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Calibrating the subaqueous seismograph: Using recent events to inform our knowledge of the past

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Accurate records of past earthquakes improve our understanding of present seismic hazards. We investigate the sedimentary response in Alaskan lakes to recent earthquakes to resolve outstanding uncertainties in the generation of earthquake records from subaqueous environments.

Subduction zone seismicity

Subduction zones host the largest earthquakes in the world, and are formed through the collision of oceanic and continental crust; a process in which the less buoyant oceanic plate dives beneath the continental lithosphere (Fig. 1a). Subduction zones are typically associated with three types of earthquakes. The first type (megathrust) occurs due to movement along the plate interface and has the potential to produce giant earthquakes, such as the 2011 moment magnitude (M_w) 9.1 Tohoku-oki earthquake in Japan. The second type of earthquake (crustal) is caused by tectonic stresses in the upper ~30 km of the crust, and is related to displacement on sub-vertical crustal faults. The 2002 M_w 7.8 Denali Earthquake in Alaska, USA, is an example of a crustal seismic source. The third seismic source is the result of extension related to differential stresses within the oceanic plate as it journeys into the mantle. Earthquakes of this type are termed intraslab earthquakes because the displacement takes place within the downward oceanic plate (i.e. the slab), and they typically occur at depths greater than 40 km. The angle of subduction and the depth of seismicity are such that intraslab earthquakes can occur directly below coastal population centers (Fig. 1a).

The challenge of developing prehistoric records

Current seismic hazard models for intraslab earthquakes rely on historical rates of intraslab seismicity and empirical earthquake magnitude-recurrence relationships to constrain the hazard from intraslab earthquakes (Frankel et al. 2015). With historic seismological data limited to the past ~120 years, the historical record may not fully capture important patterns in the spatiotemporal distribution of intraslab earthquakes, or resulting ground motions. A longer record of earthquakes, spanning hundreds or thousands of years, could improve hazard characterization. Unlike megathrust and crustal earthquakes, which produce observable surface faulting and/or significant land-level changes and, therefore, leave a characteristic signal in the geologic record, intraslab earthquakes occur too deep for the associated faulting to reach the surface. However, the shaking produced by intraslab earthquakes is frequently strong enough to produce secondary evidence such as liquefaction, rockfall, and subaqueous sediment gravity flows (Van Daele et al. 2019; West et al. 2020), hinting at the possibility of constructing long records of deep earthquakes from secondary paleoseismic evidence.

Lakes as natural seismographs

Lakes have long been used to investigate natural phenomena that take place across a range of timescales, from glacial-interglacial intervals (e.g. Thomas et al. 2021) to instantaneous events such as earthquakes (e.g. Strasser et al. 2006; Van Daele et al. 2020). If ground motions during an

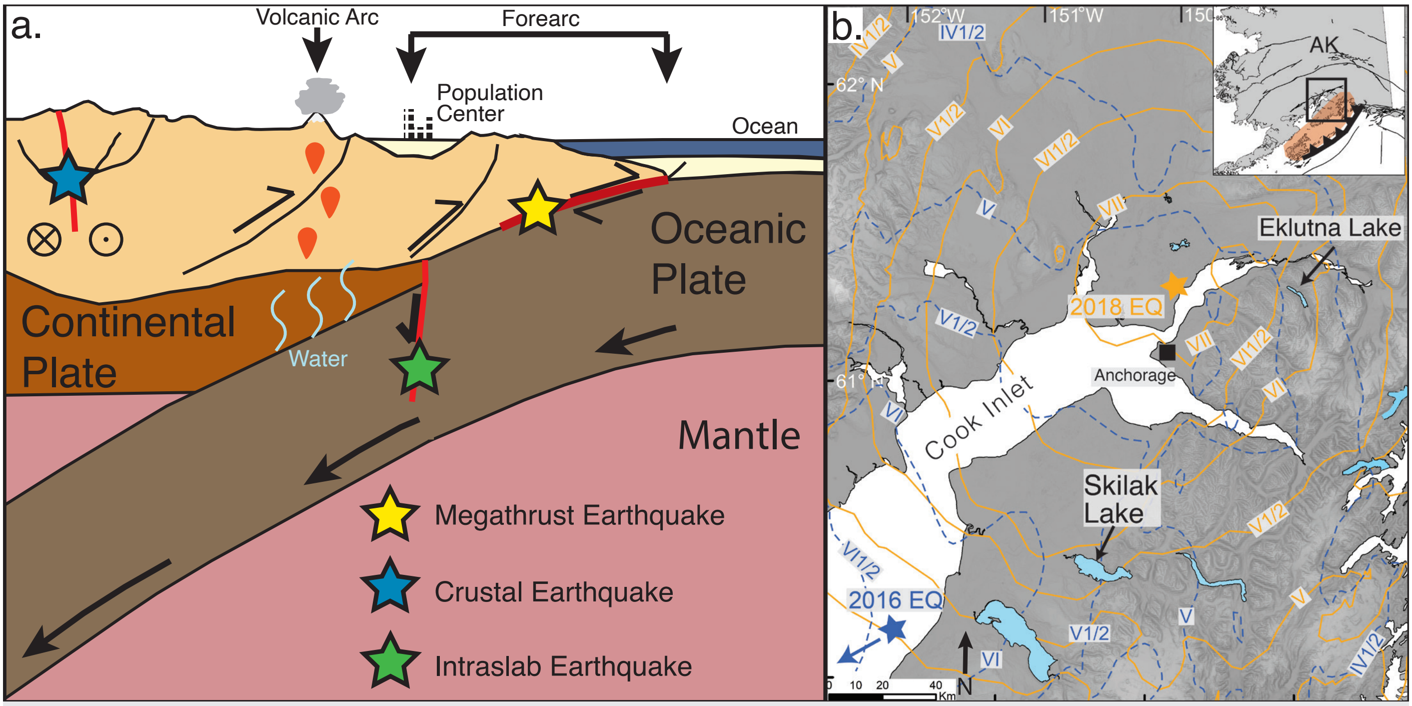

Figure 1: (A) Schematic diagram of a subduction zone. **(B)** ShakeMap Modified Mercalli Intensity (MMI) contours from the 2018 Anchorage earthquake (solid gold lines) and the 2016 Iniskin earthquake (dashed blue lines). Stars are the respective earthquake epicenters. Basins investigated by Singleton et al. (in press) are shown in light blue. Map inset shows study area within the state of Alaska, USA, and the 1964 rupture patch in orange. Figure modified from Singleton et al. (in press). ShakeMap data from USGS (2016, 2018).

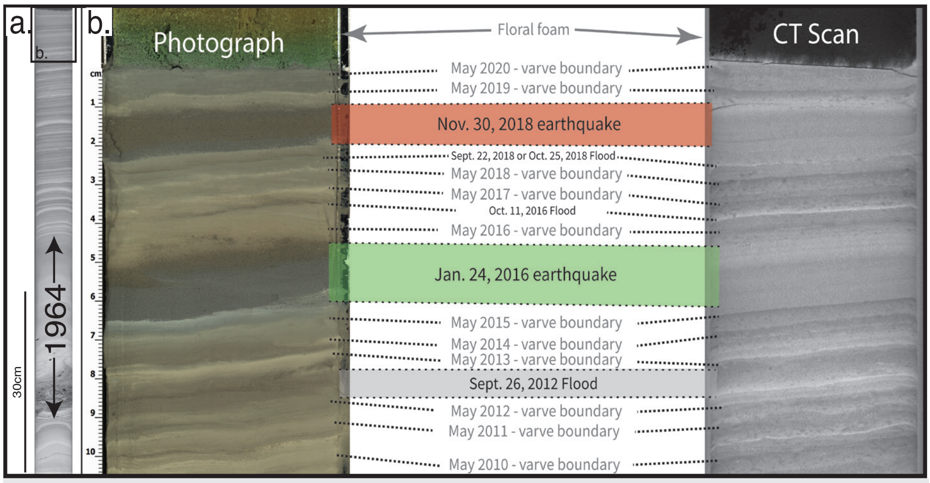

Figure 2: (A) Full CT image of core SK20-02A from Skilak Lake showing the thickness of the 1964 Alaska earthquake deposit. Black box at top corresponds to part b. **(B)** Top 10 cm of core SK20-02A. The two intraslab earthquake deposits are highlighted, as are the varve year boundaries. Figure modified from Singleton et al. (in press).

earthquake are strong enough, sediment that has accumulated on the slopes and in the deltaic environments of a lake can become resuspended in the water column and, under the force of gravity, flow downslope as a subaqueous gravity flow (Molenaar et al. 2021). The sediment gravity flow is then redeposited in the lake basin as a turbidite. Turbidites have previously been used to investigate the paleorecord of very large megathrust earthquakes (e.g. Goldfinger et al. 2012; Moernaut et al. 2014), but recent work has shown that lake basins are also sensitive to shaking produced by intraslab events (Van Daele et al. 2019, 2020; Singleton et al. in press).

However, before a complete and robust paleoseismic record from lake deposits can be developed, the underlying factors governing deposit formation need to be understood to build confidence in the idea that every earthquake that produces shaking above a certain intensity also produces an identifiable deposit. Several factors related to the lake's physiography/sedimentological character, and the character of the seismic waves, can influence the production of earthquake-triggered turbidites. Recent investigations show that both moderately steep slopes, which help facilitate the downslope gravitational movement of resuspended sediment, and coarse-grained rapid-depositional environments (deltas) are conducive to the production of earthquake-triggered turbidites (e.g. Molenaar et al. 2021; Praet et al. 2017).

Less well understood is the range of seismic parameters that influence sediment remobilization, particularly the minimum amount of shaking necessary to trigger remobilization and how variations in shaking intensity affect the resulting deposit. Two recent earthquakes in southcentral Alaska offer an opportunity to further investigate these uncertainties in the generation of earthquake-triggered deposits.

Calibrating the subaqueous seismograph

The epicenters of the 2016 M_w 7.1 Iniskin and 2018 M_w 7.1 Anchorage earthquakes are at opposite ends of Cook Inlet, Alaska (Fig. 1b) (USGS 2016, 2018). Both earthquakes occurred due to intraslab faulting and were widely felt across the region, with the 2018 event producing strong ground motions and infrastructure damage to the city of Anchorage (West et al. 2020). A few months after the 2018 earthquake, a team of researchers from the University of Ghent and the U.S. Geological Survey (USGS) observed evidence of earthquake-triggered remobilized sediment in the form of a thin (~0.1–2.4 cm) turbidite (Van Daele et al. 2020) at Eklutna Lake. This initial observation motivated an expanded investigation by the USGS into additional lakes across a range of shaking intensity (Fig. 1b), with the objective of identifying the minimum shaking that would produce an identifiable deposit.

Utilizing a dataset consisting of high-resolution sub-bottom profiles and percussion-driven gravity cores, Singleton et al. (in press) investigated six additional subaqueous basins, four lakes and two fjords for evidence of seismically triggered deposits. The steep-sided proglacial lakes receive abundant sediment and contain annual laminations (varves), which allows for yearly resolution of event deposits. The two recent intraslab earthquakes produced a range of deposit characteristics in the 2016 and 2018 varve years (Fig. 2). In those lakes that experienced minimal amounts of shaking near Modified Mercalli Intensity (MMI) values of V (a measure of shaking intensity), remobilized sediment was highly localized to only the most favorable environments (sandy deltaic slopes) (Singleton et al. in press). With increased shaking, thicker (0.5–2.7 cm) and more widespread deposits were observed in the sediment cores, suggesting that an increased amount of material was remobilized in the lake basin. At shaking intensities above MMI V1/2, enough sediment was remobilized that a deposit can be confidently identified across the basin (Singleton et al. in press). Ground motion below MMI ~V appeared insufficient to remobilize enough sediment to be differentiated from background events.

The multi-lake dataset also contains evidence for the widespread impact of the giant 1964 M_w 9.2 Alaska earthquake (Fig. 2a), a megathrust earthquake on the main plate boundary (Fig. 1b) (Singleton et al. in press). Deposits from the 1964 earthquake are generally thicker and observed more widely across the basins than those from the intraslab events, which may reflect the higher intensity and duration of shaking (Praet et al. 2022). The addition of two thin turbidites from intraslab earthquakes contribute additional data points to the hypothesis that a clear division between megathrust and intraslab earthquake deposits can be identified in some lake environments (Praet et al. 2022; Singleton et al. in press; Van Daele et al. 2019). Such a distinction will contribute to expanding the paleoearthquake record through shaking proxies and building an understanding of long-term fault behavior.

In conclusion, a multi-lake survey following two recent intraslab earthquakes constrains the minimum amount of shaking necessary to produce an identifiable earthquake-generated deposit, and confirms that variations in deposit character reflect differences in the causative earthquake.

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