth of about 200 km depth, below which the slab appears to descend steeply to at least 400 km depth (Burdick et al., 2017; Jiang et al., 2018; Martin-Short et al., 2018). The 47 km depth of the mainshock is consistent with being in the upper part of the subducting slab (see Kim et al., 2014). Because the earthquake is near the point where the slab begins to pull away from the overlying crust, it is unclear whether the slab is overlain by warm mantle material or cold forearc crust.

The mainshock was followed five minutes later by a Mw5.7 aftershock—the largest aftershock to date. During the first two months, there were more than 8,000 aftershocks with a magnitude of completeness...
Figure 1. Regional setting. Contours mark depth to slab. Significant subduction zone earthquake rupture patches marked in grey. Slow slip events (light blue) from Fu and Freymueller (2013) and references therein. Inferred Yakutat Terrane from Eberhardt-Phillips et al. (2006). See Text S1 for moment tensor details.

Figure 2. Mainshock epicenter with regional PGA contours. Aftershock locations are shown in red. Strong motion and broadband seismic stations locations are keyed to the legend. Boxes mark cross-sections shown in Figure 3.
Figure 3. Cross-sections through the cloud of aftershocks (white). Historical seismicity shown in black. Larger circles are $\geq M_4$. Grey contours are from the P-wave tomographic model of Eberhart-Phillips et al. (2019). Solid black line marks the plate interface of Slab2 (Hayes et al., 2018). Dashed black lines marks inferred continental Moho after Miller et al. (2018). Aftershocks in panels A, B, and C correspond to the three cross-section boxes outlined in Figure 2. See Figure 2 legend for aftershock size scaling.

of 1.5 and b-value of 0.77 (Okal and Romanowicz, 1994). Roughly 40 of these aftershocks exceeded $M_4$. Compared to other nearby intraslab earthquakes, such as the 1999 $M_w7.0$ Kodiak and the 2016 $M_w7.1$ Iniskin events (Figure 1), this aftershock sequence produced significantly more $M_3$-5 aftershocks, leading to its relatively low b-value. While large aftershocks ($M_4+$) were distributed throughout the aftershock zone at the beginning of the sequence, later $M_4+$ aftershocks occurred further away from the mainshock rupture.

There is good focal mechanism agreement for the mainshock between the Global Centroid Moment Tensor project solution and the USGS (both shown in Figure 2). The mechanism is consistent with the persistent historical normal faulting observed by Ruppert (2008). Lui et al. (2019) present multiple finite fault solutions assuming motion on each of the two nodal planes. They find a slightly better fit to waveform and GPS data on the west-dipping plane, though the results are not conclusive. Kinematic models from Liu et al. (2019) are in good agreement with a rupture that lasted about 12 s, propagated to the north, and expanded both deeper and shallower for a total vertical extent of around 20 km.

We relocate aftershocks to better determine the geometric distribution of the rupture. We use the double-difference algorithm of Waldhauser and Ellsworth (2000)
to relocate 894 $M_{\circ}=2.5$ aftershocks as well as 610 $M_{\circ}=2.5$ earthquakes that occurred during the prior 10 years. We include phase picks from permanent broadband and strong motion stations as well as picks from temporary stations installed a week after the earthquake (Figure 2). The relocated aftershocks extend ~25 km northward along a strike that agrees well with the strike of the mainshock.

Aftershock depths range from 22 to 61 km, with 95% of the events between 31 km and 48 km, consistently shallower than the mainshock. The relocated aftershocks form at least two distinct clusters. The northern cluster is offset slightly to the east of the southern cluster. Relocated hypocenters also hint at a different fault plane for each cluster. In the northern part of the aftershock zone, the fault plane appears to dip quite steeply (~80°) to the west (Figure 3). In the southern cluster, the aftershock lineation dips more shallowly to the east (~45°).

We use long-period regional seismic waveforms to estimate focal mechanisms (Silwal and Tape, 2016; Zhu and Helmberger, 1996) for ten well-distributed aftershocks of $M_{w}=4.5-5.0$ (Supp Text 1). The resulting focal mechanisms are remarkably similar with no systematic evolution with time or location (Figure 2). The two fault planes implied by the mainshock and aftershock mechanisms strike essentially north-south and dip either east 30° or west 60°. These dips agree qualitatively with the planes suggested by aftershocks, though they do not align exactly. It is possible that errors in the local velocity model are stretching the true aftershock depths into a more vertical profile, which erroneously steepens both the east and west dipping planes.

The mainshock rupture can be characterized by reconciling the aftershock distribution, finite source models, and point source models for both the mainshock and aftershocks. One possibility is that the mainshock initiated in the south on an east-dipping plane then migrated northward to the west-dipping plane. In this scenario, both portions of the rupture would be roughly consistent with the mainshock focal mechanism (as the sum of slip on two very different faults) and the aftershock focal mechanisms. This would also imply that—despite notable similarity among the aftershock focal mechanisms—the events in the north are rupturing along the steep west-dipping plane, while the events in the south are rupturing along the east-dipping plane. In this model, the two distinct pulses of seismic moment release in the source time function of Liu et al. (2019) might reflect rupture on two different faults.

A second possibility is that the mainshock ruptured one of the two planes and then triggered aftershocks on a separate plane that happened to be similarly oriented to the auxiliary plane of the mainshock rupture. There are prior examples of intraslab earthquakes stimulating aftershocks on adjacent faults (e.g., Macpherson et al., 2014; Melgar et al., 2018a). As with the first possibility, this model would suggest that the fault plane of the larger aftershocks essentially flips between the north and south clusters.

A third possibility is that one fault plane was responsible for the mainshock and aftershocks. This was the assumption used within the finite-source modeling of Liu et al. (2019), who showed (their figure 5) that the preliminary aftershock locations did not align with either of the two fault planes of the mainshock mechanism. The one-fault interpretation would imply that the complex aftershock patterns in Figure 3 are either incorrect (perhaps distorted by the influence of strong heterogeneity) or are unrelated to the geometry of the rupture of the mainshock. This possibility seems to be the least likely among the three.

Future studies that include higher precision aftershock relocations, 3-D seismic velocities, and multi-plane finite source models should be able to validate or rule out the various models above.
TSUNAMI ASSESSMENT

The National Tsunami Warning Center issues tsunami alerts for the coasts of Canada and the continental U.S. (U.S. Dept. Comm., 2009) with localized warnings for the U.S. Pacific coastline beginning at M7.1 (Whitmore et al., 2008). For earthquakes with sources near the U.S. coastline, tsunami bulletins are issued within 5 minutes of origin time. To provide the earliest alerts possible, initial warnings are based on earthquake location and magnitude.

Three to four minutes after the 30 November earthquake, initial magnitude estimates showed good agreement of Mw6.8-7.0, leading NTWC to issue a Tsunami Information Statement. Roughly five minutes after the earthquake, Earlybird software began providing magnitudes of Mw7.2-7.4 (Huang et al., 2007). Following special procedures for interior waterways which begin at M≥7.1 (Whitmore et al., 2008), NTWC issued a tsunami warning for the coastlines of Cook Inlet and the southern Kenai Peninsula, with a preliminary magnitude of Mw7.2 (Figure S1). (https://tsunami.gov/events/PAAO/2018/11/30/pjool4/1/WEAK51/WEAK51.txt)

Protocol is to hold an initial tsunami alert until it can be confirmed that there is no danger. At 25 minutes past origin-time, the Pacific Tsunami Warning Center provided NTWC with a W-phase magnitude (Wang et al., 2017) of Mw7.17 (Table S1). This was followed at 29 minutes after origin-time by an Mw7.0 solution, with a normal faulting mechanism, from the National Earthquake Information Center. NTWC protocol is to issue products following NEIC’s information when it is released. NTWC revised the magnitude to M7.0 on Tsunami Warning #2 (issued 30 minutes after origin-time) and continued to assess the coastal hazard, considering all possible tsunami sources and locations. The immediate concerns focused on the potential for coastal liquefaction and ground failure (especially near the Little Susitna River and Susitna River deltas, and Ship Creek), underwater slumping in Cook Inlet, and landslides in Turnagain Arm. From the shakemap (Figure 2), NTWC was able to determine that the rupture was largely to the north of the epicenter, and not under Cook Inlet. This alleviated some concerns for underwater slumping. The new USGS ground failure and liquefaction estimates were also helpful in this regard (Figure S2), though the absence of bathymetry and underwater hazards currently limit their use for tsunami applications.

Several factors combine to reduce tsunami impacts in upper Cook Inlet. The water depth does not generally exceed 20 meters and Anchorage is surrounded by extensive tidal flats. The tide at the time of the earthquake was also low. However, there has been no comprehensive study of tsunami hazard in upper Cook Inlet. The 1964 earthquake demonstrated that the bluffs and mudflats characteristic of the area are prone to sliding under the right conditions. It is unclear, however, how tsunamigenic these modes of failure may or may not be. Though the tsunamigenic potential of these slides is uncertain, similar geology in the Puget Sound region has been known to generate impactful tsunamis (González et al., 2003).

The tide gauge at the Port of Anchorage confirmed that no massive slumping or ground failures occurred in the Anchorage area. The remaining tide gauges, in Nikiski and Seldovia, were too far from the source to be useful in rapid assessment. Shallow-water travel time estimates from likely sources within Cook Inlet to the Anchorage tide gauge were used to determine how long to wait before issuing an “all clear”. Because tsunami travel times are much slower in the shallow waters of Cook Inlet, substantial time was needed before declaring an all clear. Due to the large amount of unmonitored and unpopulated coastline, NTWC also queried numerous partners for reports of coastal waves or unusual water.
activity before cancelling the tsunami warning 90 minutes after origin-time (Supp Table 1).

DEFORMATION

Interferometric Synthetic Aperture Radar (InSAR) provides a broad view of deformation caused by the earthquake. Despite the long-demonstrated ability of SAR to map coseismic deformation (e.g., Wright et al., 2003; Lu et al., 2003), it was not until the recently launched Sentinel-1 C-band SAR constellation, with its regularly-acquired and free-and-open data, that SAR has been elevated to a widespread data source for routine hazards monitoring and response (Potin et al., 2014; Meyer et al., 2015; Ajadi et al., 2016). One approach to this is the SARVIEWS processing system (sarviews-hazards.alaska.edu), a fully-automated monitoring service providing rapid image and deformation information from Sentinel-1 SAR for events related to severe weather, earthquakes, and volcanic unrest. (See text section in the supplemental material for a detailed overview of SARVIEWS processing).

Following the Anchorage earthquake, the first post-event Sentinel-1 acquisitions (descending orbit direction) became available 04 December at 16:18 UTC, five days after the event. The Sentinel-1 observation strategy over the Anchorage area favored descending orbit geometries at the time of the event, so an earlier acquisition opportunity on 01 December (ascending orbit direction) was not realized.

The SARVIEWS processing protocol (Supp Text 2) is to pair the post-event image with the two prior InSAR images closest in time. Interferograms were formed with acquisitions from 10 November, 2018 and 22 November, 2018, resulting in 12-day and 24-day interferograms. Weather conditions before and after the earthquake were not conducive to strong InSAR coherence, with temperatures fluctuating around freezing and a mix of snow and rain. The 24-day interferogram (not shown) lacked sufficient coherence. The 12-day interferogram, however, reveals clear systematic patterns centered on the epicenter (Figure 4a).

The repeating cycles of phase information in Figure 4a can be compounded, or ‘unwrapped’, and scaled to surface deformation in the line-of-sight direction of the satellite (Figure 4b). Though the line-of-sight vector includes both a vertical and horizontal component, based on the source depth and mechanism, we infer that this displacement field largely reflects vertical motion. The unwrapped data demonstrates that areas northwest of the epicenter moved downward by more than 5 cm while comparatively modest uplift was recorded toward the east. Though Figure 4b aggregates all deformation between 22 November and 04 December, the aftershocks have far smaller moment release and are presumably negligible contributions compared to the mainshock. The predominant downward deformation across the region is consistent with the normal fault focal mechanism of the mainshock and extension in the slab. The uplift to the east of the source region, which is not observed immediately to the west of the source region, favors the steep west-dipping fault plane over the east-dipping, broadly consistent with observations in section 2.

GROUND MOTION

Ground motion from this earthquake was sufficient to saturate broadband sensors within a few hundred kilometers of the epicenter, rendering them unusable for estimates of shaking. Fortunately the area has better strong motion capabilities than most of Alaska (Figure 2). Strong motion instruments provided high fidelity acceleration records at dozens of locations in the densely populated Anchorage Bowl. At more distant sites that lack strong motion capabilities, broadband velocities were
Figure 4. SARVIEWS Sentinel-1 interferometry. (A) Interferogram showing the cumulative surface deformation between the 12-day period 22 November to 04 December 2018. Mw4+ aftershocks between 30 November and 04 December shown as white circles. Larger circle is the mainshock. One cycle of color contours corresponds to 2.8cm of deformation in the line-of-sight of the satellite. Stippled data indicates areas of low signal coherence. (B) Line-of-sight surface deformation derived from the interferogram. The image aggregates all motion during this time including the mainshock and aftershocks.
Figure 5. Instrumental and inferred peak ground accelerations as a function of three-dimensional distance from the source. Black line marks the estimate from the Zhao et al. (2006) ground motion prediction equation used to derive the shakemap for this earthquake.

Figure 6. Hydrologic response. (A) Map showing percent change in discharge at 9 stream gages and well SB01400223BCCD1, InSAR-derived line-of-sight displacement and peak ground acceleration contours. KA = Knik Arm, TA = Turnagain Arm. (B) Discharge before and after the mainshock recorded at USGS well SB01400223BCCD1 (source: waterdata.usgs.gov/ak/nwis/rt)

derived to create acceleration records. These are used together with the empirical relationships of Worden et al. (2012) to provide a ground intensity measure in the
shakemap. Where no ground motion records exist, shaking can be estimated from ground motion prediction equations. Together these two data types provided the underpinnings of the various shakemaps for the event. At the time of the earthquake, the Alaska Earthquake Center was using the USGS ShakeMap v3.0 software to produce shakemap parameters and geospatial data served through the center’s website and through the ANSS ComCat portal (https://earthquake.usgs.gov/earthquakes/eventpage/ak20419010/shakemap).

While the initial shakemaps were based on automated processing, later iterations were manually curated to incorporate as many additional observations as possible, from partners including USGS, the IRIS Transportable Array, the National Tsunami Warning Center, and the Alaska Volcano Observatory. Key among these data are the dense observations in and around downtown Anchorage provided by the dedicated urban strong motion network (Martirosyan et al., 2002; Dutta et al., 2009). While these observations provide excellent coverage in the Anchorage Bowl—the low-lying peninsular region that includes the most developed areas of the city—strong motion data are sparse or absent in other population centers including Wasilla, Palmer and Eagle River. To account for the lack of instrumental data, the Alaska Earthquake Center decided to include aggregated ‘Did You Feel It?’ reports from the USGS. While these data are inherently qualitative, they have been shown to correlate with certain aspects of instrumental recordings (Caprio et al., 2015). The shakemaps were further enhanced by including a 20 km-long NNE-striking linear source inferred from aftershocks and estimates of finite fault motion. When combined, these various data sets provide the best-available assessment of shaking patterns across south-central Alaska.

The shaking pattern is best described as a broad region of moderate to strong ground motion. While the highest peak ground accelerations exceed 50%g, accelerations of 25%g or more were experienced across an area of more than 8,000 km². Because of the earthquake’s depth, no person, building or infrastructure was within 50 km of the hypocenter (Figure 4a). The earthquake depth is singularly responsible for the absence of stronger ground motions that would have been expected for a shallow earthquake of comparable magnitude (e.g., Boore et al., 2014). The depth is also responsible for the broadly uniform distribution of shaking over a large area. The true hypocentral distance varies much less than a map-view perspective of the epicenter suggests.

Figure 5 shows the estimated peak ground acceleration (PGA) values as a function of hypocentral distance, using the Zhao et al. (2006) ground motion prediction equation that underlies the ground acceleration estimates in Figure 2. Superimposed are the instrumentally recorded PGA values (triangles), as well as the PGA values inferred from Did You Feel It? reports. The distribution illustrates PGA exceeding 10% g at 100 km from the source, reinforcing the broad extent of strong ground motions. Beyond ~100 km, the measured accelerations progressively exceed the GMPE-predicted values. Site class adjustments or a regionally-tuned GMPE would likely bring this into better alignment.

The length scale of the shakemap reflects the sparse distribution of instrumental records. Figure 5 demonstrates that the ground motion varied over short distances in ways that are not captured in the shakemap. The only Vs30 corrections used are the theoretical adjustments of Wald and Allen (2007) inferred from topography—no empirical Vs30 data layer available across the region. Downtown Anchorage is the only area with sufficient observations to constrain shorter length-scale variations in the ground motion. The scatter in Figure 5 demonstrates shortcomings in our knowledge of site effects across the region. This is a clear direction for research and one that can directly impact seismic hazard assessments going forward.
HYDROLOGIC RESPONSE

Within minutes of the earthquake, hydrologic sensors in the region registered water level changes that persisted for days to weeks. By noon of the following day, nine ice-free stream gauges recorded increases of 2-40% (Figure 6a). In addition, groundwater levels in the only monitored well decreased by ~6 cm (Figure 6b). Researchers attribute similar observations from other earthquakes to increases in aquifer permeability and pore pressure caused by static stress changes and/or dynamic strain from passing seismic waves (Manga and Wang, 2015, and references therein). Several lines of evidence suggest that the hydrologic response was caused by the expulsion of groundwater: (1) the increases in discharge scale with the discharge prior to the earthquake, which should reflect the size of the shallow aquifer systems feeding each river under frozen surface conditions (Figure S5a), (2) increased streamflow was accompanied by temperature increases of 1-2 °C (waterdata.usgs.gov) suggesting water from the subsurface where ambient temperatures are comparatively warmer at that time of year, and (3) a drop in water level is observed in the sole monitored well (Figure 6b). None of the gauges are located near the epicenter, and the discharge occurred in regions where liquefaction was neither observed at the surface (section 7) nor predicted (Figure S2). The rapid hydrologic response, however, suggests that subsurface liquefaction may have contributed to the increase in flow (Montgomery and Manga, 2003; Manga, 2001).

To examine whether these observations could result from permanent changes in strain, we use the InSAR-derived subsidence (Figure 4b) as a proxy for strain change and compare it to discharge (Figure 6a). We limit comparison to areas with InSAR coherence exceeding 80%. Least squares regression (Figure S5b) reveals a weak negative correlation suggesting that subsidence could have triggered the expulsion of groundwater. However, the correlation is weak and based on a sample size of just six.

Alternatively, strong ground motions may have enhanced streamflow through dynamic mechanisms including aquifer consolidation, micro-fracturing, and fracture clearing (e.g., Manga et al., 2012). We use the peak ground acceleration (Figure 2) as a proxy for dynamic strain during the shaking. Least squares regression shows a positive correlation with PGA at nine gauges (Figure S5c). A correlation (negative) also exists with epicentral distance (Figure S5d). Both demonstrate that streamflow scales to first-order with ground motion, consistent with prior observations (e.g., Manga and Wang, 2015).

The dataset relating stream discharge to ground motion is stronger than the comparison to subsidence. However, because ground motion and subsidence both decrease as a function of epicentral distance, correlation alone is insufficient to unequivocally separate the influence of the two.

FAILURE OF NATURAL MATERIALS

Two of the authors (R.W. and A.B.) conducted a 225-km overflight the day after the earthquake to assess large ground failures and to help guide subsequent response activities (Figure 7). This reconnaissance was guided by seismic landslide hazard maps for Anchorage (Jibson and Michael, 2009), and initial estimates of landslide and liquefaction hazard from the USGS ground failure products (https://earthquake.usgs.gov/earthquakes/eventpage/ak20419010/ground-failure).
Figure 7. Map of locations referred to in text and figures. P marks places. B marks buildings. F marks figures. S marks figures in the electronic supplement. The thin red line marks the route of the 225-km overflight on December 1 referenced in the text.
Figure 8. Complex slumping along the Alaska Railroad overlooking the tidal flats of Turnagain Arm, looking northward. Failure of these low bluffs, known as Potter Hill slides (Hansen, 1965), occurred previously during the 1964 great Alaska earthquake and again during an earthquake in 1954 (61.0874°, -149.84214°). Photo: Adrian Bender.

Four categories of ground failures were observed: 1) rockfalls and snow avalanches; 2) slumps, earthflows, and ground cracking in natural materials; 3) debris avalanches on steep walls of river canyons; and 4) liquefaction-related failures. Widespread failures of anthropogenic fill materials were also observed (see next section).

The earthquake shook loose rockfalls and snow avalanches in the Chugach Mountains, which were visible during the initial overflight but obscured by snowfall within a few days. The largest rockfall reported by local eyewitnesses occurred on the southeast face of Rainbow Peak (Figure S6). The Chugach National Forest Avalanche Information Center reported earthquake-triggered snow avalanches and rockfalls in alpine terrain surrounding Girdwood (http://www.cnfaic.org/site/observations/rainbow-peak/). Two large rockfalls also occurred along the Seward Highway between Potter Marsh and McHugh Creek, which resulted in a road closure the day of the earthquake. Although small rockfalls were observed in higher terrain above the Eklutna River and in peaks to the north, no ground failures were observed along the Chugach Mountains range front where near-real-time ground failure maps had predicted high hazard.

Complex slumping and long-runout earthflows occurred along coastal bluffs in south Anchorage where the ground had failed during prior earthquakes and heavy rainfall. Two- to three-meter-tall headscarps encroached a ~300 m long section of the Alaska Railroad Corporation southern mainline—a single track connecting Anchorage to Seward. This failure destabilized the right-of-way, but caused little damage to the track (Figure 8). Recurrent landslides, known as the Potter Hill slides, destroyed ~100 m of track and right-of-way in the same area during the 1964 Great Alaska earthquake (Hansen, 1965). Miller and Dobrovolny (1959) reported damage to railroad tracks in the same area following an earthquake in 1954. The first account of landsliding comes from an official of the Alaska railroad who recalled heavy rains that caused ground failure impacts to hundreds of meters of track in the late 1920s and early 1930s (Hansen, 1965). D.S. McCulloch and M.G. Bonilla (written communication, 1964, as cited in Hansen, 1965) describe the composition of the bluffs as till overlying outwash, which in turn overlies blue clay, silt, and fine sand. These layers are similar to the notorious Bootlegger Cove Formation which was responsible for some of the most extreme soil failures in 1964 (Miller and Dobrovolny, 1959; Updike et al., 1988). In 1964 groundwater springs, sourced from permeable beds in the outwash, flowed into ponds that saturate tidal mud flats along the base of the bluff. The 2018 failures appear similar to the slides described in 1964—a series of rotational slump blocks that disintegrated into earthflows consisting of clay, silt, and sand derived from the lower part of the bluff, the adjacent mudflat, or both. In 1964, McCulloch and Bonilla concluded that bearing strength failure and flowage of materials in the bluff and/or mudflat caused the slides. A similar mechanism probably led to ground failure during this earthquake.

Shallow (<2 m deep) landslides occurred in canyon walls and steep slopes of river valleys where frozen soils shook loose from underlying unconsolidated deposits. Most obvious from the air were debris avalanches on steep slopes underlain by loose Pleistocene sand and gravel at Point Woronzof (Miller and Dobrovolny, 1959; Schmoll and Dobrovolny, accepted for print in Seismological Research Letters.
Figure 9. Comparison of ground failure relative to 1964. (a) View to the west showing the Government Hill School collapsed into a graben, or linear trough, formed by the Government Hill landslide in 1964 (Hansen, 1965). (b) Same view in 2013 (photo: Game McGimsey). The graben formed by the landslide is still expressed in the landscape in the lower photo. (c) Crack along headscarp of 1964 slide observed on 4 December 2018. Photo: Rob Witter.
Figure 10. Sand boil, about one foot in length, along a sidewalk in south Anchorage. Photo: Howard Weston.
1972) and Pleistocene glacial gravel, sand and silt in the Eagle River (Schmoll et al., 1980) and Eklutna River valleys (Figure S7). The slope failures appeared to be superficial sloughs of frozen, unconsolidated deposits that spread downhill into debris aprons at the base of hillslopes. The slides removed snow on steep slopes and left scars of freshly exposed gravel, sand, and silt making them easy to distinguish from undisturbed slopes.

Liquefaction-related deformation and venting of saturated sediment occurred beneath tidal flats along Turnagain Arm, Cook Inlet, Knik Arm, and the Little Susitna River delta. The most voluminous liquefaction occurred at the Little Susitna River delta where sand boils blotted the coastal plain and linear features defined lateral spreading along channel margins (Figure S8).

A primary objective of our initial overflight was to assess the potential for reactivation of 1964 ground failures. From the air there was no obvious evidence for the movement of large translational slides observed in 1964. We flew over Earthquake Park and along the entire Turnagain Heights landslide that was triggered in 1964 and observed no large displacements at the top of the bluff or bulges along the toe in tidal flats that would have indicated reactivation. Overflights of other areas that moved in 1964 also showed a lack of movement in 2018, including Sunset Park, the former Native Hospital site, and Buttress Park in downtown Anchorage. Because trees obscure the hummocky ground at Earthquake Park, aerial surveys could not rule out the possibility of small (<0.1 m) cracks associated with slide blocks.

To more closely inspect the 1964 landslides, we visited Earthquake Park and Sunset Park on foot four days after the earthquake. These two parks preserve the slide-block landscape that resulted from large translational slides that occurred in 1964, which are comprehensively described by Hansen (1965). At both sites we observed ~0.01 m wide ground cracks along landslide block boundaries and headscars. One ~0.01 m wide crack at Sunset Park extended ~32 m along the headscarp of the translational landslide that destroyed Government Hill Elementary School in 1964 (Figure 9). Apparently, the duration (20–40 sec) and amplitude of strong shaking in the 2018 earthquake stopped short of reactivating large translational landslides that failed previously during much longer (4 to 5 min) shaking in 1964.

FAILURE OF ANTHROPOGENIC FILL SOILS

One of the main causes of damage to buildings was the permanent movement of soils, sands, and gravels emplaced during construction projects. We refer to these simply as fill soils. These ground failures can be split into four categories: liquefaction-induced settlement, lateral spreading, settlement not involving liquefaction, and slope displacement. Liquefaction caused structural damage in several locations in Anchorage. Homeowners with crawl spaces noted piles of fine sand and displaced foundations and utilities. Several residences suffered from settlement of interior concrete floor slabs with fine sand ejecta flowing in through cracks at the edges of the slabs. Sand boils were also noted along sidewalks and roadways in southwestern Anchorage, where groundwater is relatively shallow and subsurface soils consist of sands and gravels (Figure 10). No direct measurements of liquefaction are available because there are no soil pore water pressure transducer arrays in these areas.

We observed at least one case of lateral spreading near East Tudor Road and Elmendorf Road in an area where a gravel pit had existed in the 1970s and 1980s and was subsequently backfilled with sand and fine gravel. Surficial cracking and displacements following the
earthquake indicated lateral spreading of the shallow slope towards an adjacent artificial pond. We also identified damage to the Alaska Railroad due to ground failures in artificial materials placed on top of intertidal mudflats northeast of Birchwood Airport. Slumps and saturated earthflows damaged the railroad embankment that abuts and probably overlies natural estuarine silt and sand along the Knik Arm shoreline (Figure S9). These ground failures may have initiated in natural materials underlying the railroad embankment. These failures caused the rail line north of Anchorage to close for four days, shutting off rail service to interior Alaska. One of the more famous ground failures of artificial material occurred along Vine Road in Wasilla. Lateral spreading disrupted the road where its artificial embankment crossed a low bog (Figure S10). Many failures of engineered materials occurred on or adjacent to saturated lowlands filled with organic sediment, silt, or sand.

Across the region, the majority of the settlement that caused structural damage does not appear to be related to liquefaction, but rather the behavior of uncontrolled fill—defined as fill that may not have been placed and compacted appropriately. Figure S11 shows an example of this in a neighborhood where fill soils were used to raise homes significantly above street level during construction. Most of the homes in this neighborhood, constructed at the same time, suffered structural damage as a result of settlement near the surface. There was no visible ejecta and groundwater does not approach the surface in this area. These factors suggest that liquefaction did not play a role in the settlement. Instead, these materials may have settled during the earthquake because they were ill-suited for the use and/or improperly compacted when they were emplaced.

Numerous slope displacements occurred in both urban and rural areas. Notably, very few of these displacements appear to have occurred in natural slopes. Many slopes constructed of fill materials exhibited displacement, with subsequent failures in nearby structures. Observations at several sites indicate that fill soils moved away from structures, causing foundations to settle and crack (Figure S12). In areas where structural fill had been placed and properly compacted, little to no displacement was observed. As reconstruction efforts continue, one hypothesis that appears to be true, is that the fill slopes that exhibited the largest displacements were constructed with poor quality fill, were inadequately compacted, poorly designed, or a combination of factors. A thorough cataloging of observed geotechnical failures can be found in Franke et al. (2019).

**DAMAGE TO STRUCTURES AND UTILITIES**

There is reasonable correlation between the amplitude of shaking and observed damage (Figures 11, S13). In areas such as Sand Lake and downtown Anchorage, there is qualitative agreement between the two. But other areas show less of a relationship. There were few yellow and red-tagged buildings in south Anchorage despite having ground motions on par with surrounding areas. This is likely because many buildings in the area are newer one- and two-story wood-frame structures.

Though shaking caused some direct structural damage, most damage appears tied to foundation damage resulting from ground failure. Reports of foundation damage in single-family residential buildings are widespread (Figure 12). A significant percentage of the structural damage occurred in pre-1980 buildings lacking seismic details or in non-code conformant buildings (Figure S14). The most common structural damage includes: foundation damage, the failure of CMU (concrete masonry unit, or “cinder blocks”) wall-to-floor connections and the buckling of CMU walls (Figure S15),
deformation and unseating of floor joists, permanent residual drift in one-story residential buildings, diagonal wall cracking in wood and masonry buildings, and walls offset and disconnected from foundations. Less common structural damage included cracks in concrete shear walls and girders, failures in base plates and foundations for steel braces, cracks in concrete columns, and detachment at the wall corners in residential buildings (Hassan et al., 2019, Hassan et al., 2018, Archbold et al., 2018). In some instances, the large number of strong aftershocks exacerbated the structural damage. For example, shear cracks in girders at the Westmark Hotel widened from hairline to \( \sim 60 \) mm during aftershocks triggering a seismic retrofit. Some impacts are less easy to inspect and we anticipate hidden structural damage including damage to concrete beam-column connections, cracks punched in concrete flat plates, and yielding in steel columns and older base plates that do not incorporate the design improvements learned from the 1994 Northridge earthquake.

The six buildings in Anchorage that are instrumented with strong motion seismographs experienced light to moderate damage. Most ground motion spectra recorded at these facilities were below the design earthquake. The 21-story Atwood building, a 1982 building with a steel frame and steel shear walls, was yellow-tagged for considerable flooding and failure of the suspended ceiling grid on three floors. The 14-story Frontier Building, a 1981 concrete moment-resisting frame, experienced light non-structural ceiling and partition wall damage, damage to the elevator counterweight system, and cracks in the concrete cover of exterior and edge columns. The BP building experienced cosmetic non-structural damage, water flooding, and some structural damage to staircases. The Engineering Building on the University of Alaska Anchorage campus, a 2015 four-story steel moment frame building experienced light cosmetic cracking. The VA hospital also experienced minor nonstructural damage.

The most common non-structural damage was the failure of glass facades and windows in low-story retail buildings, tile and grid damage in suspended ceilings, damage to fire-fighting piping and sprinkler systems, and extensive cracking in drywall, partition walls, and masonry veneer. Water boilers proved particularly vulnerable with many instances of pipe failures and subsequent flooding caused by broken restraints and sliding (Figure S16).

The three major hospitals in Anchorage experienced light to heavy non-structural damage, water leaks and flooding, and some equipment damage. The emergency rooms remained open, except for one that was closed briefly to repair water damage. Providence Alaska Hospitals canceled elective surgeries but kept emergency rooms open. Alaska Regional Hospital experienced water flooding due to a failure in the fire-fighting system that forced the shutdown of two outpatient clinic buildings. Two weeks after the earthquake they were open but still operating at 20-30% capacity. The Mat-Su Regional Medical Center remained open after the earthquake. One of the hospitals, in a pre-1970 building, experienced shear cracking in the concrete core walls. Another hospital experienced a boiler failure that led to building flooding and an electrical short circuit that activated the fire alarm system. This is an important lesson because the evacuation message conveyed by a fire alarm is directly at odds with the drop, cover, and hold message advocated for earthquake response.

Most schools in the Anchorage and Mat-Su school districts experienced some level of non-structural damage and closed for a week to allow for inspections, clean up, and repairs (Figure S17). 85 of the 97 schools in the Anchorage School District experienced light to heavy non-structural damage and flooding (https://www.asdk12.org/2018Earthquake). Roughly one in five schools in the Anchorage and Mat-Su districts delayed their re-opening further to allow time to address minor
Figure 11. Comparison of building damage and ground motion for the Anchorage Bowl. (Left) Original inspection placard value. Source: Municipality of Anchorage Geographic Data and Information Center. Last retrieved: April 26, 2018. (Right) Observed PGA ground motions (triangles) supplemented with PGA values inferred from DYFI reports (circles). See Figure S14 for comparable figure for communities to the northeast.
Figure 12. Foundation and structural damage resulting from shifting soils. (Top) Cracked concrete footer. Photo: Wael Hassan. (Bottom) House subjected to extreme permanent shear resulting from offsets in the foundation due to soil failure. Photo: Chris Motter.

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** from Okal (2005).

Figure 13. Historical intraslab earthquakes in Alaska, greater or equal to magnitude 7, and 40 km or deeper.

accepted for print in Seismological Research Letters
structural damage. More severe structural damage caused four schools to close for at least a year and potentially permanently. These include two in Eagle River (Eagle River Elementary and Gruening Middle), one school in Anchorage (Alaska Middle College) and one in Mat-Su (Houston Middle). Most of the damage in these schools was to CMU walls and steel beam connections (Rodgers et al. 2019, Hassan et al. 2019, and Rodgers J. 2019). The geographic distribution of the closed schools is an indication that their damage is attributable to construction and not to a peculiar ground motion effect in one location.

Damage to the region’s inventory of 245 bridges was generally minor, with 20 bridges identified by the Alaska Department of Transportation as having more significant damage (http://dot.alaska.gov/earthquake2018). Common bridge damage included shifting girders, damage to shear keys, bent anchor bolts, and damage to the grout pads under bearings (Figure S18). Less common bridge damage included cracks in abutments, and settling under approach ramps. The earthquake caused widespread non-structural damage to highway road paving and substructures. Despite winter conditions pavement damage was generally repaired quickly, though much of this work will be redone at a later date under warmer conditions.

No damage to the trans-Alaska pipeline occurred. At its closest point, the facility is 200 km east of the epicenter. The pipeline was however shut down briefly for precautionary inspections. The earthquake caused a wide variety of utility outages, including power and water, that impacted thousands of residents. While the natural gas utility responded to hundreds of reported leaks, there were no significant explosions or fires such as those that occurred following the 2016 M7.1 Iniskin earthquake. During the first couple of hours following the earthquake, many of the major news outlets in the region were offline due to power failures. This slowed the flow of information and complicated initial efforts to assess the impact of the quake. In general, however, most utilities were back on line within hours to a few days. Damage in the utility sector was not catastrophic.

**DISCUSSION**

The 30 November 2018 Anchorage Earthquake offers a glimpse into large intraslab earthquakes and our societal response. The earthquake provides a unique set of observations that can be used to refine ground motion predictions and hazard models, emergency response procedures, and construction practices. The earthquake also highlights a number of challenges in understanding both the science and the impacts of comparable earthquakes elsewhere.

The Anchorage earthquake occurred within the subducting slab, near the down-dip end of a region of flat-slab subduction and close to the nose of the mantle wedge (Figures 1, 3). It is unclear whether there is a sliver of mantle above the earthquake source region. If there is, it is still presumably colder and outside of the convective flow of the more substantial parts of the wedge. This is a very different environment than the 2016 M7.1 Iniskin earthquake that occurred 250 km to the southeast at a greater depth of 125 km, adjacent to far hotter mantle and at greater pressures. Earthquakes like Iniskin are thought to arise, in part, from the volumetric contraction brought on by eclogite phase transitions (Hacker et al., 2003; Nakajima et al., 2013) beginning around 70 km depth. This metamorphism is thought to compound other plate forces to generate earthquakes at intermediate depths in most of the world’s subduction zones (Astiz et al., 1988).

Metamorphic processes are likely responsible for the 100 km depth M7.9 Little Sitkin earthquake in 2014 that occurred further west.
in the Rat Islands (Macpherson and Ruppert, 2015). But the source region of the Anchorage earthquake is too shallow, and potentially too cool, to make a strong argument for metamorphism-driven stresses. The earthquake was located substantially down dip of the 1964 M9.2 rupture zone (Ichinose et al., 2007). Recent slow-slip events have occurred at comparable locations along-strike (Fu and Freymueller, 2013). Wech (2016) highlights seismic tremor in this same region. Together these observations indicate that the earthquake was down dip of the locked zone, in a region where slab-pull is expected to be a more significant force. The normal fault mechanism of the mainshock and aftershocks (Figure 2) aligns strongly with the tectonic regime inferred from slab-pull. The earthquake also occurred near the depth where the slab transitions from horizontal “flat slab” motion to more steeply-dipping. This bend adds stresses in the slab, though the exact depth of compressional (bottom) vs. tensional (top) stresses depends highly on the thickness and rheology of the slab. The fact that the rupture extended toward the top of the slab (Figure 3) is consistent with the tectonic stresses that would be expected in the upper parts of the plate.

The earthquake raised legitimate questions concerning tsunami warning. The ground displacements for an intraslab earthquake, even a larger one, are too small (Figure 4) to initiate a tectonic tsunami of consequence. However, strong shaking is capable of initiating subaerial and submarine landslides which can, in turn, generate tsunamis on a local scale. Landslide-generated tsunamis were a primary contributor to the impacts and casualties of the 1964 earthquake, and have been implicated more recently in earthquakes such as the September 2018 Mw7.5 event in Sulawesi, Indonesia (Sassa and Tomohiro, 2019). While the steep bluffs and tidal mudflats that are pervasive in the area could have generated subaerial or submarine landslides, these same features offer some protection to coastlines. Residents away from the immediate coastline certainly did not need a tsunami warning. But it is not clear how exactly to treat the coastline itself. Community and agency dialog is needed to better assess how, or if, tsunami warnings should be issued for highly localized coastal hazards. There is also a clear need for an education campaign to make sure residents are informed of how to respond on their own to strong shaking, and where they do and don’t need to worry about tsunami inundation. Both of these activities could be facilitated by a comprehensive tsunami hazard evaluation of the area.

Another lesson from this earthquake is the importance of duration and frequency in triggering ground failure. The proximity of Anchorage resulted in strong ground accelerations. However, these motions were dominated by high-frequency energy (Beyzaei et al., 2019) with the strongest shaking lasting just a few tens of seconds. Because of this, the ground velocities and displacements were comparatively smaller than they might have been for a larger more distant earthquake, such as 1964. The short duration of strong shaking also meant that soils were not exposed to as many cycles of ground motion as they might have been for other earthquakes with comparable peak accelerations. This fact is not captured by intensity or peak ground acceleration maps intended to provide a concise regional summary.

Following the M9.2 earthquake and tsunami in 1964, seismic building regulations improved significantly in Alaska. The 1964 earthquake led to seismic policy changes in Alaska and helped pave the way nationwide for better codes and later to the creation of the National Earthquake Hazards Reduction Program (NEHRP) in 1977. Alaska has been credited with some of the strictest seismic safety code requirements. These are reflected in local amendments to the International Building Code (IBC) though it should be noted that, for bureaucratic reasons, at the time of the earthquake the state had adopted only the
2012 IBC and not the more recent 2018 IBC. Even so, the decades of code recognition, combined with building stock in southcentral Alaska that is generally less than 30 years old, created a region with reasonably progressive seismic resilience.

Though strong codes have been in place for decades, the level of enforcement varies widely between the City of Anchorage and many outlying cities and towns including Eagle River and Girdwood. These communities are part of the Municipality of Anchorage, but code conformance is not mandatory, especially for residential construction.

A few factors are responsible for the overall damage being less than what might have been anticipated. The primary factor is that the depth of the rupture prevented the strongest shaking that would have been expected had the earthquake occurred near the surface. The ground motions did not generally exceed that of the design earthquake though it came close at high frequencies. Damage was also minimized by the relatively short duration of the highest amplitude motions. A third important factor appears to have been the recent history of good construction practices and the relatively young age of the building stock in the region. The fact that no structures collapsed entirely and no one was killed are laudable, and are not accidents. We should not overlook however the considerable damage and ongoing vulnerabilities caused by non-engineered and pre-1980 construction. The code history described above is directly responsible for the relative resilience of the region demonstrated during this earthquake. Even the failures that did occur can generally be associated with ill-fit types of construction or the lack of enforcement (sections 9), and only serve to further validate the building codes where they were followed. The higher rates of building damage outside of the Anchorage Bowl do not appear to correlate with higher ground motions. This argument would be more credible if sufficient instrumental records were available northeast of Anchorage. But the juxtaposition of regions with and without code enforcement provides a rare controlled study. The results of this serendipitous, if unintended, test implies that code enforcement improves earthquake resilience—a conclusion that may not be shocking, but is rarely demonstrated so clearly.

Across the Aleutian arc, there have been ten recorded earthquakes of magnitude seven or larger below a depth of 40 km since 1906 (https://earthquake.usgs.gov/data/comcat). These events have been distributed across the 2500 km arc and have occurred, on average, every 11 years (Table S2). The largest of these was the M8.3 event in 1906 (Okal, 2005). Compared to earthquakes on the megathrust, the upper magnitude limits on intraslab earthquakes are smaller. However, intraslab events can occur far inland from the trench in much closer proximity to population. In this regard, the earthquake is quite similar to the 2017 M7.1 Puebla-Morelos earthquake near Mexico City (Sahakian et al., 2018; Melgar et al., 2018b).

Of the three primary contributors to seismic hazard in southern Alaska—the intraslab region, the subduction megathrust, and the continental crust—intraslab earthquakes are the most difficult to quantify in probabilistic terms. Unlike faults that rupture the surface, geologic features cannot be used to estimate fault length or slip rate. Because the slab is decoupled from the overriding continental plate, geodetic motions on the surface similarly have little relation to deformation within the slab. Lake paleoseismology is one potential approach for evaluating the frequency of intraslab earthquakes. Turbidites and sublacustrine landslides in lake sediments can be an indicator of strong shaking. If the crust and megathrust earthquake record is sufficiently understood, it could be possible to attribute the remaining sediment features to earthquakes occurring in the slab. (Praet et al., 2016; Boes et al., 2018; Fortin et al., 2019).
Even historical seismicity is a marginal indicator of the hazard. The brief historical record in the Anchorage region is insufficient to constrain probabilities. For much of the earthquake record prior to the mid-20th century, questionable location and source mechanism information make it difficult to distinguish between neighboring, but very different, source regions. Silwal et al. (2018) propose an intraslab source for the 1954 Mw 6.4 earthquake that occurred 75 km southwest of Anchorage. However, the authors state that the data cannot entirely rule out a source on the subduction interface. The events in Table S1 support only rudimentary statistical consideration assuming large intermediate depth earthquakes are distributed evenly across the arc. A systematic comparison of slab properties and focal mechanisms might shed insight on where such events are unlikely. However, focal mechanisms (and reliable depths) are only available for the most recent of these earthquakes. A more fruitful approach may be to use this small sample of events to calibrate against global observations of comparable earthquakes. But this brings challenges in reconciling the properties of different subduction zones. Barring explicit knowledge of the cause of the different earthquakes in table S1, there is no evidence to rule out an event like the 1996 M8.3 earthquake occurring under south-central Alaska.

The Anchorage Earthquake is unlikely to cause a significant reevaluation of the fundamental processes occurring within subducting plates. It should, however, serve as a stern reminder of the importance of accounting for intraslab earthquakes, despite their challenges, in seismic hazard analyses. And for an area that has not experienced comparable shaking in half a century, it serves as a reminder of why seismically-informed construction matters, what we have done well over the past few decades, and where we still need work.

DATA AND RESOURCES

All seismic waveform data is available through the IRIS Data Management Center (https://ds.iris.edu/ds/nodes/dmc). Review strong-motion seismic records are available from the Center for Strong Motion Engineering Data (https://strongmotioncenter.org). The catalog of Alaska earthquakes is distributed through the ANSS Composite Catalog (https://earthquake.usgs.gov/data/comcat). InSAR data available through the SARViews project (sarviews-hazards.alaska.edu). Hydrology distributed at https://waterdata.usgs.gov. Photographs of damage and soil failures, as well as accompanying descriptions, are courtesy of the photographer, as noted. The building damage database is available from the Municipality of Anchorage. Full data and parameters used to derive the ground acceleration contours in Figure 2 are available at http://earthquake.alaska.edu/event/20419010/shakemap.

ACKNOWLEDGEMENTS

This paper builds on the observations and efforts of a wide range of individuals and funding sources. This manuscript benefited from careful reviews by Honn Kao, Brian Sherrod and three anonymous reviewers. We thank the Earthquake Engineering Research Institute for coordinating routine conference calls in the days following the earthquake. These improved the quality and depth of observations, especially in the short window of time before winter weather obscured ground observations. Janise Rodgers and Chris Motter were instrumental in gathering information on Mat-Su schools. This research was supported in part by the Office of Alaska State Seismologist (L.G., M.G., N.R and M.W.) and the National Science Foundation award number EAR 1251971 (C.R. and C.T.).
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Supplemental Content to

The 30 November 2018 M_w 7.1 Anchorage Earthquake

By Michael E. West, Adrian Bender, Matthew Gardine, Lea Gardine, Kara Gately, Peter Haeussler, Wael Hassan, Franz Meyer, Cole Richards, Natalia Ruppert, Carl Tape, John Thornley, Rob Witter

The content of the main article spans a range of disciplines. Where possible, we have focused the article on summary observations. The purpose of this electronic supplement is to provide depth to many of the topics discussed. We do this by including: (i) methodological descriptions; (ii) tables with supporting details; and (iii) figures that illustrate various discussion points; and (iv) photographs that provide examples for some of the observations presented in the main article. While the main article was written to stand on its own, all of the content in this supplement is referenced from the article and will hopefully be of value to the motivated reader.

SUPPLEMENTAL TEXT

Text S1: Moment tensor methodology

We use long-period regional seismic waveforms and a modified version of the ‘cut-and-paste’ (CAP) code (Silwal and Tape, 2016; Zhu and Helmberger, 1996; Zhu and Ben-Zion, 2013) to estimate point-source moment tensor for mainshock. We calculate synthetic seismograms using the frequency-wavenumber approach (Zhu and Rivera, 2002) and the standard 1D model used in southern Alaska for earthquake location and moment tensor estimation. For the bandpass periods of 40–200 s, the waveforms can be well-modeled assuming a simple layered model of Earth structure and a point source representation for the earthquake. We generate a large number of uniformly distributed moment tensors, evaluate a waveform misfit function between recorded and synthetic seismograms, and then choose the moment tensor that provides the lowest misfit (i.e., best waveform fit). We perform two grid searches over the space of moment tensors and depths. In the first search, we constrain the moment tensor to be a double couple, which is equivalent to assuming that the earthquake ruptured on a single plane. In the second case, we search the full space of moment (FMT) tensors (e.g., Alizuri and Tape, 2016; Alizuri et al., 2018). For each case, after we establish the best-fitting depth, we perform an additional grid search using ΔMw= 0.01 to obtain a more precise magnitude estimate. As we would expect, the waveform fits are quantitatively better in the case where a larger parameter space is allowed (i.e., FMT). The FMT solution contains a small negative isotropic component; a more extensive analysis is needed to investigate whether this result is statistically significantly
different from the best-fitting double couple. The choice of moment tensor constraint (DC, deviatoric, FMT) will impact other source parameters, notably depth and magnitude, but also the orientation. For example, in our case, constraining the moment tensor to be a DC changes the depth from 45.2 to 50.2 km (bracketing the first motion-derived hypocenter depth) and the magnitude from 7.07 to 7.09 (Table A1). The two possible fault planes are either east-dipping 30° or west-dipping 60°.

Text S2: SARVIEWS Data Processing

The SARVIEWS system features both amplitude and phase-based products to support situational awareness and enable tracking of an ongoing event (Figure S3). All processing is currently based on full-frame Sentinel-1 SLC products. A move to burst-based processing is currently being considered.

The workflows behind the main SARVIEWS hazard products are schematically shown in Figure S3. Phase-based (InSAR) products (Figure S3; top row) include wrapped image products to support situational awareness as well as unwrapped line-of-sight deformation maps and coherence maps for more quantitative analysis. A more detailed description of our fully-automatic InSAR workflows is published in (Meyer et al., 2015). Amplitude products (Figure S3; middle row) include fully terrain corrected and radiometrically corrected image time series products (Meyer et al., 2015) as well as change detection maps (Ajadi et al., 2016). RGB-colored image products utilize the polarization diversity available in the dual-pol Sentinel-1 data. They were developed to improve the interpretability of SAR images by analysts used to colorized optical data. The approach decomposes the co- and cross-pol signal into simple bounce (polarized) with some volume scattering, volume (depolarized) scattering, and simple bounce with very low volume scattering. These are assigned to the red, green and blue color channels, respectively (Figure S3; bottom row).

To reduce the need for user interaction, we fully automated the SARVIEWS production chains by integrating with the USGS earthquake and volcano notification services (ENS and VNS, resp.). A cron-job regularly checks for incoming hazard notifications. If a notification is detected that meets pre-defined event criteria, a SARVIEWS subscription is automatically created and production of InSAR and amplitude-based hazard products commences. For earthquake events, processing starts with the event date and continues for a period of three months to capture potential post-seismic deformation. All SARVIEWS products are being made available free-and-open to the general public via the SARVIEWS hazard portal (http://sarviews-hazards.alaska.edu).

SARVIEWS data processing continued until Feb 22, 2019, two months after the event. At the time of writing, a total of 18 co-seismic and 38 post-seismic interferograms were automatically processed and made available. All data products specific to this event can be downloaded from http://sarviews-hazards.alaska.edu/Event/134.
# SUPPLEMENTAL TABLE

## National Tsunami Warning Center Event Chronology: Nov. 30, 2018

<table>
<thead>
<tr>
<th>Time [UTC]</th>
<th>Minutes after 0-time</th>
<th>Event</th>
<th>Additional Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>17:29</td>
<td>0:00</td>
<td>Large Local Earthquake</td>
<td>Issued for a Magnitude 7.0. Initial estimates showed good agreement for Mwp=6.8-7.0. Below threshold (M7.1) for a local warning. However, around 5 minutes after o-time Earlybird software analysis was for Mwp=7.2-7.4</td>
</tr>
<tr>
<td>17:32</td>
<td>0:03</td>
<td>Tsunami Information Statement #1</td>
<td>Magnitude 7.2, Tsunami Warning for Cook Inlet and the lower Kenai Peninsula following NTWC special procedures for interior waterways (M&gt;=7.1)</td>
</tr>
<tr>
<td>17:35</td>
<td>0:06</td>
<td>Tsunami Warning #1</td>
<td>Personal communication with Pacific Tsunami Warning Center</td>
</tr>
<tr>
<td>17:54</td>
<td>0:25</td>
<td>Mw7.17</td>
<td>Local warning. No danger for West Coast or other parts of Alaska. Concern not for faulting mechanism or the rupture causing a tsunami, but for localized effects causing coastal hazard from ground failures (landsides, slumping, liquefaction). No anomalous water level observations on the Anchorage tide gauge at this time. NTWC monitoring all tide gauges in Cook Inlet, and fully operational, but our observational network does not provide enough information to ensure all coastlines are safe immediately. NTWC will wait to issue an all clear and cancel the warning.</td>
</tr>
<tr>
<td>17:58</td>
<td>0:29</td>
<td>Mww7.0</td>
<td>Personal communication with National Earthquake Information Center (NEIC)</td>
</tr>
<tr>
<td>18:00</td>
<td>0:31</td>
<td>Conference Call #1</td>
<td>AEC/USGS ShakeMap and Ground Failure Maps reviewed</td>
</tr>
<tr>
<td>18:05</td>
<td>0:36</td>
<td>Tsunami Warning #2</td>
<td>Personal communication with Pacific Tsunami Warning Center</td>
</tr>
<tr>
<td>18:10</td>
<td>0:41</td>
<td>Ongoing decision support and analysis</td>
<td>Tsunami Warning continues</td>
</tr>
<tr>
<td>18:24</td>
<td>0:55</td>
<td>Mw7.06</td>
<td>Tsunami Warning continues</td>
</tr>
<tr>
<td>18:29</td>
<td>1:00</td>
<td>Tsunami Warning #3</td>
<td>A sufficient amount of time has passed with no observations on any coastal tide gauges. No reports from any contituents of hazardous water or ground failure.</td>
</tr>
<tr>
<td>18:55</td>
<td>1:26</td>
<td>Conference Call #2</td>
<td>Cancellation</td>
</tr>
</tbody>
</table>

▲ Table S1. National Tsunami Warning Center event chronology

## SUPPLEMENTAL FIGURES
**Figure S1.** Tsunami alert levels defined. Credit: NOAA National Weather Service.

**Figure S2.** From the USGS Ground Failure overlay showing Liquefaction and Landslide potential. https://earthquake.usgs.gov/earthquakes/eventpage/ak20419010/ground-failure
Figure S3. SARVIEW processing scheme for automated InSAR product delivery. See Meyer et al. (2015) for thorough treatment. http://sarviews-hazards.alaska.edu
**Figure S4.** Cross-section through aftershocks illustrating the approximate hypocentral distance to various communities. Cross-section cuts roughly perpendicular to the slab dip. Seismicity prior to 30 November 2018 marked in black. Mainshock and aftershocks are white.

**Figure S5.** Stream discharge as a potential function of deformation and ground motion. C. Log-log plot of absolute increase in discharge versus pre-earthquake discharge. D-E. Plots of percent increase in discharge versus: D. InSAR-derived line-of-sight displacement, E. PGA, and F. distance from mainshock hypocenter.
Figure S6. Large rockfall on a southeast-facing slope of Rainbow Peak, about 13km miles east of Potter Marsh along the Seward Highway (61.0023°, -149.6453°). Within three to four days after the earthquake, newly fallen snow had obscured this landslide. Photo: Jeremiah Drage.

Figure S7. Debris avalanches on steep canyon walls composed of glacial outwash sediments along the Eklutna River. View to the southeast (61.4202°, -149.2207°) Photo: Rob Witter.
Figure S8. Sediment vented by earthquake-triggered liquefaction at the mouth of the Little Susitna River. This view is looking south over Cook Inlet. (A) Extensive liquefaction shown by dark ejected sediment deposited on frozen ground. White spots may indicate sources of ejected material. (B) Lateral spreading and ejected liquified sediment. (C) White circular depressions interpreted as water frozen overnight in source vents of liquified sediment. (D) Lateral spreading, likely involving channel-parallel extensional ground cracking, and expulsion of fluidized sediment evident as black and brown deposits on snow. (61.2860°, -150.2980°) Photo: Rob Witter.

Figure S09. Complex earthflow slumping along the Alaska Railroad southern line overlooking tidal flats along Knik Arm, near Mirror Lake in this view toward the south. Failure of these low bluffs may have involved liquefaction. (61.4376°, -149.4496°) Photo: Rob Witter.
**Figure S10.** Lateral spreading disrupted Vine Road near the town of Wasilla in this view looking north. Many failures of engineered materials occurred on or adjacent to saturated lowlands filled with organic sediment, silt, or sand. (61.4376°, -149.4496°) Photo: Marc Lester.

**Figure S11.** House built on anthropogenic fill. Significant ground cracks and settling are present. Variable settling is indicated well by the tilted rooflines and gap between the structures. The sloped driveway demonstrates how, in this neighborhood, a large volume of soil was used to elevate structures above street level. Settling in these types of soils was one of the primary drivers of residential damage. (61.1380°, -149.9379°) Photo: Michael West.
Figure S12. House built partly on fill materials. The foundation of the house was compromised when soils settled and moved away from the structure. Photo: Loren Holmes.
**Figure S13.** Comparison of building damage and ground motion for communities in the Municipality of Anchorage, north of downtown. (Left) Original inspection placard value. Source: Municipality of Anchorage Geographic Data and Information Center. Last retrieved: April 26, 2018. (Right) Observed PGA ground motions supplemented with PGA values inferred from DYFI reports.

**Figure S14.** Examples of damage in non-engineered single-family houses. (Left) Porch cover detached from house and fell in front of doorway. Photo: Wael Hassan. (Right) Substantial wall cracks. Photo: Chris Motter.

**Figure S15.** Examples of CMU (concrete masonry unit, or “cinder block”) failures. (Top left) Shifting between blocks. Photo: Janise Rodgers. (Top Right) Buckled CMU wall temporarily buttressed for safety. Photo: Wael Hassan. (Bottom left) A failed CMU wall-to-floor joist connection at a school in the Mat-Su region. Photo: Bill Noyes. (Bottom right) Severe cracking and spalling in a CMU wall that exposed structural columns at a school gymnasium in the Mat-Su region. Photo: Wael Hassan.
Figure S16.
Examples of typical non-structural damage. (Top) Suspended ceiling grids proved particularly susceptible to damage. Photo: Wael Hassan. (Middle) Pipe connections were sheared from unstrapped water boilers atop a 14-story Anchorage building causing several floors to flood. Photo: Wael Hassan. (Bottom) Failures in the fire suppression system—pipes and sprinkler heads—at the Alaska Airlines Center caused the arena to flood. Photo: University of Alaska Anchorage.

Figure S17. Examples of school damage. (Top) Major non-structural ceiling damage in a classroom. Photo: Mat-Su School District. (Bottom) Major structural damage in an exterior brick wall at Eagle Elementary School. Photo: Chris Motter.
Figure S18. Bridge damage. (Top) Major cracking in a bridge wall. Photo: Alaska Department of Transportation. (Bottom) Moderate to severe shear-key damage exposing the embedded steel reinforcement. Photo: Alaska Department of Transportation.
REFERENCES


