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The 1960 tsunami on beach-ridge plains near Maullín, Chile: Landward descent, renewed breaches, aggraded fans, multiple predecessors

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ABSTRACT. The Chilean tsunami of 22 May 1960 reamed out a breach and built up a fan as it flowed across a sparsely inhabited beach-ridge plain near Maullín, midway along the length of the tsunami source. Eyewitnesses to the flooding, interviewed mainly in 1988 and 1989, identified levels that the tsunami had reached on high ground, trees, and buildings. The maximum levels fell, from about 10 m to 2 m, between the mouth of the tidal Río Maullín and an inundation limit nearly 5 km inland across the plain. Along this profile at Caulle, where the maximum flow depth was a few meters deep, airphotos taken in 1961 show breaches across a road on a sandy beach ridge. Inland from one of these breaches is a fan with branched distributaries. Today its breach holds a pond that has been changing into a marsh. The 1960 fan deposits, as much as 60 cm thick, are traceable inland for 120 m from the breach. They rest on a pasture soil above two additional sand bodies, each atop its own buried soil. The earlier of the pre-1960 sand bodies probably dates to AD 1270-1400, in which case its age is not statistically different from that of a sand sheet previously dated elsewhere near Maullín. The breach likely originated then and has been freshened twice. Evidence that the breach was freshened in 1960 includes a near-basal interval of cobble-size clasts of sediment and soil, most of them probably derived from the organic fill of pre-1960 breach. The cobbly interval is overlain by sand with ripple-drift laminae that record landward flow. The fan of another breach near Maullín, at Chanhué, also provides stratigraphic evidence for recurrent tsunamis, though not necessarily for the repeated use of the breach. These findings were anticipated a half century ago by description of paired breaches and fans that the 1960 Chilean tsunami produced in Japan. Breaches and their fans may provide lasting evidence for tsunami inundation of beach-ridge plains. The breaches might be detectable by remote sensing, and the thickness of the fan deposits might help them outlast an ordinary tsunami sand sheet.

Keywords: Tsunami, Erosion, Deposition, Hazard, Chile.

RESUMEN. El tsunami de 1960 en una planicie de cordones litorales cerca de Maullín, Chile: descenso tierra adentro, surcos renovados, abanicos agradados, múltiples predecesores. El tsunami chileno del 22 de Mayo de 1960 reabrió un surco y construyó un abanico cuando fluía a través de una poco habitada planicie de cordones litorales cerca de Maullín, en medio de la fuente del tsunami. Testigos de la inundación, entrevistados mayormente en 1988 y 1989, identificaron los niveles que el tsunami habría alcanzado en suelos altos, árboles y edificios. Los niveles máximos disminuyeron, desde casi 10 m a 2 m, entre la boca del Río Maullín y el límite de la inundación, alrededor de 5 km a través de la planicie. A lo largo de ese perfil, en Caulle, donde la profundidad máxima del flujo fue de unos pocos metros, fotos aéreas de 1961 muestran surcos, a modo de canales de erosión, que cruzan un camino sobre un cordón litoral arenoso. Tierra adentro desde uno de esos surcos hay un abanico con distributarios ramificados. Hoy, el surco contiene una poza que ha evolucionado a ciénaga. Los depósitos del abanico de 1960, de hasta 60 cm de espesor, son trazables tierra adentro por 120 m desde el surco. Descansan sobre un suelo de pasturas por sobre otros dos adicionales cuerpos de arena, cada uno cubriendo su propio suelo enterrado. El más antiguo de los cuerpos arenosos pre 1960 probablemente data del 1270-1400 DC. Así, su edad no se diferencia estadísticamente de la edad de una capa de arena previamente datada en otro sitio cercano a Maullín. Probablemente el surco se originó en ese entonces y ha sido reactivado dos veces. Evidencia que el surco fue utilizado nuevamente en 1960 incluye un intervalo basal de cantos rodados compuestos de sedimentos y suelo, la mayoría de ellos probablemente provenientes desde el relleno orgánico del surco pre 1960. La arena sobre los cantos contiene laminación cruzada que indica flujo tierra adentro. El abanico de otro surco cercano, en Chanhué, también provee evidencia estratigráfica de tsunamis recurrentes, aunque no necesariamente del uso repetido del surco. Estos hallazgos fueron anticipados medio siglo atrás con la descripción de surcos y abanicos que el tsunami de 1960 produjo en Japón. Los surcos y sus abanicos podrían proveer evidencia duradera de inundación de tsunami en planicies con cordones litorales. Los surcos podrían ser detectables mediante sensores remotos, y el grosor de los depósitos del abanico podría ayudar a que se preserven por más tiempo que una capa de tsunami ordinaria.

Palabras clave: Tsunami, Erosión, Depositación, Peligro, Chile.

1. Introduction

This paper offers two kinds of findings about tsunami history. First, it adds to previous Chilean descriptions of the 1960 tsunami. Among descriptions of the waves, high-water marks, and losses of life from the Pacific Ocean tsunami that originated during the giant (magnitude 9.5) Chile earthquake of 22 May 1960, most refer to distant effects in Hawaii (Eaton *et al*., 1961; Dudley and Lee, 1998) and Japan (Japan Meteorological Agency, 1961; The Committee for Field Investigation of the Chilean Tsunami of 1960, 1961). The tsunami's effects in Chile are known mainly from a report published in Spanish (Departamento de Navegación e Hidrografía de la Armada, 1961) and English (Sievers, 1963). In a few areas this contemporary evidence was later supplemented by eyewitness accounts that have been excerpted in public-safety booklets (Atwater *et al*., 2005a; Cisternas *et al*., 2010). The paper draws on the later eyewitness accounts to derive tsunami-height estimates that might be applied most directly to the mapping of tsunami hazards and the calibration tsunami-inundation models in south-central Chile.

Second, the paper offers geological findings that may have international application in tsunami research and preparedness. A tsunami commonly writes its own geological history by spreading sand hundreds or thousands of meters inland (Bourgeois, 2009). The deposit can serve as a long-term warning of future tsunamis, most importantly on a coast where outsize tsunamis recur centuries apart and have yet to happen in the area's written history. The sandy forewarning described in this paper is notable because the sand is distinctly paired with a breach. The main idea, adapted from studies in Japan (Konno *et al*., 1961; Minoura and Nakaya, 1991), is cartooned in figure 1. A tsunami flows through a sandy beach ridge, either for the first time or by reaming a breach that an earlier tsunami created. The landward-directed outflow from the breach builds a sandy fan as it spreads out on a plain, or it builds a delta if it runs into water already standing there. The resulting fan-shaped deposit may form on the landward side while the tsunami floods, on the seaward side while it drains, or both. The combination of breach and fan may endure for centuries as a geological forewarning of the area's next catastrophic tsunami.

We collected eyewitness accounts and examined breaches and fans near the town of Maullín, south-central Chile. This study area includes the estuary of the Río Maullín and beach-ridge plains that adjoin it (Fig. 2).

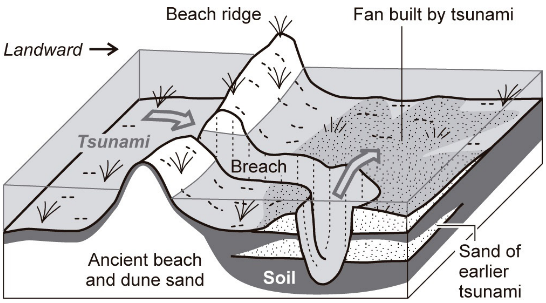


FIG. 1. Cartoon of breach and fan formed by recurrent tsunamis flowing from left to right.

2. Previous work

2.1. Earthquake and tsunami history in the source region of the 1960 Chilean tsunami

Earth's largest 20th century quake, of magnitude 9.5, resulted from a fault rupture at the boundary between the subducting Nazca plate and the overriding South America plate (Fig. 2a) in the Chilean afternoon of 22 May 1960. The rupture extended more than 800 km along this subduction zone and lowered most adjoining parts of Pacific coast of south-central Chile by a meter or two (Fig. 2b) (Plafker and Savage, 1970). Crossing the Pacific Ocean, the ensuing tsunami took lives as far away as Hawaii and Japan (Atwater *et al*., 2005b, p. 55).

Written records tell of preceding earthquakes in 1575, 1737, and 1837 (Lomnitz, 1970; Cisternas *et al*., 2005). The 1575 earthquake rivals the 1960 earthquake in reported effects: minutes of strong shaking at all Spanish outposts from Concepción to Castro, inferred subsidence, a devastating tsunami near Valdivia, and landslide damming of a lake in the Andean foothills. By contrast, the 1737 earthquake is known only from secondary written records in Chile and is not known to have produced a tsunami in Chile or Japan. The earthquake in 1837, perhaps generated mainly in the southern half of the 1960 fault-rupture area, spawned a Pacific Ocean tsunami that caused documented flooding and damage in Hawaii and Japan.

Among these four historical events, only those from 1575 and 1960 are evident in sequences of sand sheets and buried soils previously described near the study area. This stratigraphy, at the lowlands of Chuyaquén (Fig. 3a, g), provides an inferred history of recurrent earthquakes and tsunamis of the past 2,000 years (Cisternas *et al*., 2005). The sand sheets rest on the buried soils of tidal marshes and supratidal meadows. Some of the sand sheets record tsunami deposition, while others represent sandy tidal flats that record coseismic subsidence. The four most recent of the geologically recorded earthquakes and tsunamis at Chuyaquén date, at two standard deviations, to AD 1020-1180, 1280-1390, during or soon after 1450-1620 (probably 1575), and 1960.

Evidence for recurrent earthquake shaking has been found in deposits beneath Lago Puyehue, about 175 km northeast of Maullín (Moernaut *et al*., 2007), and twice that distance to the north-northeast beneath Lago Calafquén and Lago Villarrica (Moernaut *et al*., 2009). This lacustrine evidence extends south-central Chile's earthquake history as much as 10,000 years into the past.

2.2. Tsunami deposits associated with breaches

The pairing of a tsunami's breaches and fans was first noted as an effect of the Pacific Ocean tsunami associated with the giant Chilean earthquake of 22 May 1960. The initial descriptions came from far-field shores of northeast Japan, where both flooding and subsequent draining breached roads and levees (Konno *et al*., 1961), and from Chile, where the tsunami breached sand spits near Puerto Saavedra (Weischet, 1963, p. 1247; Wright and Mella, 1963, p. 1369) and Maullín (Fig. 2e) (Thomas *et al*., 1963). Fan deposits nearly a meter thick in the Chilean near field were later reported from Mehuín (Fig. 2b), where they formed behind a seaside beach ridge that the 1960 tsunami breached (Bourgeois and Reinhart, 1989).

Other pairing of tsunami erosion and tsunami deposition has been reported for the 2004 tsunami in Aceh, Indonesia (Paris *et al*., 2009) and the 2006 tsunami in the Kuril Islands (MacInnes *et al*., 2009), and has been inferred from eolian landforms and archaeological materials in New Zealand (Goff *et al*., 2009).

Breaches paired with fans have been used to estimate heights that tsunamis likely attained as they overtopped beach ridges. At Seaside, Oregon, Cascadia tsunamis of the past few thousand years repeatedly incised gravelly beach ridges and built fans behind the incisions (Peterson *et al*., 2010). At Anegada, British Virgin Islands, waters of the North Atlantic breached sandy beach ridges a few meters high during a tsunami or an unusual storm in the decades

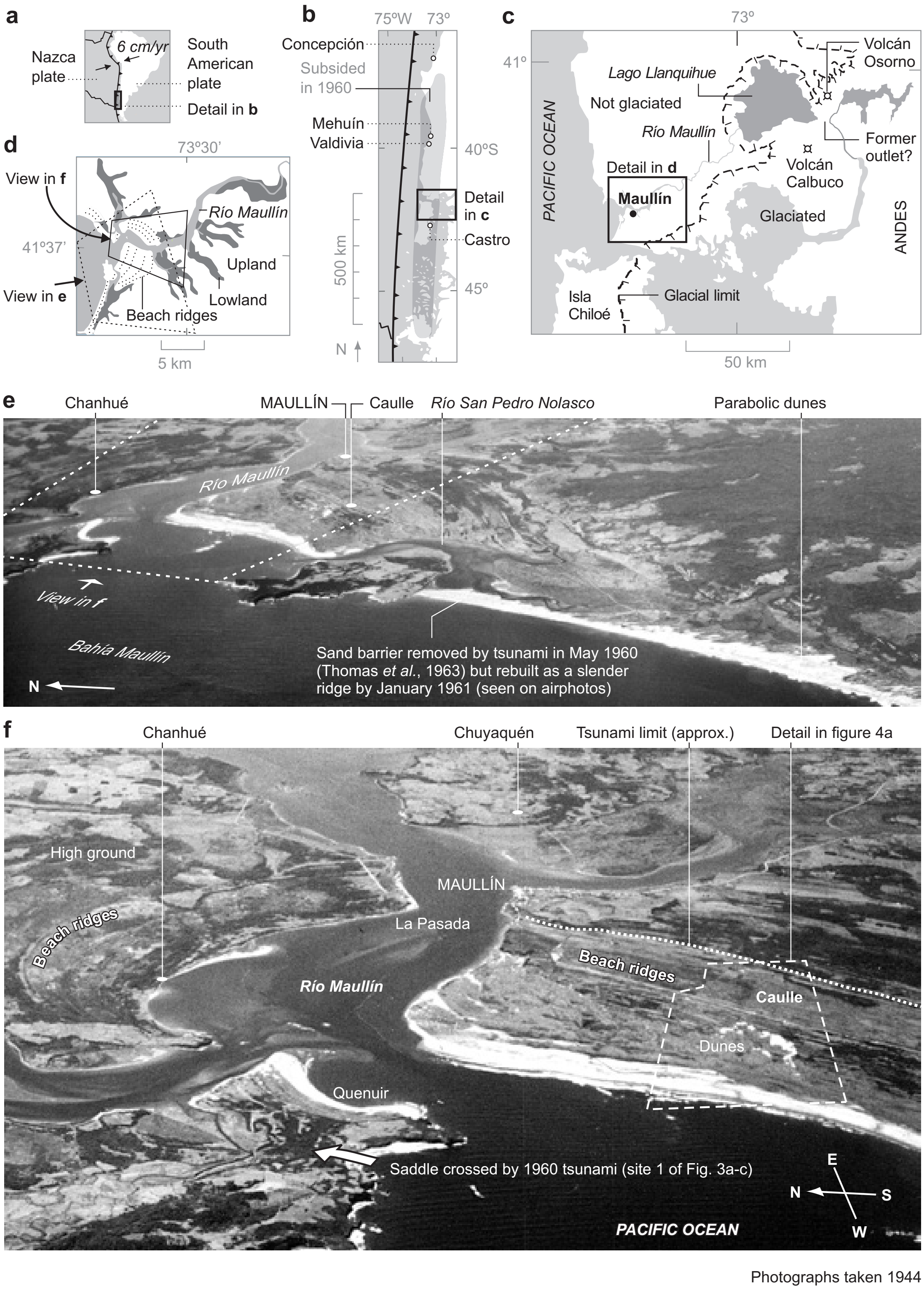


FIG. 2. Index maps (**a-d**) and oblique aerial views (**e**, **f**) showing study area in south-central Chile. Glacial limit in c from Porter (1981).

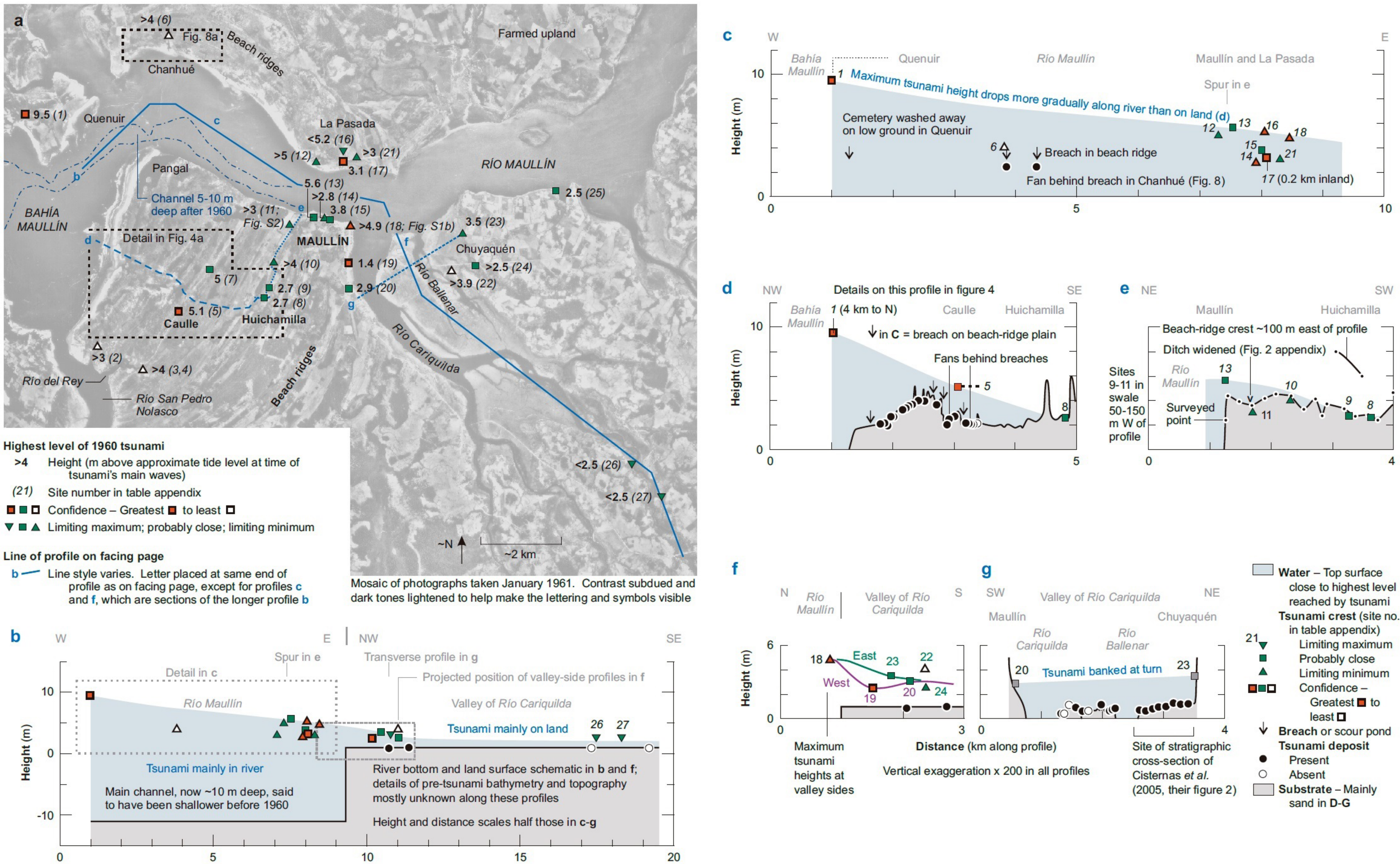


FIG. 3. Maximum heights attained by the 1960 tsunami as inferred from the recollections of eyewitnesses interviewed in 1988-1989 (Table appendix).

between 1650 and 1800, and during an earlier time of overwash as well (Atwater *et al*., 2012).

The 1755 Lisbon tsunami likely accounts for overwash fans on the back side of a sand spit in Spain (Luque *et al*., 2001; Lario *et al*., 2010). These fans were recently cited as analogs for overwash fans that have been interpreted as evidence for tsunamis at Tierra del Fuego (Bujalesky, 2012).

The 2004 Indian Ocean tsunami breached beach ridges in Indonesia, Thailand, and Sri Lanka (Choowong *et al*., 2007; Goff *et al*., 2007, p. 11, 29, 31; Fagherazzi and Du, 2008). The Thai breaches widened seaward across the modern beach, a form ascribed primarily to drainage of tsunami waters (Fagherazzi and Du, 2008). Such breaches were also produced on sand spits in Japan by the tsunami from the 2011 Tohoku earthquake (Tanaka *et al*., 2012). Longshore drift of beach sand filled most of the Japanese breaches in the first months after the tsunami.

3. Methods

This study began with a four-month reconnaissance in 1988 and 1989. The work was aided by oblique airphotos taken by the United Stetes military in 1944 (Fig. 2e, f), low-altitude vertical airphotos of tsunami damage taken June 4, 1960 by the Chilean airforce (Figs. 1a, b, 2 appendix), and vertical airphotos of 1:50,000 scale taken January 1961 (Figs. 3a, 4a, b) and 1:20,000-scale vertical airphotos taken in 1979. The work included interviews of eyewitnesses to the 1960 tsunami (Table, Text appendix), measurement of tsunami high-water levels (Fig. 3) and topographic profiles (Fig. 4a, c) by means of third-order leveling linked to readings on a tide staff (Table appendix), and measurement of tsunami-deposit thickness in shovel pits and hand-auger holes (Figs. 3g, 4d, e).

Paired breaches and fans noticed in this reconnaissance received further field study in 2006. This field work focused on fans at Caulle, 2 km inland from the sea, and Chanhué, a few hundred meters from the Río Maullín. We dug pits, made sediment peels, and surveyed topography along a transect (Figs. 5-8). Most of the pits extended 1.5 m in length and width and reached 1 m in depth (example, Figs. 5, 7d). The sediment peels (Figs. 6, 7) were made with OH-1A, a hydrophilic grout that contains toluene di-isocyante and methyl ethyl ketone. Grain size was estimated in the field by hand lens. The leveling plotted in figure 5 had a closure error of 1 cm.

A horizontal woody root in growth position yielded the radiocarbon age introduced in this paper (Fig. 6c). We converted its age in radiocarbon years to a two-standard deviation range in calibrated (approximately sidereal) years with the Southern Hemisphere calibration data of McCormac *et al*. (2004) and with Calib 5.01, a recent version of the radiocarbon-calibration program of Stuiver and Reimer (1986).

4. Eyewitness accounts of the 1960 tsunami

Published accounts of the 1960 tsunami near Maullín begin with a summary prepared soon afterward by the Chilean Navy (Departamento de Navegación e Hidrografía de la Armada, 1961) and later published in English (Sievers, 1963). It states that the 1960 tsunami reached Maullín around 20 minutes after the mainshock, which began about 3:10 p.m. local time on 22 May. It further states that the tsunami began with a withdrawal, reached a maximum height of 14 m, and included eight large waves of which the second and the fourth were the highest. We presume that the height of 14 m was estimated from debris observed in trees.

Eyewitnesses interviewed in 1988 and 1989 identified vertical and horizontal limits of the 1960 tsunami near the Río Maullín. We surveyed the heights relative to a local datum that we related to tides in 1988 and 1989. We estimated the height of this datum relative to the heights of the tide in the Río Maullín during first hours after the mainshock of 22 May 1960 (details in Table appendix, footnote 2). The tsunami heights reported herein are referenced to this estimated post-earthquake tidal level.

The maximum heights reached by the tsunami diminish inland. The greatest of the well-substantiated heights, 10 m, was attained by the tsunami as it poured across a bedrock saddle north of the river mouth (Figs. 2f, 3b, c). Seven kilometers upriver the heights inferred from interviews diminish to about 6 m in La Pasada and 5 m in Maullín (Fig. 3c). On an overland profile across the beach-ridge plain west of Maullín, the estimated high-water levels diminish more abruptly, descending to 5 m at Caulle, 2 km from the sea, and further declining to little more than 2 m at a site nearly 5 km from the sea (Figs. 3d, 4a-c). The 1960 Chilean tsunami similarly descended inland near Tsugaruishi and Tanabe, Japan (Atwater *et al*., 2005b, p. 64-65, 88-89).

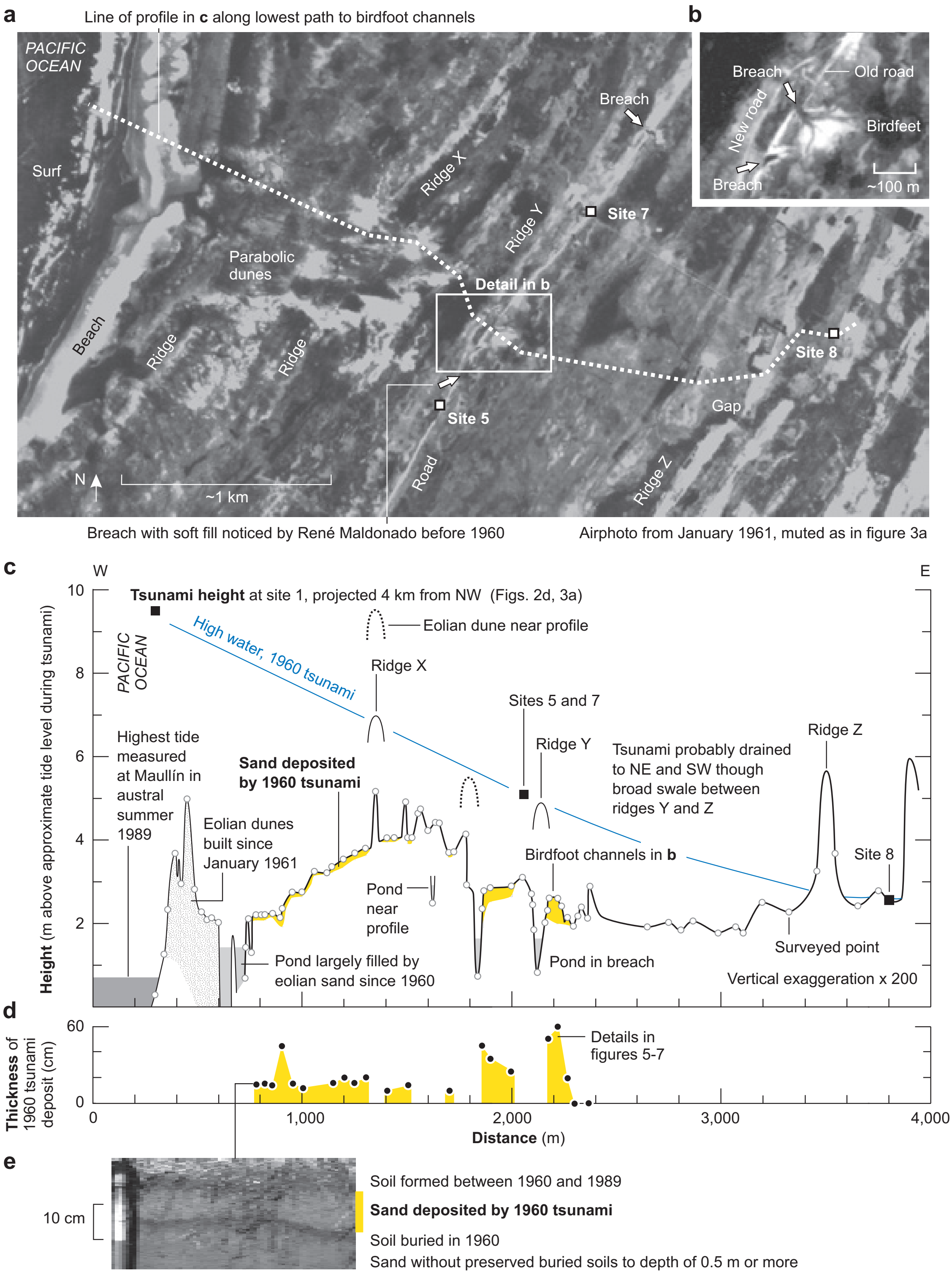
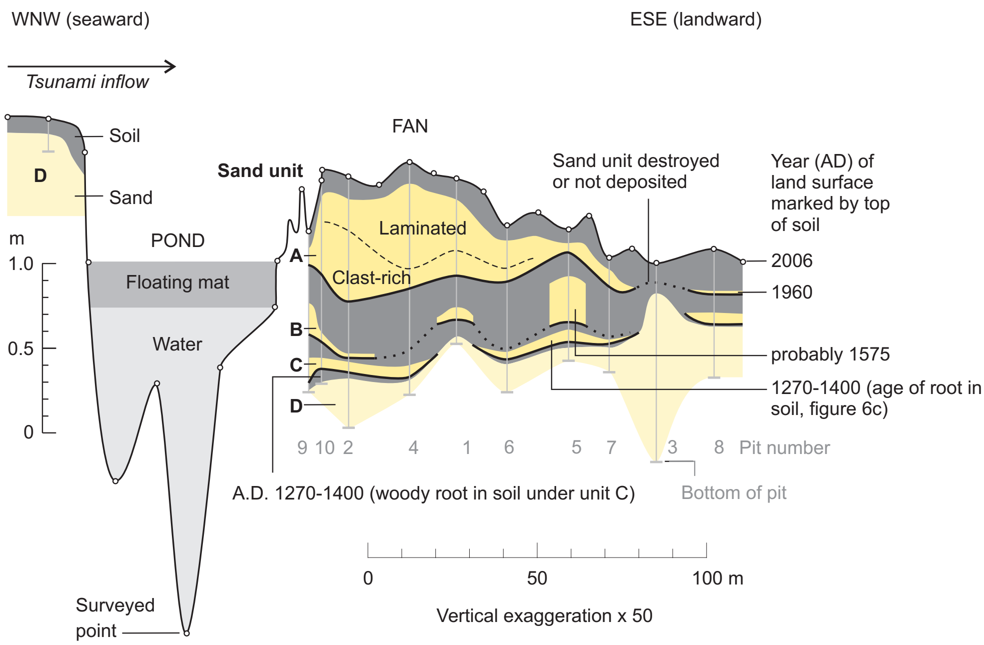


FIG. 4. Setting of breach and fan studied in Caulle (Fig. 3d, e), viewed in an airphoto taken seven months after the 1960 tsunami (**a, b**) and along a leveled profile (**c, d**). The enlargement in **b** retains the photo's original tones.



SAND UNITS

Each sand unit consists mostly or entirely of fine, well-sorted, arkosic sand. Details in section 6.1.

A – Prominent in area of birdfoot channels (Figure 4b). Maximum measured thickness 60 cm, tapering to fan's landward edge. Capped by sandy modern soil. Abruptly overlies brownish gray sandy soil. The unit is mainly oxidized. Deposited by 1960 tsunami.

B – As much as 30 cm thick where undisturbed. Mainly dark gray. Abruptly overlies soil consisting of soft peaty mud (Fig. 6). Widely trampled by livestock. Probably deposited by 1575 tsunami.

C – Tabular, mainly 5-10 cm thick. The underlying soil, which is typically less than 5 cm thick, contains horizontal, growth-position woody roots probably killed between AD 1300 and AD 1400.

D – Several meters thick. Interpreted as having formed the beach-ridge plain that tsunamis later overran and locally modified. Probably of Holocene age.

FIG. 5. Cross section and stratigraphic units of the Caulle fan. The cross-section line passes about midway between the distributary channels that are evident in the airphoto from January 1961 (Fig. 4b).

Several reliable observers who were in or near the town of Maullín recounted three tsunami waves before dusk. The first arrived within 45 minutes of the earthquake. The second, probably the largest, exceeded the first. The difference is evidenced in snapshots taken in the town plaza between the afternoon's waves. These show structures standing after one wave but not after another (Fig. 1 appendix).

At least 116 people reportedly died from the tsunami along the lower reaches of the Río Maullín (Text appendix). Nearly all were close to the river mouth when the tsunami first came ashore; a former official recalled a death toll of 105 in Quenuir (Fig. 2f), and families of victims mentioned at least 10 deaths on the beach-ridge plain west of Maullín. An additional person who died is known to have been swept away by the tsunami beside the plaza of Maullín itself (Fig. 1c).

4.1. Caulle

Further clues to the relative sizes of the first two waves near Caulle were provided during the 1989 reconnaissance by Nelly Gallardo and René Maldonado and were clarified by Ms. Gallardo in the early 2000s. Ms. Gallardo, 23 years old in 1960, was close to the sea, near the mouth of Río del Rey (Fig. 3a), when the first wave reached her. It crested at her knees. The second wave swept her off her feet and left her afloat on a wooden rail (Atwater *et al.*, 2005a, p. 14).

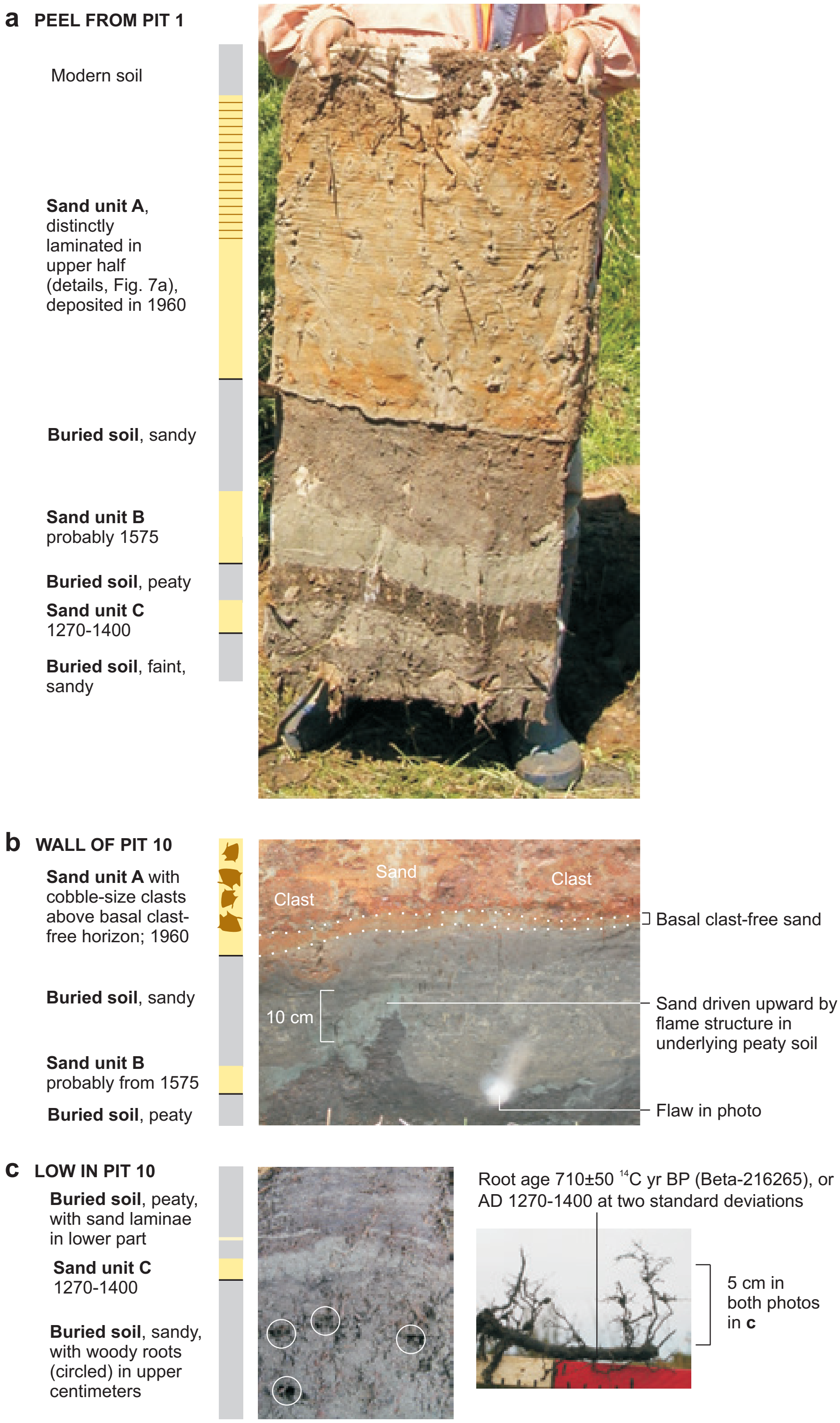


FIG. 6. Examples of evidence for recurrent tsunamis at the Caulle fan. Sand unit **A** represents the 1960 tsunami, while sand units **B** and **C** are inferred to record earlier tsunamis.

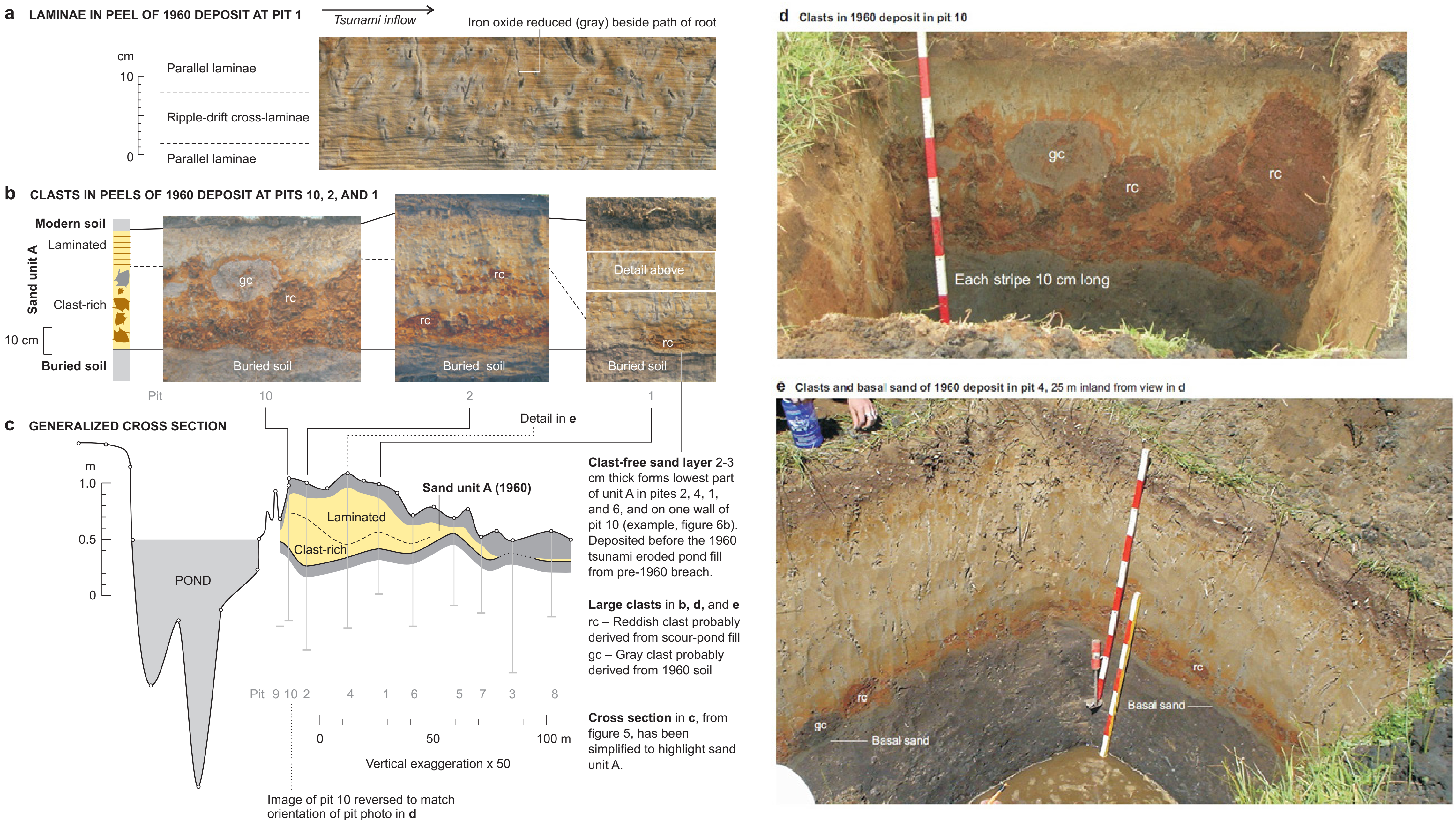


FIG. 7. Internal structures of the tsunami deposit from 1960 at the Caulle fan.

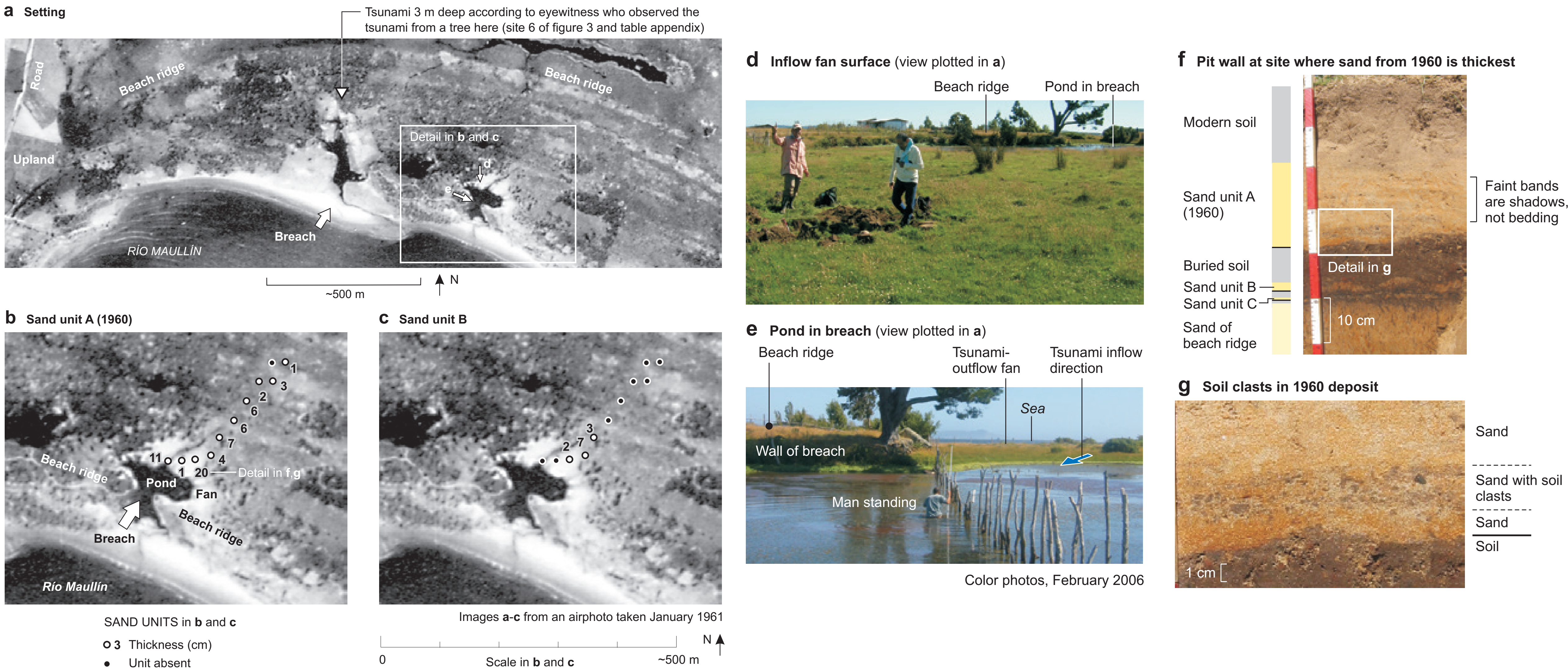


FIG. 8. The Chanhué fan (Figs. 2e, f, 3a) is evident on airphotos from 1961 from its light-toned apron of sand (**a-c**). The 1960 tsunami laid down sand as much as 20 cm thick (**b**), while an underlying sand sheet is as much as 7 cm thick (**c:** dots locate pits and the adjoining numbers give the sand thickness in centimeters). The field views of landforms and deposits (**d-g**) are keyed to locations in a and **b**.

Mr. Maldonado, age 30 in 1960, was in Maullín during the earthquake. On horseback he raced home to Caulle, 5 km by dirt road, to check on his mother. After picking her up he proceeded southeastward to high ground. Because he never saw the tsunami throughout this trip, it is likely that the first wave did not reach the Caulle breaches that would be later cut or reamed and which he had to cross to reach his home. However, the tsunami eventually succeeded in flooding Mr. Maldonado's home, where it left a high-water mark on interior walls (Atwater *et al*., 2005a, p. 11). This flooding probably took place during the second wave. The high-water mark, surveyed in 1989, was about a meter above the ground surface and 5 m above the estimated tide level at the time of the tsunami.

Both Ms. Gallardo and Mr. Maldonado reported that the 1960 tsunami left ponds on the beach-ridge plain west of Maullín. Mr. Maldonado further inferred that the 1960 tsunami cleaned out the fill of a pre-1960 pond. He stated that, prior to this tsunami, what would become the scour pond nearest his home in Caulle (southern 'Breach' in figure 3b) had been made of soft ground that offered little support for a fence he attempted to build. He described resorting to fence poles as much as 10 m long, and he recounted that the ground would sink under his feet and rise around him-as does the floating mat in the Caulle pond that we surveyed.

4.2. Chanhué

Tulio Ruiz provided eyewitness accounts of the first two waves at La Pasada, about 2 km up the Río Maullín from Chanhué (Figs. 2f, 3a). Mr. Ruiz, 23 years old in 1960, waded through waist-deep water of the first wave on his way to high ground, where he watched the second wave carry away his family's home.

According to Mr. Ruiz, the tsunami left a high-water mark that he observed on a religious statue a few hours later. In 1989 we surveyed that level as 5 m above our estimate of the tide level at the time of the tsunami.

5. Landforms

The beach-ridge plains breached at Caulle and Chanhué swing inland from the present Bahía Maullín to the vicinity of Maullín and La Pasada, respectively (Fig. 2d-f). The breach and fan studied at Caulle fan is 2 km inland from the 1960 shoreline (Fig. 3a), while the Chanhué features are little more than 100 m from the shore (Figs. 3a, 8a).

5.1. Beach ridges

Dozens of beach ridges curve across the plains on both sides of the lower Río Maullín. Though none of the ridges have been dated numerically, their weakly developed soils and parallel curvature imply that all are of Holocene age.

The ridges are founded on beach sand and capped by dune sand, as judged from beachfront outcrops that expose the core of a beach ridge 5-10 m high near Chanhué. The lowest meter of these outcrops consists of parallel-laminated fine sand with abundant heavy-mineral layers. This probable swash-zone deposit grades upward into arkosic fine sand that contains cross-beds in sets decimeters thick.

The Río Maullín cuts across the trends of beach ridges west of Maullín and east of La Pasada. We speculate that this cross-cutting resulted from enlargement of the river through capture of the catchment of Lago Llanquihue. Llanquihue, a lake largely fringed by a Pleistocene moraine, may have drained eastward past the south flank of Volcán Osorno some thousands of years ago (Fig. 2c). An Osorno eruption may have blocked that path, spilling the lake across the moraine into the Río Maullín.

Sand dunes cross and obscure the beach-ridge trends west of Caulle (Figs. 2f, 4a). They reach heights several meters greater than the ridges (Fig. 4b). In size and orientation on airphotos taken in 1944 they resemble coastal parabolic sand bodies that abound to the south-southwest (Fig. 2e). Like so-called chevrons on other coasts (Bourgeois and Weiss, 2009), they are more readily explained by wind than by tsunamis, though tsunami erosion and deposition may yield a sandy plain on which wind may build parabolic dunes (Goff *et al*., 2009). The dunes west of Caulle may have served as sand sources for the Caulle fan, and they also may have even funneled the 1960 tsunami toward that fan.

5.2. Breaches

The breaches near Caulle and Chanhué form openings a few tens of meters wide in the beach ridges they cut. Each breach holds a shallow pond several meters below the ridge crest. The pond floors in 2006 felt like dense sand both when walked on and when tapped with a surveying rod. In the Caulle pond the maximum measured depth to the floor is 2.2 m (Fig. 5); in the Chanhué pond, about 1 m (Fig. 8e). By 2006 the Caulle pond was choked with aquatic plants that form a floating mat barely capable of supporting a prone adult. The Caulle pond extends a few tens of meters seaward of its breached beach ridge, perhaps because of nickpoint retreat.

5.3. Fans and their geomorphic evidence for tsunami flow directions

Fans on the landward sides of the Caulle and Chanhué breaches are evident on black-and-white airphotos taken in January 1961, seven months after the 1960 tsunami. They are marked by white aprons that extend several tens of meters inland and probably represent bare sand (Figs. 4a, b; 8a-c).

Two lines of geomorphic evidence show that the 1960 tsunami flowed mainly or exclusively inland through the breach that adjoins the Caulle fan. First, on the January 1961 airphotos, the Caulle fan includes distributaries that radiate landward from the breach in a birdfoot pattern (Fig. 4b). Second, the lowest topographic path across the beach-ridge plain rises seaward from the breach to Bahía Maullín (Figs. 3d, 4a, c). To return to the sea by this northwestward path, waters of the 1960 tsunami at Caulle would need to have flowed 2 m uphill. A similar rise impedes drainage from the Caulle fan northeastward into the tidal Río Maullín (Fig. 3e). The receding waters more likely flowed into the Río San Pedro Nolasco (Figs. 2e, 3a). Perhaps the tsunami drained southwestward from Caulle in the broad swale that separates beach ridges Y and Z of figures 4a and 4c. The Caulle fan extends landward into this swale, from the breach through ridge Y, as does modern drainage from the pond, which follows the tsunami's birdfoot channels.

Landforms at Chanhué, by contrast, suggest both inflow and outflow. The 1961 airphotos show tributary gullies on both sides of the beach ridge; these give the pond an hourglass shape (Figs. 8a-c). The pond now drains to the Río Maullín, little more than 100 m away. It is also entered, according to residents interviewed in 2006, by extreme high tides in winter.

6. Fan stratigraphy and facies

The fans studied rest on well-sorted fine arkosic sand termed unit D (Fig. 5). Its thickness and genesis were difficult to determine, because being saturated with water, the sand collapsed in pits and auger holes. However, because fine arkosic sand is widespread elsewhere on the area's beach-ridge plains, we assume that unit D accumulated on beaches, back-beach dunes, or both.

Above this foundation lie as many as three buried soils, each overlain by very fine to fine, well-sorted arkosic sand. We illustrate this sequence mainly for the Caulle fan (Figs. 5-7), where the sand units are thicker and were studied more thoroughly than at Chanhué (Fig. 8).

The Caulle fan deposits are probably limited to the vicinity of the white apron and distributary channels on the 1961 airphoto (Fig. 4b). Their landward taper contrasts with the uniform thickness with the 1960 sand sheet to the west, which stays in the range 10-20 cm thick except near other breaches (Fig. 4d, e). The fan differs further in overlying two earlier sand layers that each rest on a buried soil. We did not find evidence for pre-1960 tsunamis west of ridge Y in figure 4c, even though we usually dug to a depth at least twice the thickness of the 1960 deposit. Furthermore, in the two places checked we found no sand sheets of any age landward of the toe of the Caulle fan (Fig. 4d).

Three successive sand units above the basal unit D can be traced across the Caulle fan. Each rests on a distinctly different buried soil. Unit C, the lowermost, probably represents a prehistoric tsunami, while units B and A probably represent the tsunamis of 1575 and 1960, respectively.

6.1. Unit C

Unit C, tabular and mainly 5-10 cm thick, is found between apparent crests in beach-ridge sand of unit D. The soil beneath is typically less than 5 cm thick. In pit 1 this soil is sandy and olive gray (Fig. 6a), as it is in pit 10.

The upper half of the underlying soil in pit 10 contains horizontal, growth-position woody roots as large as 1 cm in diameter (Fig. 6c). Such roots are absent from overlying unit C itself and from any deposit above it. One of the roots gave an age of 710±50 ^{14}C yr BP (Beta-216265). The corresponding calendar age range, AD 1270-1400 at two standard deviations, is probably a close maximum age for the tsunami represented by unit C. In that case, unit C, probably correlates with the youngest prehistoric sand sheet at Chuyaquén, which also dates to the 14th century AD (location, Figs. 2e, 3g; stratigraphy, Cisternas *et al*., 2005).

Unit C may contain eolian deposits less than 15 m from present scour pond. In that area the upper part of the unit includes several sand layers a few millimeters thick that are intercalated with peaty layers as much as 3 cm thick. If the sand laminae were not deposited by wind, the peat layers may have been deposited as detritus.

6.2. Unit B

Unit B consists of dark gray sand that rests on soft peaty mud. The sand is as much as 30 cm thick where preserved in its entirety. But the unit's depositional thickness and extent are poorly known because of widespread trampling by livestock. The trampling caused upward injection of the peaty mud into the stronger, sandy soil that separates sand units A and B, and which formed the land surface in the years before 1960. Grazed and perhaps plowed in those years, this stronger soil probably loaded the soft peaty mud (Fig. 6b).

Bracketed in time between the 14th century AD (unit C) and 1960 (unit A), unit B probably represents the enormous and well documented Chilean tsunami of 1575. This tsunami likely accounts for the penultimate sand sheet at Chuyaquén (Cisternas *et al*., 2005).

6.3. Unit A

Unit A is evident in birdfoot channels shown on figure 4b. From a maximum measured thickness of 60 cm it tapers to fan's landward edge, where it is broken and swirled by hoofs. The sand ranges in color from olive gray to orange. It abruptly overlies brownish-gray sandy soil 20-40 cm thick, and it is capped by the sandy modern soil, which is firm on high ground and soft on low ground.

Where thicker than 30 cm, the uppermost sand unit at each of the two studied fans contains primary sedimentary structures. At Caulle, close to the scour pond, unit A shows a consistent internal sequence, summarized here from bottom to top (Fig. 7a, b) and interpreted below in section 7.2:

1. Basal structureless sand: A few centimeters of fine sand that lacks larger clasts and also shows no internal structure. The unit, evident in figures 6b, 7b, and 7d, is too thin to plot in figures 7c. It is locally absent in pit 10 where a boulder-size clast rests directly on the buried 1960 soil (Fig. 7b).
2. Clast-rich sand: The next division contains lenses of sedimentary breccia marked by angular to subrounded clasts mainly of pebble and cobble size (Fig. 7b, d, e). The largest clast found, 0.5 m in diameter, spans entire thickness of unit A (pit 10). Most of the clasts are sand-poor, light weight, and reddish brown to orange. Their low density and paucity of sand suggest that they originated as peat, and their color suggests that iron within the clasts was oxidized by desiccation after their deposition on the fan. Other clasts, brownish-gray and sandy, resemble the slightly organic upper part of the soil beneath sand unit A. These sandy clasts may have been eroded from the adjoining sandy plain. Sand between the clast lenses locally contains indistinct parallel laminae.
3. Laminated sand: The upper part of unit A consists of distinctly laminated sand (Figs. 6a, 7a). The laminae are defined by slight differences in heavy-mineral content and in penetration by peeling grout. The laminae are entirely parallel >50 m from the present scour pound. Closer to the pond, in pits 10, 2, 4, and 1, the laminated division also contains an interval 5-10 cm thick of ripple-drift cross-laminae, with landward-dipping foresets. In pits 2, 4, and 1 this interval is bounded by parallel laminae below and above (Fig. 7a).

An indistinct version of this sequence appears to be present where unit A is thickest in Chanhué. In the trench wall shown in figure 7e, unit A contains a basal sand layer free of rip-up clasts and an overlying layer that contains soil clasts (like internal sequences 1 and 2, above). In a sediment peel of this trench wall, sand above the clast-rich layer contains parallel laminae (like sequence 3).

7. Interpretations

7.1. Correlation with the 1960 tsunami

Landward-directed flow during the 1960 tsunami probably deposited most or all of unit A at both Caulle and Chanhué. This inference best explains the white fringe on the landward side of scour ponds on the 1961 airphotos. It also explains the birdfoot distributaries on the Caulle fan, the likely derivation of the Caulle clasts from a pre-existing scour pond, and the landward climb of the ripple-drift cross laminae.

At the Caulle fan, pebble- and cobble-size clasts rule out an eolian source for the lower part of sand unit A, as does the small amplitude of the ripple-drift laminae. The fan's strongest candidates for eolian deposition are indistinct laminae in the sandy soil beneath unit A (described in figure 5) and sand laminae in the peat above unit C (Fig. 6c).

7.2. Correlation with individual waves of the 1960 tsunami

Eyewitness accounts presented above (under the heading '1960 tsunami') aid in assigning subdivisions of Caulle unit A to particular phases of the 1960 tsunami. The accounts imply that the tsunami's first wave did not reach the fan we studied at Caulle, and that the second wave was probably the largest. Accordingly, the internal sequence of unit A can be interpreted as follows:

As it began pouring through a pre-existing breach, the second wave deposited the basal fine sand of unit A. This sand may have been derived from beach ridges and dunes farther west on the beach-ridge plain (Fig. 4).

As the second wave continued to its crest, the flow depth and velocity through the breach increased. The flow ripped out the previous pond's fill and broke off chunks of adjoining beach-ridge soil. The erosion bulked up the flow with clasts and sand. Upon exiting the breach these aggraded the fan with the indistinctly laminated, clast-rich horizon of unit A.

After the breach had been cleaned of its fill, the waning part of the second wave, or perhaps a later wave, laid down the laminated sand that forms the upper part of unit A.

The increasing flow inferred for phases 1 and 2 can be explained by analogy with video footage of the 2004 Indian Ocean tsunami. Some of this footage shows a tsunami wave as a surge that grows in height and speed, as illustrated by a sequence of scenes from Banda Aceh that can be found on the cover of a UNESCO tsunami-safety booklet (Yulianto *et al*., 2010). The increase in flow may result from a tsunami wavelength that is long enough for the wave crest to arrive tens of minutes after the wave front.

7.3. Recurrence of breaching and fan deposition

René Maldonado's evidence for a pre 1960 tsunami-his finding soft ground where the 1960 tsunami scooped out a pond (section 4.1)-accords with stratigraphic evidence for pre 1960 inception of the tsunami-scour fan that we studied nearby in Caulle. Pre 1960 tsunamis probably account for sand units B and C (Figs. 5, 6). Though largely deformed by the trampling of livestock across soft ground, unit B locally shows an original thickness of 30 cm or more (Fig. 5, pits 9 and 5). If analogous to the 1960 tsunami deposits along the profile in figure 4c, unit B records the sandy waters of a tsunami that poured through a breach and buried a soil behind it.

The occurrence of one or two pre 1960 tsunamis is also implied by pre 1960 sand layers at the tsunami-scour fan at Chanhué (Fig. 8). These sand layers are thin enough, however, that they might represent ordinary tsunami sand sheets, produced without the aid of beach-ridge breach. Alternatively, although tabular, these layers might have been deposited by wind.

7.4. Correlation with earthquakes and tsunamis recorded at Chuyaquén

The sequence of sand units C, B, and A of the Caulle fan probably matches one-for-one with the three most recent sand sheets dated by Cisternas *et al*. (2005) at nearby Chuyaquén. We base this match mainly on radiocarbon dating of unit C and of its probable Chuyaquén correlative. The small woody root below unit C at Caulle gave an age (AD 1270-1400) that overlaps with ages of *Juncus* (rush) culms surrounded by tsunami deposits of unit C at Chuyaquén (AD 1280-1390).

The dated plants in both places probably died from the event that produced the sand layer, so the age of the dated material is probably indistinguishable from the time of the event. At Caulle, the woody roots are small, covered with bark, difficult to cut or break, and still connected with dozens of rootlets (Fig. 6c). The roots are restricted to the soil below unit C. The soil above unit C, soft and peaty, probably represents a wetland in which the woody plant died. Perhaps the wetland resulted from rise in local ground-water level in response to cutting of the nearby breach, regional tectonic subsidence, or localized subsidence from shaking-induced settlement. At Chuyaquén, the pre-earthquake *Juncus* marsh subsided to intertidal levels below those where the *Juncus* can survive.

8. Conclusions

1. Maximum heights reached by the 1960 tsunami decrease inland, more steeply across a beach-ridge plain than along the tidal Río Maullín. A post-tsunami survey that emphasized tsunami runup, conventionally measured as height at the landward limit, would greatly underestimate heights reached nearer the shore of the beach-ridge plain.
2. As it crossed beach-ridge plains, the 1960 tsunami reamed out breaches that already existed in the ridges and aggraded fans behind them. The fan behind one of the breaches, 2 km inland, was likely aggraded by three tsunamis. The breach was probably cut during a tsunami between 1270 and 1400, and it was probably refreshed by the outsize historical tsunami of 1575 as well during the 1960 catastrophe.
3. Paired breaches and fans may aid in identifying and quantifying tsunami hazards on coasts dominated by beach-ridge plains. A breach may be visible on airphotos, satellite images, and laser topographic maps. It may endure for centuries or more if, as in the example near Caulle, it was cut too far inland to be healed by longshore drift, and if it escapes burial by eolian sand. The associated fan deposits may aid in showing how the breaches formed, when they originated, and how often tsunamis have poured through them.

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APPENDIX

Text. Deaths from the 1960 tsunami at the Río Maullín

At least 116 people died from the tsunami along the lower reaches of the Río Maullín. Nearly all these people were close to the mouth of the river when the earthquake occurred; 105 to the north in Quenuir Bajo, at least 10 to the south on the sand plain west of Maullín. At least one additional person died from being swept away by the tsunami in the town center of Maullín itself.

Quenuir Bajo

René Serón counted 105 fatalities from Quenuir Bajo. Thirty-six years old in 1960, Sr. Serón was at that time a civil servant charged with keeping records of births, deaths, and other public matters for citizens of Quenuir Bajo. He recalled that the town had about 50 houses, a church, a cemetery, and 400-450 inhabitants. Mr. Serón was in Quenuir Bajo during the earthquake, survived the first wave in a boat, then went ashore 4 km north-northeast of Quenuir Bajo, at Caleta Piedra Blanca.

The authoritative death toll provided by Sr. Serón accords with the rough estimate of 75-100 given by Estalino Hernández and María Gallardo, who lost their 13-year-old son to the tsunami. Hernán Cárcamo Gómez estimated 36-56 deaths.

Most of the deaths from Quenuir Bajo were blamed, by various informants, on attempts to flee the earthquake shaking. Many citizens, like Mr. Serón, reportedly took to boats that were swept away by the tsunami; some of these boats capsized. It was said that people took to boats because the earthquake shaking had made them distrust the land.

Sand plain west of Maullín

The tsunami killed eight members of the family of Armanda Cubate and her nephew, Nelson Cubate: her mother, brother (Nelson's father), and six of her nieces and nephews. Armanda, Nelson, and five others survived the tsunami afloat on the roof of the family house, which had been located along the Río del Rey (5389.0 N, 612.5 E). Nelson stated that the third wave swept away not only the house but also a nearby tree containing his father and at least one other person; these people drowned. Armanda stated that survivors on the roof recovered the body of her mother while the roof was still adrift.

Antonio Mancilla stated that the tsunami killed three members of his family. These people were probably located a few hundred meters east of the Cubate home.

Nelly Gallardo stated that she lost an uncle to the tsunami. He was probably at or near their home (5389.7N, 611.7E), which was close to the Río Pasaje about 1 km northest of the Cubate home. Ms. Gallardo also stated that she heard a man cease crying for help during the night, while she and Mr. Mancilla were both floating on a pole, and that this man's body was found later. The total number of dead from the sand plain was 10 or more according to Ms. Gallardo, 14 according to Mr. Mancilla, and 18 according to Ms. Cubate. René Maldonado reported that he heard of 15 deaths in the area.

Maullín

The second wave swept away a building containing Ramón Atala, who was never seen again. This incident, the basis of a cautionary tale in Maullín, was confirmed by Sr. Atala's son, Eduardo Atala, and by another relative, Nabih Soza (Atwater *et al*., 2005a). The building was located near the center of town, on the waterfront near the site of the present-day ferry ramp (5392.3N, 617.4E). Photographs taken during the tsunami confirm that it removed the building (Fig. 1 appendix).

Pedro Soto Soto of Maullín may have lost a son to the tsunami, perhaps at the site of the former Soto house along the Río Cariquilda on the southern outskirts of Maullín. We lack conclusive notes about this possible loss.

TABLE APPENDIX. ESTIMATES OF MAXIMUM HEIGHT REACHED BY THE 1960 TSUNAMI AT THE RÍO MAULLÍN. LISTED FROM WEST TO EAST. ALL POINTS EXCEPT SITE 28 ARE PLOTTED IN FIGURE 3A.

Site	Area	UTM east (km)[1]	UTM north (km)	Height[2] (m)	Reliability[3]	Evidence[4] (subtract 1 m from height above 1989 tide-staff datum to obtain approximate height above tide level during first waves of the 1960 tsunami; see footnote 2).	Informant (and age in 1960)
1	Quenuir	610.2	5394.9	9.5	A	**Wetted floor of house.** Informant saw second wave inundate floor of uncle's house, which remained standing. Water was pouring across divide between Caleta Pichicuyén and Río Las Lajas; it did not splash to the observed level. Surveyed relative to Caleta Pichicuyén; estimated uncertainty ±0.5 m, mainly from use of a single low tide to relate measurements to elevation datum at Maullín.	Tulio Hernández (28)
2	West of Maullín; near mouth of Río San Pedro Nolasco	611.7	5389.7	>4	C	**Debris in trees.** Observed by informant several months after tsunami, upon return to site of her home. (The home had been washed away by the tsunami, which the informant survived by floating on a pole; Atwater *et al.,* 2005a, p. 14.) She pointed to limbs about 4 m above ground. This ground surface is above highest modern tides. Not surveyed.	Nelly Gallardo (23)
3	West of Maullín; lower reach of Río del Rey	612.5	5389.0	>4	C	**Recollection of view from roof of house.** Informant estimated first wave as about 5 m and second wave as 8-10 m. These estimates are probably relative to ground surface at house site, which is above highest modern tides. Informant observed much of tsunami from roof of house, which she estimated to have been as much as 12 m high. Compare with estimate for same site, from Nelson Cubate. Not surveyed	Armanda Cubate (38)
4	West of Maullín; lower reach of Río del Rey	612.5	5389.0	>4	C	**Recollection of view from roof of house.** Informant estimated first wave as 1 m, second as 5 m, third wave as even higher. Stated that third wave swept away house, on whose roof he had taken refuge with his aunt (Armanda Cubate) and five others. Asked about his young age as of 1960, he stated that he nonetheless remembers enough (*bastante*). Not surveyed.	Nelson Cubate O. (4)
5	West of Maullín; Los Caulles	613.2	5390.1	5.1	A	**Water or water line in house.** Water covered floor of informant's house to depth of 20-30 cm (Atwater *et al.,* 2005a, p. 11). Evidence for this water not recorded during interview, except for presence of sand noted by informant's wife (who was not present at interview). Surveyed; closure error <0.2 m.	René Maldonado (30)
6	Chanhué (between Quenuir and La Pasada)	613.6	5396.5	>4	C	**Inundated base of tree.** Informant estimated maximum level at a peta tree (*Mircuegenia exucca*) in which she and 8 others had taken refuge from the tsunami (Atwater *et al.,* 2005a, p. 13). She gave maximum level as 3 m above base of tree. Tree was several hundred meters inland from beach of 1960. Elevation listed at left was not surveyed; it is based on informant's estimate of water depth and on interviewers' estimate that site of tree is at least 1 m above highest modern tides.	María Vera (44)

table appendix continued.

Site	Area	UTM east (km)[1]	UTM north (km)	Height[2] (m)	Reliability[3]	Evidence[4] (subtract 1 m from height above 1989 tide-staff datum to obtain approximate height above tide level during first waves of the 1960 tsunami; see footnote 2).	Informant (and age in 1960)
7	West of Maullín; Los Caulles	614.2	5391.3	5	B	**Inundated base of tree.** Informant identified approximate water level on cypress tree in which he had taken overnight refuge from tsunami (Atwater *et al.,* 2005a, p. 13). Base of tree has a surveyed elevation of 5.25 m above 1989 tide-staff datum, with a closure error of <0.2 m. Water level identified is about 0.8 m higher, with uncertainty-perhaps ±0.3 m-from a lack of distinctive features on inundated part of trunk.	Ramón Ramírez Solís (15)
8	West of Maullín; Huichamilla	615.4	5390.6	2.6	B	**Debris limit near apple orchard.** Noted by informant after tsunami, who fled toward Tentén hill immediately after earthquake. Approximate site relocated by informant was surveyed as elevation 3.56 m above 1989 tide-staff datum, with closure error <0.2 m.	José Elizardo Torralbo (27)
9	West of Maullín; Huichamilla	615.5	5390.8	2.7	B	**Inundated base of tree.** Informant stated that third wave reached base of an arrayán tree (*Luma apiculata*) and several bushes about 25 m from home, and that this was maximum level reached near his home by tsunami. Informant may have fled toward Maullín during tsunami, in which case he probably inferred the level from debris found upon his return. Surveyed; closure error <0.2 m	Ricardo Águila (34)
10	West of Maullín; northeast of Huichamilla	615.6	5391.4	>4	B	**Debris limit near house.** Informant found wood within about 30 m of his house soon after tsunami, which occurred while he was near Quenuir. Surveyed point (elevation 5.37 m above 1989 tide-staff datum; closure error <0.2 m) is about 30 m from a large shed on informant's property, probably at or near debris limit he identified.	Enoc Ojeda (20)
11	West of Maullín, near Los Pinos	616.0	5392.2	>3	B	**Washed-out bridge across drainage ditch.** Bridge shown as washed out on air photo taken by the Chilean government on June 4, 1960. Photo also shows many scours into bank of ditch and many tree trunks scattered on adjacent fields. Ditch drains northeastward. Surveyed point (elevation 4.17 m above tide-staff datum) is on low, reconstructed bridge; closure error <0.05 m.	air photo 7601
12	La Pasada	616.5	5393.8	>5	B	**Transported lumber.** Flooring from informant's family house came to rest on a small rise west of La Pasada. Informant identified it by its wood. The wood is no longer present on the rise. We surveyed the lowest (elevation 6.18 m on 1989 tide-staff datum) and highest (6.91 m; same datum) parts of the rise. Estimated uncertainty 0.1 m, as with water line on statue.	Tulio Ruiz (23)
13	Maullín; western outskirts	616.5	5392.4	5.6	B	**Water line on outside of house.** Informant found wood siding wetted. He estimated the high water line on the house when interviewed in 1989, and he said he observed this line the day after the tsunami. Surveyed; closure error <0.05 m.	René Garcia (39)

table appendix continued.

Site	Area	UTM east (km)[1]	UTM north (km)	Height[2] (m)	Reliability[3]	Evidence[4] (subtract 1 m from height above 1989 tide-staff datum to obtain approximate height above tide level during first waves of the 1960 tsunami; see footnote 2).	Informant (and age in 1960)
14	Maullín, western part of town	616.80	5392.40	>2.8	A	**Transported house.** House came to rest at intersection of two main streets, Gaspar del Río and Eduardo Rodríguez, where it was photographed soon after the tsunami (Atwater *et al.,* 2005a, p. 4). It was removed by June 4, 1960, as judged from air photos of that date (frames 7597, 7598). Surveyed point, elevation 3.81 m on the 1989 tide-staff datum, is on sidewalk a few tens of meters east of intersection, close level of intersection. Closure error <0.05 m.	Photograph from municipal records
15	Maullín; western part of town	616.90	5392.35	3.8	B	**Evidence not recorded in field notes.** Site at foot of rise toward Cerro Tentén. Surveyed elevation 4.84 m on the 1989 tide-staff datum; closure error <0.05 m.	
16	La Pasada	617.1	5393.85	<5.2	A	**Dry floor of school.** School served as refuge for many in La Pasada, including informant, who went there after the third wave and found no water on its floor. Surveyed elevation 6.2 m on the 1989 tide-staff datum, subject to same 0.1 m uncertainty as water line on statue.	Tulio Ruiz (23)
17	La Pasada	617.15	5393.70	3.1	A	**Water line on statue.** By flashlight a few hours after highest waves, informant noted a water line at the neck of a small statue of the Virgin Mary. Statue stands beneath an arch that provides protection from rain. We surveyed the neck as elevation 4.10 m on the 1989 tide-staff datum, with an estimated uncertainty of 0.1 m from use of five synoptic water-level readings to relate measurements at La Pasada to the elevation datum at Maullín.	Tulio Ruiz (23)
18	Maullín; Plaza de Armas	617.3	5392.3	>4.9	A	**Water in kiosk.** Informant observed that hollow interior of kiosk foundation was full of water after tsunami. He stated that water can enter this space only though holes in elevated floor of kiosk, which is sheltered from rain by kiosk roof. We surveyed the top of these holes as elevation 5.86 m above the 1989 tide-staff datum, with closure error <0.05 m. Floor of informant's store (surveyed 4.83 m above that datum), which fronts on plaza a few tens of meters from kiosk, was also inundated by tsunami (this report, Fig. 3B).	Nabih Soza (27)
19	Maullín; along Río Cariquilda	617.3	5391.4	2.4	A	**Dry floor of hospital.** Hospital floorboards were wet below but not on top, even though hospital doors were left open when it was evacuated between earthquake and tsunami. Lowest three boards of hospital siding were wet. As a hospital employee in 1960, she observed these things soon after the tsunami. Palmira Estrada Estrada also saw dry floor upon returning to hospital four days after earthquake. She was interviewed independently while employed by the hospital in 1989 (Atwater *et al.,* 2005a, p. 1). We surveyed the top of the dry floor (elevation 3.46 m) and the top of the third siding board (3.48 m; both elevations with respect to the 1989 tide-staff datum), with a closure error less than 0.05 m.	Julia Paredes Toledo (54)

table appendix continued.

Site	Area	UTM east (km)[1]	UTM north (km)	Height[2] (m)	Reliability[3]	Evidence[4] (subtract 1 m from height above 1989 tide-staff datum to obtain approximate height above tide level during first waves of the 1960 tsunami; see footnote 2).	Informant (and age in 1960)
20	Maullín; south end of Tentén hill	617.3	5390.8	2.9	B	**Debris limit near house.** Informant found, morning after tsunami, fish and pieces of houses up to a line that ran through her yard and across an adjacent road. She did not see this material being deposited because she climbed Tentén hill after seeing first wave. She also found no water on floor of first story of house in morning after tsunami. We surveyed the road at or near the debris limt (elevation 3.9 m above the 1989 tide-staff datum) as well as the house floor (4.01 m above that datum), but we did not measure a closure error. The house, known as Casa Grande, provided shelter for some 40 families in the first weeks after the earthquake and tsunami (Atwater *et al.,* 2005a, p. 16).	Yolanda Montealegre Mücke (40)
21	La Pasada	617.4	5393.8	>3	B	**Washed-up ferryboat.** A ferryboat grounded on a broad flat surface 0.5 km northeast of the wharf where it had been tied up before the tsunami. The boat is no longer present on this surface. We surveyed the surface as elevation 4.44 m above the 1989 tide-staff datum, subject to same 0.1 m uncertainty as the water line on statue (site 17).	Tulio Ruiz (23)
22	Chuyaquén	619.6	5391.4	>3.9	C	**Wet floor of barn.** Informant reported as hearsay. Barn belonged to a Sr. Buschman. Before the tsunami, informant lived 1.5 km to west (Atwater *et al.,* 2005a, p. 12).	José Miguel Navarro Silva (44)
23	Chuyaquén	619.9	5392.1	3.5	B	**Debris at foot of hillside.** Informant pointed out approximate landward limit of woody debris left by tsunami on his property. He probably observed this debris in the first few days after the tsunami. Surveyed elevation 4.54 m above the 1989 tide-staff datum, subject to error of ±0.3 m or more from difficulty of relocating exact site and from using synoptic measurements of tides to relate elevation to datum at Maullín. Informant also reported that the tsunami deposited sand in low places on his property (Atwater *et al.,* 2005a, p. 15).	Juan Vera Mancilla (34)
24	Chuyaquén	620.2	5391.5	>2.5	B	**Tranported fence.** Found by informant near road from Chuyaquén to Maullín, probably in first few days after tsunami. Interpreted by him as having been derived from his property on nearby lowland between Buschman's barn and Río Ballenar. Approximate site, as identified by informant, surveyed to elevation 3.66 m above the 1989 tide-staff datum, subject to error of ±0.3 m or more from difficulty of relocating exact site and from using synoptic measurements of tides to relate elevation to datum at Maullín.	Alejandrino Mancilla (age not recorded)
25	Chuyaquén	622.0	5393.0	3.5	B	**Inundated fence above highest modern tides.** First wave reached base of fence; second wave passed through fence. Level of second wave about 1 m above highest modern tides, as estimated from sighting to horizon above river. Highest modern tides assumed similar to those measured at La Pasada and along Río Cariquilda.	Óscar Navarro Navarro (34)

table appendix continued.

Site	Area	UTM east (km)[1]	UTM north (km)	Height[2] (m)	Reliability[3]	Evidence[4] (subtract 1 m from height above 1989 tide-staff datum to obtain approximate height above tide level during first waves of the 1960 tsunami; see footnote 2).	Informant (and age in 1960)
26	Cariquilda; upper tidal reaches of Río Cariquilda	623.8	5387.0	<2.5	B	**Comparison with modern high tides.** Soon after tsunami, informant saw debris near site where his rowboat had been washed away. In 1989 he estimated that highest debris was close to level of highest modern tides, which is marked by wrack of bulrush stems. We surveyed highest such stems as elevation 2.5 and 3.3 m above the 1989 tide-staff datum. Uncertainties from surveying estimated as ±0.3 m, mainly from importing Maullín datum by synoptic measurement of three low tides and two high tides.	Jorge Ruiz (34)
27	Cariquilda; upper tidal reaches of Río Cariquilda	624.4	5386.5	<2.5	B	**Comparison with modern high tides.** Informant estimated that tsunami did not reach levels more than 1 m above level of highest modern tides. Level of these tides is marked by modern bulrush stems and a bridge. Informant observed wood stranded by tsunami at a place that Atwater estimated to be 0.3-0.5 m higher than the modern bulrush stems. A second informant 1 km to north, René Leichtle Krebs, also stated that maximum level of tsunami along upper Río Cariquilda was about same as reached by highest modern tides. Not surveyed. However, highest modern tides reach a surveyed elevation of 2.6 m at La Pasada and near lower Río Cariquilda beside site of barn belonging to a person Sr. Argomedo called Sr. Buschman.	José Argomedo Hernández (22)
28	Misquihué	636.1	5401.2	<2.5	B	**Comparison with modern high tides.** Tsunami reached same approximate level as modern high tides in winter. We assume that levels of these tides are similar to those farther west.	José Ojeda Muñoz (40)

[1] UTM coordinates read off 1:50,000-scale topographic map and checked in some cases by identifying the site on vertical airphotos taken in 1979 and comparing the airphotos with the map. The most-exact locations are reported to the nearest 0.05 km.

[2] Relative to ambient tide during the first few tsunami waves at Maullín in 1960-a datum estimated to be 1 m higher than the survey datum in the 'Evidence' column (see footnote 4). Based on surveys in 1989. We assume that the sites of the high-water marks surveyed had already subsided before the tsunami arrived, and that post-seismic land-level changes were small in the Maullín area between 1960 and 1989.

[3] A, most reliable; C, least reliable.

[4] Heights in this column were surveyed with reference to high tides and low tides observed at a temporary tide staff in Maullín during days when surveying was done during the austral summer of 1989. We estimate that the datum for this staff is about 1 m below the predicted level of the tide during the 1960 tsunami. This estimate is based on measurements of the heights and times of low and high tides on the staff in 1989, comparisons of these measurements with tide-table predictions for Valparaíso in 1989, and Valparaíso tide-table predictions for 22 May 1960.

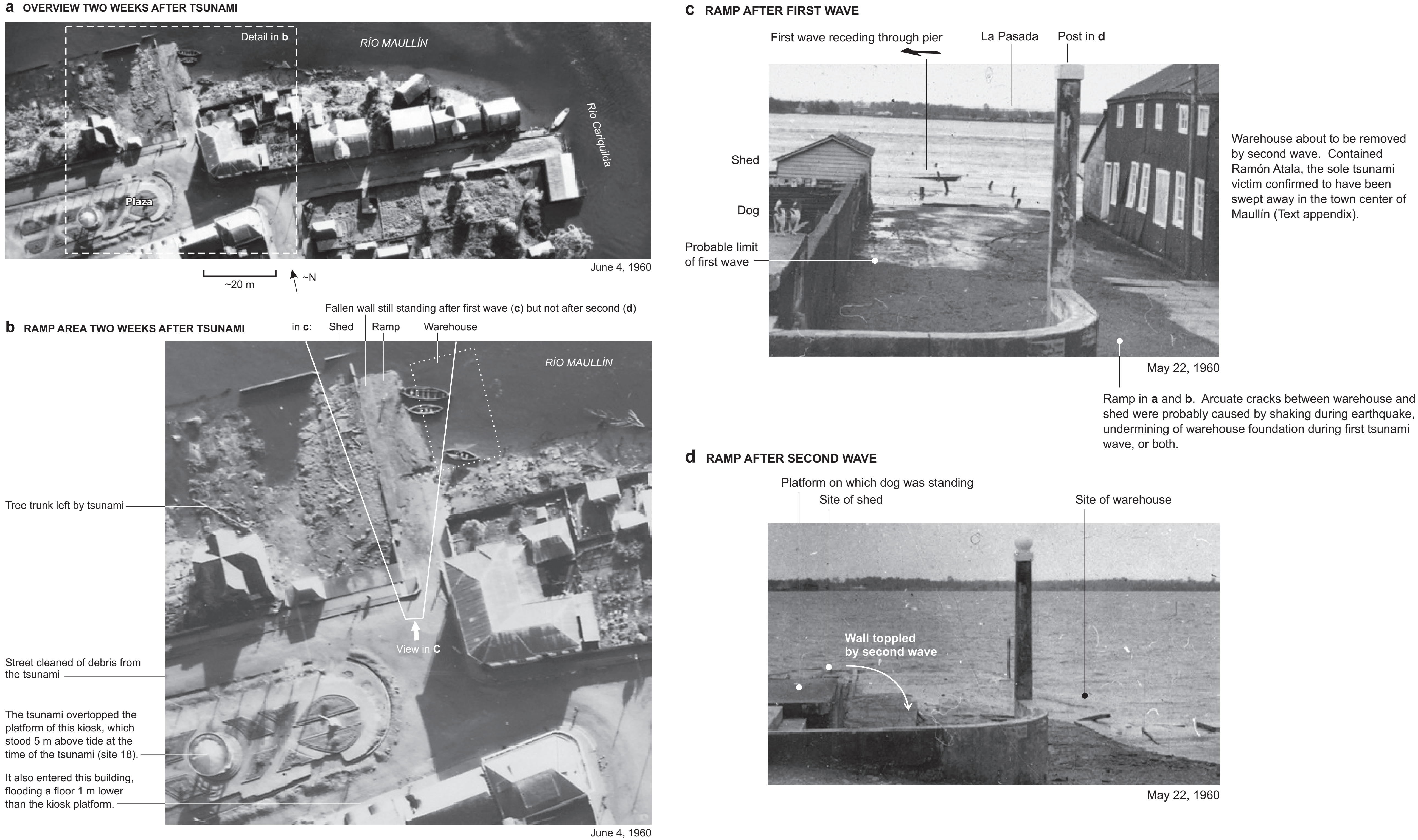

FIG. 1 appendix. Evidence for inundation by the first and second waves of the 1960 tsunami at Maullín. The story of Ramón Atala is also recounted in a public-safety booklet (Atwater *et al*., 2005a, p. 10).

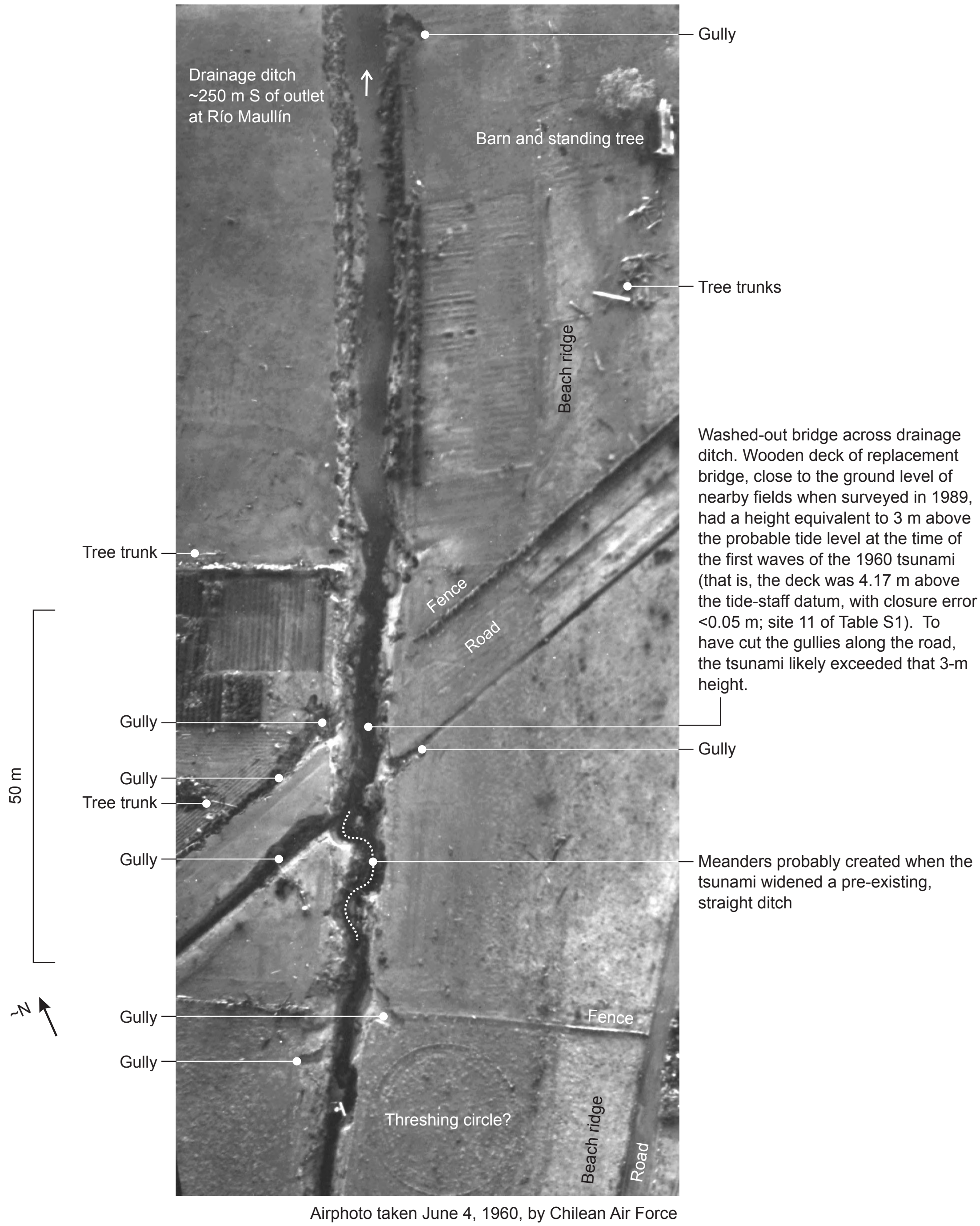

FIG. 2 appendix. Evidence for tsunami source at a drainage ditch west of Maullín. Site 11 of Table appendix, plotted in figure 3e.