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Unusual geologic evidence of coeval seismic shaking and tsunamis shows variability in earthquake size and recurrence in the area of the giant 1960 Chile earthquake

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ABSTRACT

An uncommon coastal sedimentary record combines evidence for seismic shaking and coincident tsunami inundation since AD 1000 in the region of the largest earthquake recorded instrumentally: the giant 1960 southern Chile earthquake (Mw 9.5). The record reveals significant variability in the size and recurrence of megathrust earthquakes and ensuing tsunamis along this part of the Nazca-South American plate boundary. A 500-m long coastal outcrop on Isla Chiloé, midway along the 1960 rupture, provides continuous exposure of soil horizons buried locally by debris-flow diamicts and extensively by tsunami sand sheets. The diamicts flattened plants that yield geologically precise ages to correlate with well-dated evidence elsewhere. The 1960 event was preceded by three earthquakes that probably resembled it in their effects, in AD 898–1128, 1300–1398 and 1575, and by five relatively smaller intervening earthquakes. Earthquakes and tsunamis recurred exceptionally often between AD 1300 and 1575. Their average recurrence interval of 85 years only slightly exceeds the time already elapsed since 1960. This inference is of serious concern because no earthquake has been anticipated in the region so soon after the 1960 event, and current plate locking suggests that some segments of the boundary are already capable of producing large earthquakes. This long-term earthquake and tsunami history of one of the world's most seismically active subduction zones provides an example of variable rupture mode, in which earthquake size and recurrence interval vary from one earthquake to the next.

1. Introduction

As departures from recent historical experience, the 2004 Indian Ocean and 2011 Tohoku earthquakes and tsunamis underscore the importance of using geological evidence to help estimate the variability among earthquakes that a given subduction zone can produce (Satake, 2014). Variable rupture mode, in which a long segment of a subduction zone sometimes ruptures in a single great earthquake, but in other times ruptures in a series of relatively smaller earthquakes (Kanamori and McNally, 1982), was inferred decades ago from written records of earthquakes between AD 684 and 1946 in southwest Japan (Ando, 1975), from instrumental records of earthquakes between 1906 and 1979 in Colombia and Ecuador (Kanamori and McNally, 1982), and later from geological evidence for earthquakes at several subduction zones (see Satake and Atwater, 2007).

This paper explores variation in rupture mode in the region of the largest earthquake ever recorded instrumentally—the giant 1960 mainshock, Mw 9.5, in south-central Chile (Fig. 1). A variable behavior was previously inferred for this region by comparing historical earthquakes of 1575, 1737, 1837, and 1960 with stratigraphic evidence for land-level change and tsunamis from estuaries (Cisternas et al., 2005; Ely et al., 2014; Garrett et al., 2015; Hong et al., 2016), and with evidence for shaking in lakes of the Andean foothills (Moernaut et al., 2007; Moernaut et al., 2014). These previous findings reinforce written evidence indicating that the 1575 and 1960 earthquakes resembled one another, and that both exceeded the relatively smaller 1737 and 1837 earthquakes in fault-rupture area.

Our work focuses on an uncommon combination of stratigraphic evidence for seismic shaking and coincident tsunami inundation since AD 1000 at Cocotué on Isla Chiloé (Figs. 2–5). Geological traces of shaking and tsunamis are rarely found together; in a notable exception, sand blows from sediment liquefaction contributed to the 2011 tsunami deposit on the Sendai Plain (Goto et al., 2012). The Cocotué stratigraphy

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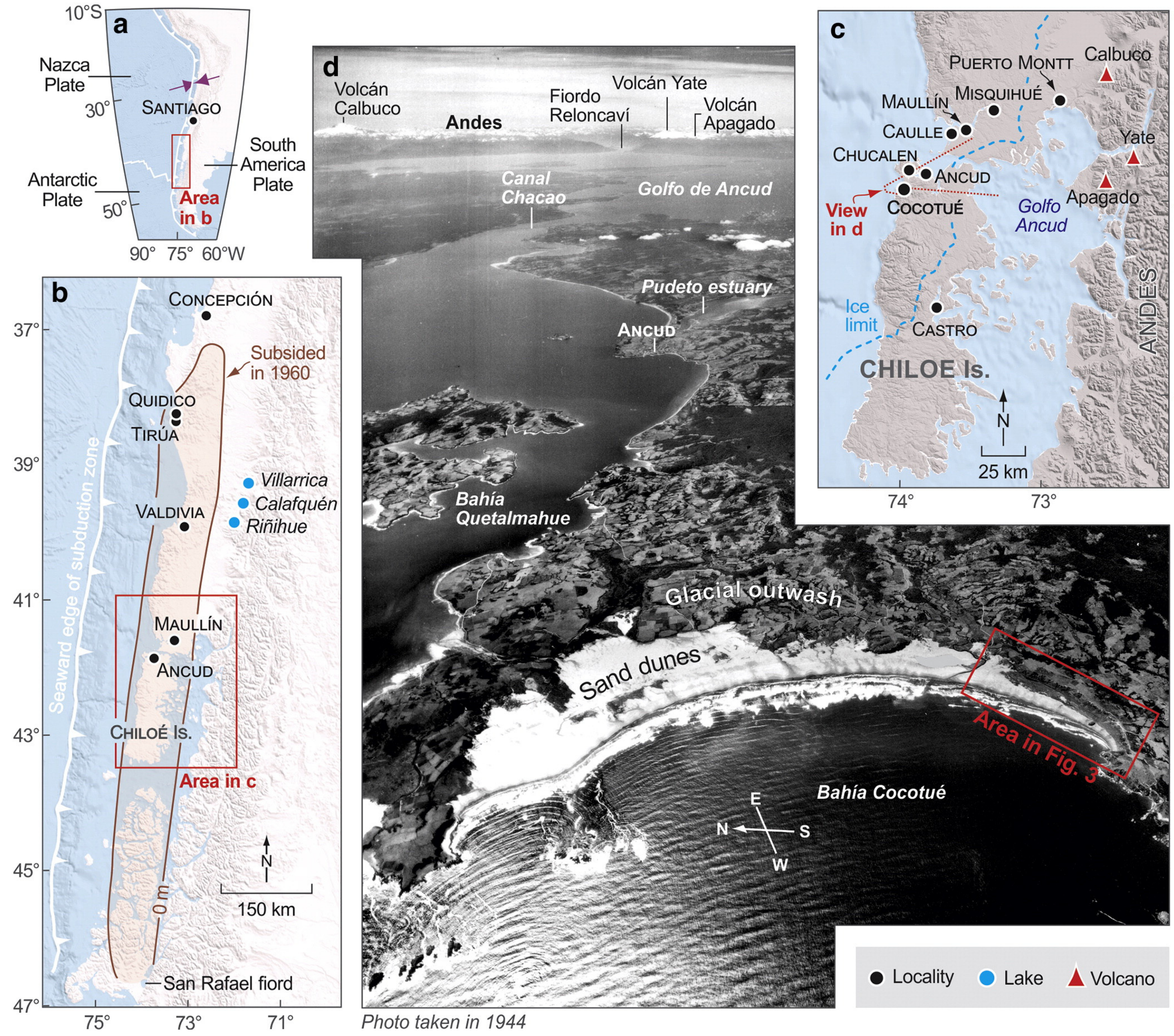

Fig. 1. Index maps and pre-1960 aerial view of the study area. a) Plate-tectonic setting of Chile. Purple paired arrows indicate plate convergence of 6.6 cm yr^{-1} (Angermann et al., 1999). b) Area of 1960 earthquake. Brown elongated ellipse outlines the area that subsided tectonically in 1960 (Plafker and Savage, 1970). Black dots mark places mentioned in the text. Blue dots mark Andean lakes studied by Moernaut et al. (2014). c) Location of Cocotué. Dashed blue curve shows western limit of the last glacial advance (Porter, 1981). d) Oblique 1944 air view of Cocotué and surroundings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

suggests the sequence of events cartooned in Fig. 2: (a) An earthquake triggers a debris flow on the former sea cliff, either for the first time or by destabilizing a scarp made by a previous earthquake. (b) The resulting debris-flow diamict covers soil at the foot of the slope, where it flattens and buries plants that had been growing there. (c) An ensuing tsunami entrains sand as it comes ashore and continues onto the toe of the debris-flow fan. The resulting sand sheet tapers across the diamict and locally entrains some of its clasts. (d) A new soil develops above both the tsunami sand and the debris-flow deposits. (e) This sequence repeats each time an earthquake sets off another debris flow followed by a tsunami.

We combine the Cocotué stratigraphic record with previously reported geological and historical evidence elsewhere in the 1960 region to reconstruct an earthquake history spanning the last 1000 years (Fig. 6). We propose that three earthquakes since AD 1000 resembled the 1960 mainshock in fault-rupture area, and that five other earthquakes likely radiated from smaller ruptures.

2. Setting

2.1. Cocotué outcrop

Our new geologic findings come from a previously undescribed outcrop along the beach on the Pacific coast at Cocotué, on Isla Chiloé (Figs. 1, 3, S1). The site is midway along the length of the 1960 mainshock rupture. The outcrop was incised by a migrating creek and ocean waves that eroded into a low terrace at the foot of a former sea cliff. The cliff, about 40 m high and composed of Pleistocene glacial outwash, was cut in the late Holocene (Heusser and Foster, 1977; Porter, 1981; Heusser, 1990). The low terrace stands about 3 m above present sea level (Fig. 4) despite about 1 m of subsidence in 1960 (Plafker and Savage, 1970). Campaign GPS measurements 13 km to the northwest show that the coast subsided 6 mm per year between 2005 and 2009 (Moreno et al., 2011).