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ORIGINAL ARTICLE

Assessment of paleoseismic heritage sites of Holocene megathrust earthquakes and tsunamis along the coast of south-central Chile (38°-42°S)

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Abstract
Earthquakes and tsunamis are natural phenomena that have strongly affected communities located along the Chilean active plate margin. Large-magnitude megathrust earthquakes produced at the plate interface of the subduction zone and their associated tsunamis have repeatedly impacted the Chilean coast, leaving a sedimentary record at particular sites from historic and prehistoric times. Here we assess paleoseismic sites related to late Holocene (< 1.5 ka) earthquakes and tsunamis that occurred along the Pacific coastline of south-central Chile (38°-42°S), which record critical information for the study of megathrust earthquakes. We focus on sites along the Valdivia segment that were affected by the great earthquake and tsunami of 1960 (Mw = 9.5; the largest recorded by modern seismology), which host geologic evidence of coseismic land-level changes found in tidal marshes and wetlands. We present an inventory of seven paleoseismic geosites composed mainly of different layers of buried soils and sand deposits, and a quantitative assessment of their scientific value, their potential touristic and educational value, and their degradation risk. These sites are considered part of the paleoseismic heritage of Chile and are relevant globally. Our inventory contributes to the establishment of management strategies for geoconservation of the coastal area of south-central Chile, and the mitigation of the effects of seismological hazards through the promotion of educational, touristic and outreach activities.

Keywords Paleoseismic heritage sites · Holocene · Megathrust earthquakes · Tsunamis · South-central Chile

Introduction

Chile is located on the western edge of the South American continental plate, where the Nazca oceanic plate is being subducted with a slightly oblique direction at a rate of 6.6 cm/year (Angermann et al. 1999 Fig. 1). This results in the formation of the Andean Mountain range, one of the most seismically and volcanically active zones in the world. Consequently, Chile and other Andean countries are constantly affected by large-magnitude earthquakes, making this territory a world-renowned natural laboratory for the study of volcanic and seismic processes. Based on these geological characteristics, it may be assumed that Chile has an important geological heritage (Benado et al. 2019).

Earthquakes are part of the history of the country and have modified the Chilean coastal landscape. Evidence of past earthquakes and tsunamis at different sites of interest to paleoseismology, along with the historical record, have contributed to a better understanding of the seismic cycle at this subduction zone on a scale of thousands of years, and to a better estimation of the recurrence of these events in distinct seismotectonic segments of south-central Chile (Cisternas et al. 2005, 2017b; Ely et al. 2014; Garrett et al. 2015). A notable example is the great Valdivia earthquake of May 22nd, 1960, the largest magnitude earthquake ever measured by humanity, which produced a large tsunami that impacted more than 1,000 km of the Chilean coast and other

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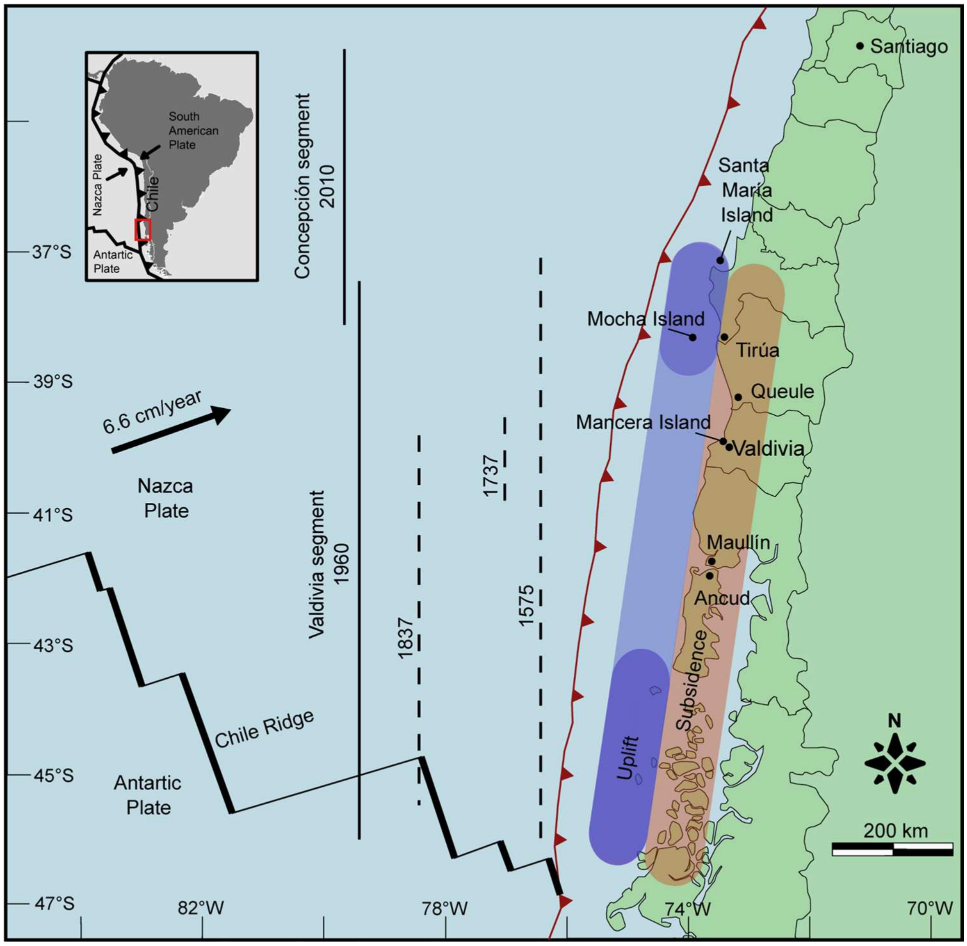

Fig. 1 Tectonic context and extent of the subduction zone's historical ruptures in south-central Chile. Solid lines show earthquake ruptures from 1960 and 2010. Dashed lines show estimated rupture lengths based on historical reports. Spatial distribution of uplift (blueish shaded areas) and subsidence (redish shaded areas) zones during the 1960 earthquake are also shown. Modified from Ely et al. (2014) and Garrett et al. (2015)

coasts and islands around the Pacific Ocean (Plafker and Savage 1970).

The movements of tectonic plates during earthquakes result in uplift or subsidence of the shoreline on a finite time scale. In specific cases, such as in low terraces formed in tidal marsh environments, there are sedimentary deposits that hold records of tsunamis associated with earthquakes that occurred in the last hundreds or thousands of years. The marshes are vegetated environments of halophilic flora that grow within the intertidal zone and the current saltmarshes (Aedo et al. 2021). Also, the coast of Chile is a great place to study the seismic cycle using geomorphological markers like marine terraces. These structures can present evidence of past relative sea levels and vertical changes of the coast that occur on time scales of hundreds to thousands of years. The youngest structures are low-lying constructional marine terraces which may contain deposits from ancient tsunamis associated with earthquakes. Paleoseismic sites are related to these low-lying marine terraces with minerogenic (e.g. sand or silt sediment sheets) and organic stratigraphic successions attributed to abrupt coseismic subsidence. The layers associated with tsunamis are laterally extensive, with sharp erosive lower contacts and can have different local sources near the coast (e.g. dunes or subtidal sediments) (Atwater et al. 1995, 2003; McCalpin and Nelson 1996; Cisternas et al. 2005; Satake and Atwater 2007; Garrett et al. 2013, 2015; Ely et al. 2014; Sawai 2020).

Some of these paleoseismic sites have additional ecological, educational, cultural, aesthetic, historical, and even spiritual values. These geosites are vulnerable and nonrenewable resources that can be affected by natural and anthropogenic processes. Consequently, these geomorphologically active sites and structures require careful management to protect them from degradation or loss of material (Gordon 2019). A successful conservation strategy must consider the social values that are involved in the management of territories where nature and society are linked (López Santiago et al. 2019).

Here, we present the first inventory and qualitative and quantitative assessment of seven sites of paleoseismic interest related to earthquakes and tsunamis that occurred during the Holocene (< 1.5 ka) on the coast of south-central Chile, between the Biobio and Los Lagos Regions (38-42°S). We estimate their scientific value, potential for touristic and educational use, and risk of degradation, to promote the conservation of these important elements of geodiversity and their use in educational activities to support communities to be better prepared for seismic hazards. Moreover, this initiative contributes to the valorization of the geological heritage of Chile, which has been promoted by various institutions at the national level, led mainly by the Geological Society of Chile and the National Service of Geology and Mining (Benado et al. 2019).

Geological Context

The seismic cycle in the active margin of south-central Chile

In south-central Chile, the main seismotectonic segments experiencing long-term differential uplift and subsidence are the Valparaiso, Concepción, and Valdivia segments (Fig. 1, Melnick et al. 2006). In certain coastal areas of Chile, there are geomorphological markers and deposits that show records of the regional uplift and subsidence associated with large subduction earthquakes (Bookhagen et al. 2006).

Large shallow earthquakes at subduction zones commonly warp Earth's surface (Sawai et al. 2004). In the interface of two plates, there are asperities such as sea mounts and fracture zones, that affect the sliding mechanics during earthquakes (Bilek et al. 2004, Seno and Hirata 2007; Scholz and Campos 2012; Lay et al. 2012; Avouac 2015). The physical mechanisms that characterize the subduction zone in Chile are not the same either along strike or with increasing depth in the seismogenic margin and depend on different variables (e.g., pressure, temperature, fluids in pores, and the roughness and geometry of the fault, among others). The width and dip direction change as the plate subducts. For this reason, it is assumed that large subduction earthquakes repeatedly rupture seismotectonic segments separated by barriers (Schurr et al. 2012). Those that have not broken for a long time in relation to the rate of convergence are called "seismic gaps" (Schurr et al. 2012).

Seismotectonic segments of the rupture zone act semi-independently and guide the deformation and the decimeter-to meter-scale changes that occur at the surface. Topographic elevation changes during the largest earthquakes follow a sinusoidal pattern of deformation across the margin (Melnick et al. 2006). This translates into uplift of the platform that is closest to the trench during the earthquake (coseismic moment) and subsidence after the earthquake (interseismic moment) (Fig. 1). In the case of south-central Chile, the Santa María and Mocha islands located offshore of the Arauco peninsula rise during earthquakes (Bookhagen et al. 2006; Melnick et al. 2006). On the other hand, coastal sectors far from the trench including Queule, Valdivia, Maullín and Ancud experience coseismic subsidence and interseismic uplift (Cisternas et al. 2005, 2017a, b; Nelson et al. 2009; Garrett et al. 2015).

Based on the comparison of the great earthquakes of Sumatra in 2004 (moment magnitude, Mw, 9.2), Maule in 2010 (Mw 8.8), and Tohoku in 2011 (Mw 9.0), Lay et al. (2012) proposed four distinct fault domains extending along the megathrust between the trench and the falling edge of the seismogenic zone (Fig. 2). Domain A extends up to 15 km below sea level; in this zone aseismic displacement and tsunamigenic earthquakes can occur. In domain B (between 15 and 35 km depth), large displacement earthquakes or megathrust earthquakes occur and can produce tsunamis. In domain C (between 35 and 55 km depth), events are smaller and more isolated and tend to release short-term energy that is transmitted both teleseismically and in strong local movements. Domain D (55 km depth and below) is a transitional zone of slow, low-frequency displacement events and tremor-type earthquakes. Understanding the segmentation of the subduction zone, which ultimately determines the size, location, and tsunami potential of subduction earthquakes, is one of the most important issues of evaluating the risk of these natural events (Schurr et al. 2012).

In the Valdivia segment, the 1960 earthquake slip occurred in the shallowest part of the plate interface (Moreno et al. 2009). Moreno et al. (2018) inferred that

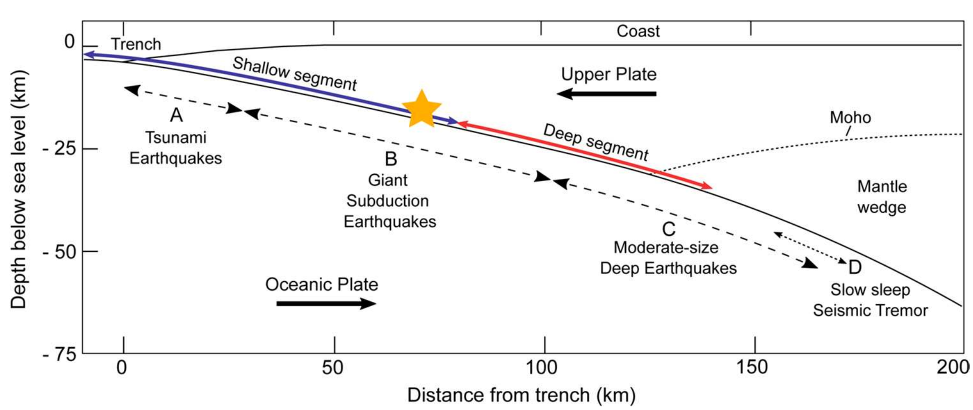

Fig. 2 Earthquake rupture domains in subduction zones (domains A, B, C and D) adapted from Lay et al. (2012). Also shown are the shallow and deep segments, and the estimated depth of the 1960 great earthquake rupture (yellow star) adapted from Moreno et al. (2018)

the 1960 rupture occurred in the shallow domain (A and B, Fig. 2) with a hypocenter at a depth of 20 km on the Nazca plate interface. In domain B, large earthquakes (> Mw 8.5) result in coseismic coastal subsidence and have a recurrence interval of a few hundred years (Melnick 2016; Moreno et al. 2018). Meanwhile, the earthquakes that occur in deeper domains (domain B-C) have lower magnitudes, greater frequency, and generate uplift of coastal land (e.g., earthquakes in Antofagasta in 1995 (Mw 8.0), Tocopilla in 2007 (Mw 7.7) and Constitución in 2012 (Mw 7.0); Melnick 2016). In the deep domain of the 1960 rupture zone, deeper and less frequent (~ 60 years) fractures occur that generate events of moderate size (e.g., Chiloé earthquake in 2016 of Mw = 7.6, Moreno et al. 2018) and precede the faulting of the shallower region that produces large earthquakes in a longer time interval of ~ 110 years (Moreno et al. 2018).

Marine terraces along tectonically active coast in south-central Chile

Seismotectonic segments in south-central Chile can structurally and topographically reflect several long-term earthquake cycles, by forming geomorphological features that maintain their respective style and deformation rate (Jara-Muñoz et al. 2015). Marine terraces have been used as reference markers of tectonic vertical deformation and associated fault-slip rates along the tectonically active coastal margin (Jara-Muñoz et al. 2016). Quantifying deformation allows for interpretation of the recurrence and magnitude of earthquakes on millennial time scales, even considering different levels of terraces (Jara-Muñoz et al. 2016). Studies of this type have been carried out on the marine terraces of the Arauco Peninsula by Melnick et al. (2009) at the limit of the Concepción and Valdivia segments, and by Jara-Muñoz et al. (2015) in the rupture zone of the 2010 Maule earthquake that covered 500 km of the subduction margin.

Due to their planar geometry and lateral extent, marine terraces of the study region are excellent geomorphological and geodesic markers of ancient sea-level positions reflecting, for example, vertical tectonism and intercalated sea-level oscillations in glacial and interglacial cycles (Jara-Muñoz et al. 2016). In marine abrasion terraces, the constant collision of waves with the coast creates a flat surface when the sea level remains approximately in the same relative position with respect to a land mass, pushing back the sea cliff (Alvarez-Marrón et al. 2008). The uplift rate of the abrasion terrace can be estimated from past changes in sea level and the age of the terrace (Bowles and Cowgill 2012). This type of study was carried out on Santa Maria Island in the Biobío Region by Melnick et al. (2006). Constructional marine terraces are formed due to the uplift and subsidence of the coast, related to the seismic cycle. This generates a difference in height between the current relative sea level and uplifted stranlines due to vertical changes produced by earthquakes.

Paleoseismic records of the coast of south-central Chile

Construction-type terraces hold records of vertical elevation changes in shorelines caused by earthquakes, which in some cases are evidenced by sedimentary sequences and deposits associated with past tsunamis in paleoseismic sites (e.g., Cisternas et al. 2005, Garrett et al. 2013, 2015, Ely et al. 2014). On the south-central coast of Chile, the vertical changes of uplift and subsidence during an earthquake are recorded in the stratigraphy of buried minerogenic and organic successions. These types of sequences are attributed to coseismic subsidence only when the layers have extensive lateral continuity (e.g. the soils are buried by sediments characteristic of lower zones like beach sand or tidal flat silt) and the subsidence is rapid and occurs synchronously at sites separated by great distances (Nelson et al. 1996; Shennan et al. 2016). The stratigraphy of these sequences presents various characteristics that distinguish them from deposits associated with hydrographic, storm or atmospheric processes. In south-central Chile, salt marshes also preserve evidence of tsunamis such as the sand layers deposited by the 1960 Valdivia tsunami that decrease in thickness inland and are distinguishable on the top of intertidal mudflats and organic soils (Garrett et al. 2013).

The interseismic uplift of the surface is gradual and the transition from minerogenic to organic sediments may be coincident with a decrease in grain size (Garrett et al. 2015). The upper contact of organic sediments is abrupt and sometimes erosive. Where tsunami deposits are preserved, they are often siliciclastic, and the grain size can be sand or occasionally silt, as in tsunami layers described by Garrett et al. (2015) at Chucalén, northern Chiloé. Tsunami sediments can have a variety of different local sources within the coastal zone such as estuaries, rivers, dunes or offshore (Hong et al. 2017, Aedo et al. 2021). In addition, they may contain diatom assemblages from mixed or marine environments that can be used to determine the provenance of sediments (Garrett et al. 2013, Hong et al. 2017, Cisternas et al. 2017b, Hocking et al. 2021). Diatom analyses also offer the potential for quantifying the amount of coseismic vertical displacement (Garrett et al. 2013; 2015). Radiocarbon analysis using charcoal or organic matter (e.g., plant leaves, seeds) from soils bracketing minerogenic sediments are used to estimate the age range of tsunami deposits or coseismic deformation events (Ely et al. 2014, Cisternas et al. 2017b). These layers are then correlated with earthquakes recorded in historical documents (e.g., Lomnitz 2004).

Valdivia segment (1960)

The earthquake of May 22, 1960 (Fig. 3) had a magnitude of 9.5, the largest recorded by modern seismology, with a rupture zone close to 1,000 km between 37° and 48° S. It was followed by a tsunami that reached 10 to 15 m high in coastal Chile. Its waves crossed the Pacific Ocean, reaching the coasts of Japan, Hawaii and the Philippines at maximum heights of 10 m (Plafker and Savage 1970; Cisternas et al. 2005). The subsidence in the coastal sector reached 2.7 m near the city of Valdivia, and the uplift in the areas near the trench resulted in an elevation increase of up to 5.7 m (Plafker and Savage 1970).

Evidence of the 1575 earthquake is found in several paleoseismological studies of the Valdivia segment and is well documented historically (Fig. 3). It resulted in the destruction of Spanish settlements from Concepción to Castro and landslides that blocked the discharge of Riñihue Lake in the Andean sector, as also occurred in 1960 (Lomnitz 2004). It also produced tectonic subsidence along the coast, although there is no record of a tsunami in Japan (Cisternas et al. 2005, 2017a). The 1737 and 1837 earthquakes are recorded by turbidites in Villarrica, Calafquén and Riñihue lakes, in the northern half of the 1960 segment (Moernaut et al. 2014). The 1737 earthquake that occurred in the northern part of the 1960 segment is poorly documented and caused little damage (Cisternas et al. 2005). Studies of coastal sediments show evidence of an unreported tsunami produced by the 1737 earthquake at Chaihuín, south of Valdivia (Hocking et al. 2021). The 1837 earthquake, however, produced more damage with land-level changes in the southern half of the 1960 segment, and a tsunami that reached as far as the Hawaiian coast (Cisternas et al. 2017a).

Methodology

The inventory and quantitative assessment of paleoseismic heritage sites along the coast of south-central Chile followed the methodology proposed by Brilha (2016). The main elements defined at the beginning of this work are: the topic (paleoseismic sites); values (scientific, educational, and touristic); scale (the Chilean coast of the Valdivia seismotectonic segment from 38°-42°S); and use (conservation, education and tourism). Based on a bibliographical review, together with interviews and fieldwork with paleoseismology experts, a list of nine potential sites of interest was generated. After a primary qualitative evaluation, seven sites were selected and assessed quantitatively for their scientific value (SV), degradation risk (DR), and educational (EV) and touristic (TV) values.

Geosites are specific places in nature that stand out for their high geoscientific value. Meanwhile, geodiversity sites do not have particularly high scientific value but have educational, touristic and/or cultural relevance for local communities (Brilha 2016; Brilha et al. 2018). These authors also mention that the numerical evaluation of both geosites and geodiversity sites requires a final reflection carried out

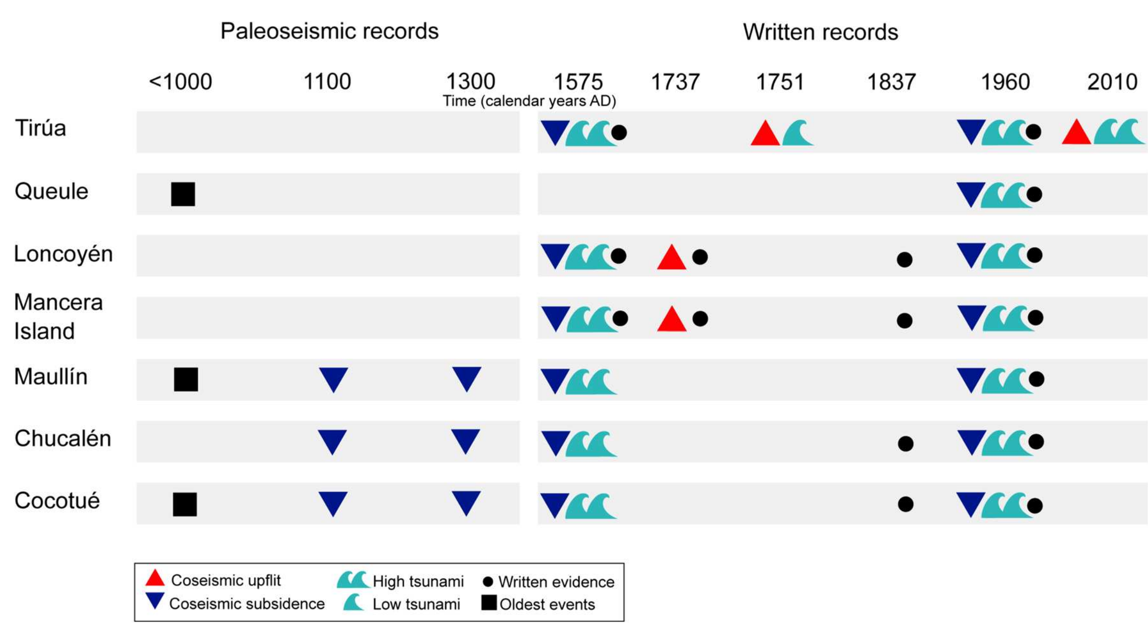

Fig. 3 Chronological comparison of paleoseismic sites located from north to south in the seismotectonic segment of Valdivia, and their paleoseismic and historical record of earthquakes and tsunamis. Also shown here is evidence of vertical deformation (coseismic subsidence or uplift), tsunami size at the coast, evidence from written historical records, and events associated with older earthquakes and tsunamis. Modified from Cisternas et al. (2005) and Cisternas et al. (2017a, b)

by the scientific committee or coordinator in charge of the inventory, to confirm the quality of the numerical results obtained and decide which sites are relevant to the final list of geological heritage sites. It is not possible to eliminate completely the subjectivity associated with geosite inventory and assessment, however, it can be reduced significantly by the numerical parameters of this evaluation (Brilha 2016).

Twenty two Chilean geological frameworks representative of the geological features and evolution of the country were proposed by Mourgues et al. (2012). They were selected with the aim of identifying the most relevant geological sites for each of these contexts. Two of these Chilean geological frameworks are partially represented by the selected paleoseismic sites: 1) the Coastal Border framework which includes abrasion coasts (marine terraces) and accumulation of sediments in south-central Chile, such as tidal marsh environments; and 2) the Mega Structures, Andean Tectonic, and Neotectonic framework, which considers large faults, the tectonic structures and evolution of the Andean mountain chain, and active structures.

Results

Paleoseismic heritage sites of south-central Chile

A list of nine potential sites of interest was obtained based on previous paleoseismological investigations. The potential paleoseismic heritage sites from north to south are: Tirúa (Ely et al. 2014), Queule (Matos 2019; Matos-Llavona et al. 2022), Pilolcura (Garrett et al.2020), Punta Calfuco (Ditzel 2019), Loncoyén (Ditzel 2019), Mancera Island (Villalobos 2005; Ditzel 2019), Maullín (Cisternas et al. 2005), Chucalén (Garrett et al. 2015), and Cocotué (Cisternas et al. 2017b) (Fig. 4). The Pilolcura and Punta Calfuco sites (Fig. 4e) did not pass a first qualitative evaluation and were excluded from the final list, as they are not representative of tsunami deposits and require more specific studies to demonstrate the vertical coastal changes associated with the seismic cycle.

Tirúa

The Tirúa paleoseismic site is located in the Biobío Region, 200 km south of the city of Concepción (Fig. 4b). The deposits are located within an area of approximately 0.25 km^2 at 2 km from the coastline, in a floodplain and on the bank of the Tirúa River (Figs. 4c and 5a). The stratigraphic sequence of 1 m thickness shows an intercalation of 4 grey sands layers, which are interbedded with silty floodplain sediments (Fig. 5b). This site shows a record of 600-year relative sea level changes and 4 tsunami deposits (Ely et al. 2014, Dura et al. 2017). The stratigraphic profile shows vertical changes associated with coseismic uplift (related to earthquakes on the Concepción segment) and coseismic subsidence (earthquakes on the Valdivia segment). The Tirua site is located at the limit of two seismotectonic segments and contributes to the understanding of this complex megathrust zone. Using radiocarbon dating, two sand layers were interpreted as having been left by the tsunamis and earthquakes of 2010 and 1751 with coseismic uplift, while the other two sedimentary layers were related to the tsunamis and earthquakes of 1960 and 1575, with coseismic subsidence (Ely et al. 2014). The lowest layer of the sequence shows historic soils with furrows in an extension of ~ 6 m along the profile, produced by agricultural activities of native Mapuche (pre-Hispanic) people, with radiocarbon ages before 1500 (Ely et al. 2014) (Fig. 5b). From Tirúa beach, it is possible to observe ancient levels of marine abrasion terraces from the Upper Pleistocene (Martinez 2020), showing processes of continuous uplift of the continental margin on longer geological time scales. This geosite is continuously affected by the erosion of high tides which truncate the front of the terrace and is also vulnerable to the fishing and farming activities of local inhabitants. The site is located on a private property and has no legal protection. However, Tirúa is part of the "Original Route" of the Biobío coast, which includes areas of conservation of natural and cultural heritage.

Queule

The town of Queule is located in the coastal area of the Araucanía Region, 81 km north of the city of Valdivia (Fig. 4). The 1960 tsunami deposits are scattered in several places around Queule. The best stratigraphic record of past tsunamis is found in the area called Nigue Sur, where trenches and cores must be dug to observe the stratigraphy that is not exposed in the surface (Fig. 6a). The 2 m thick sedimentary sequence is located in a lower terrace with an extension of 0.4 km^2. It includes 3 grey sand deposits, which are associated with tsunamis that occurred during the last 6,000 years, interbedded with organic-rich silt (Fig. 6b) (Matos 2019; Matos-Llavona et al. 2022). At the top of the stratigraphic sequence, there is a sand layer left by the 1960 tsunami, deposited in peaty soil rich in organic matter with a radiocarbon age of 5,400 years, showing a ~ 5,000-year hiatus without evidence of earthquakes and/or tsunamis (Matos 2019; Matos-Llavona et al. 2022). At the base of the sequence, there is an older tsunami-related sand deposit (C) with a radiocarbon age of 5,900 years BP (Matos 2019; Matos-Llavona et al. 2022). The site presents a history of uplift and coastal subsidence that occurred more than 6,000 years BP. The site is protected from the erosion of the Queule River and the Pacific Ocean by extensive Holocene dunes, which are the source of the 1960 tsunami sand. Therefore, tsunami-related deposits are

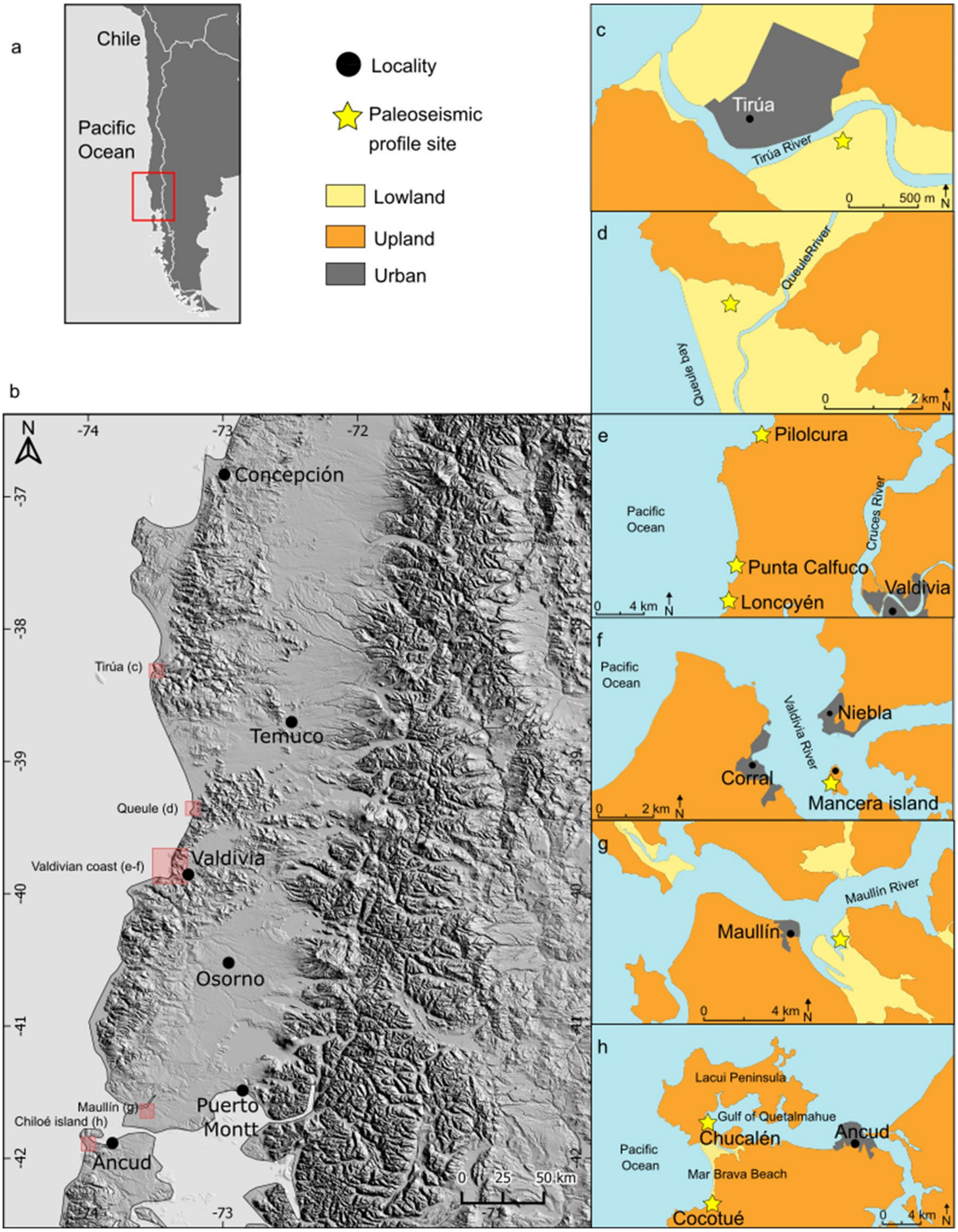

Fig. 4 a) Map of southern South America and Chile showing the study area with the red rectangle, together with symbols and legend used in figures c-h; b) Digital elevation model (DEM) image of south-central Chile with the location of the studied sites: c) Tirúa; d) Queule; e) Pilolcura, Punta Calfuco and Loncoyén; f) Mancera Island; g) Maullín; and h) Chucalén and Cocotué

very well preserved here. This site is located on a private property used for agricultural activities with large drainage channels that leave the stratigraphic sequence exposed (Fig. 6a). There are areas where the sand deposits of 1960 have been eroded by cattle and plowing. Some areas of the Nigue Sur hills preserve the native forest of the region and offer a panoramic view of the Queule site with potential use for touristic and educational activities. The towns of

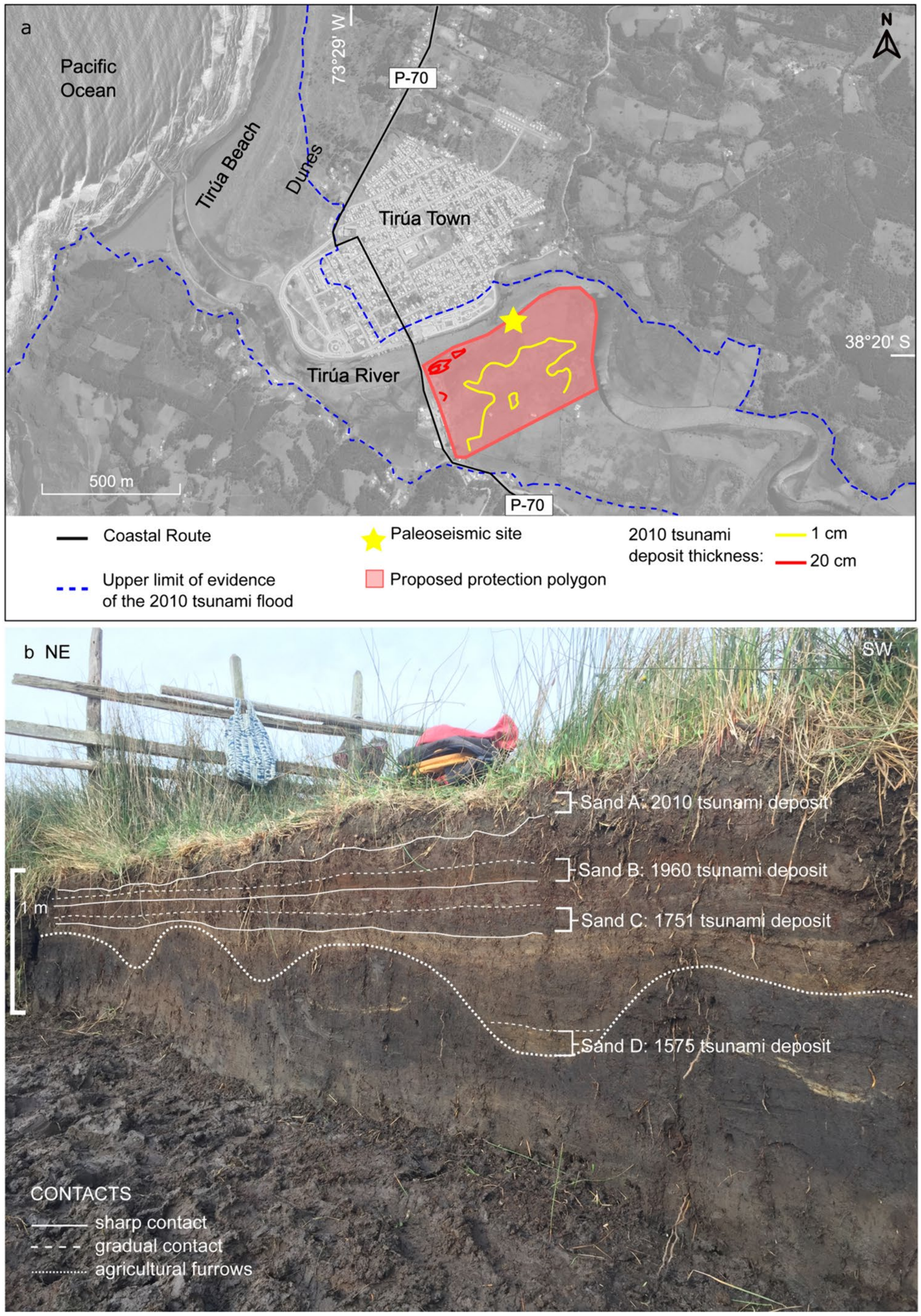

Fig. 5 Paleoseismic site of Tirúa. a) Aerial image of Tirúa paleoseismic site, Biobío Region. b) Tirúa riverbank where layers A, B, C and D represent sand deposits left by tsunamis in the last 600 years

Queule and Toltén Viejo were devastated by the tsunami of 1960. Toltén Viejo was relocated 8 km northeast, further from the sea in Toltén Nuevo. Both towns are part of the historical heritage associated with the 1960 earthquake and tsunami.

Loncoyén

On the coast near Valdivia city in Los Ríos (The Rivers) Region, there are 3 levels of marine terraces: upper, intermediate, and lower marine terraces. The low-lying terrace is found continuously from Chanchán to Mancera Island (Ditzel 2019), reaching its highest elevation of 5 m above sea level in Loncoyén. This small village is located 26 km west of Valdivia (Fig. 4e, 7a) and exhibits two

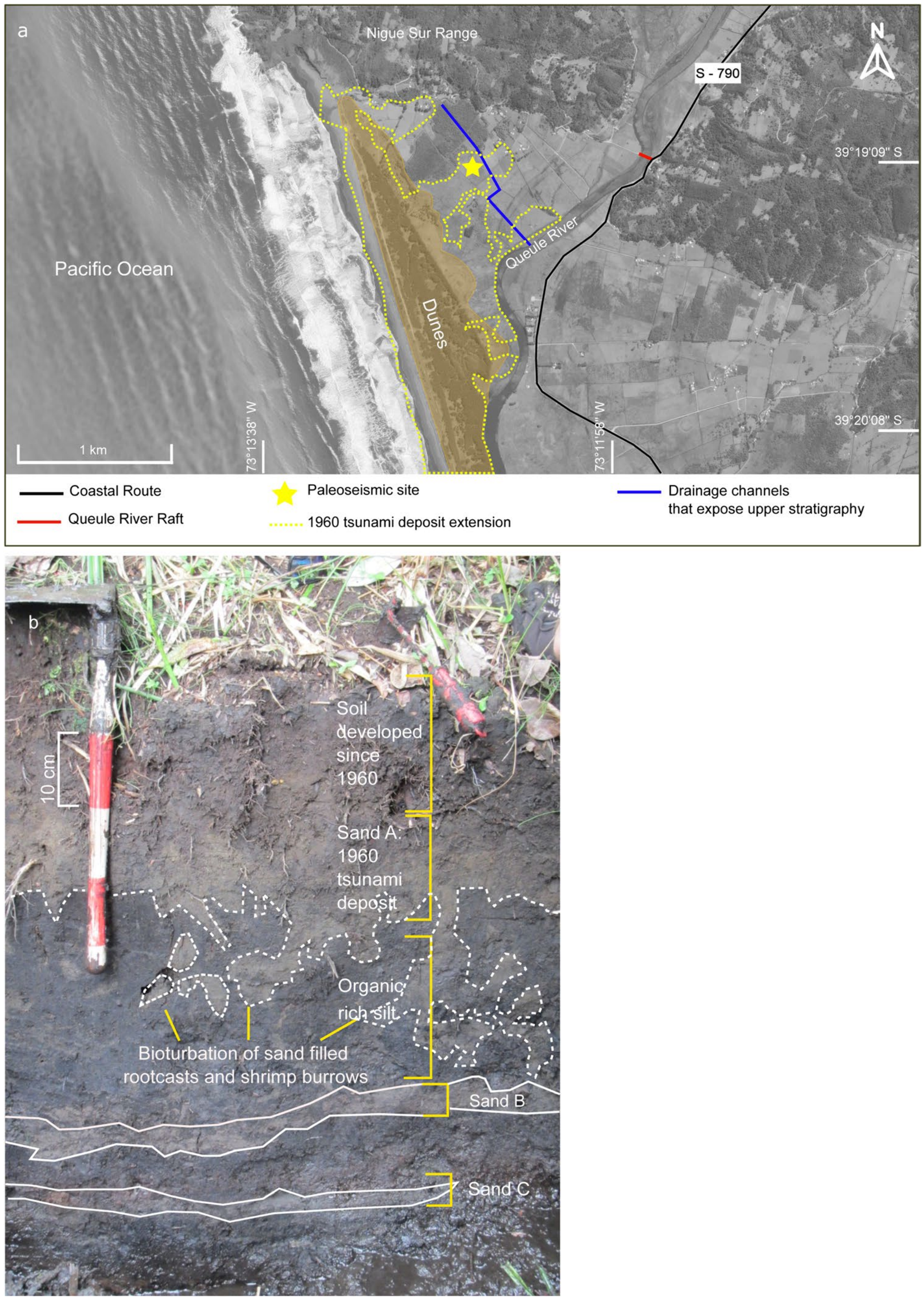

Fig. 6 Paleoseismic site of Queule. a) Aerial image of Queule paleoseismic site, Araucanía Region. b) Stratigraphic section of Queule site (Nigue Sur sector) with 3 sand deposits of tsunamis and peaty soils intercalated. Modified from Matos (2019)

well-preserved lower terraces with a total area of 1,600 m^2: North Loncoyén and South Loncoyén (Fig. 7a, c, d). Here, there is an exposed stratigraphic sequence of humified peats and sands (Fig. 7b) that represent abrupt changes in the depositional environments, and vertical changes associated with the historical subduction earthquakes of the last 500 years (Ditzel 2019). According to Ditzel (2019), this site holds records of tsunami deposits of two large subduction earthquakes (1575 and 1960) and one moderate (> 8.5 Mw) and deep-focus earthquake (1737) (Cisternas et al. 2017b). The vertical changes are shown clearly in the lower terrace (late Holocene). The main peat between sands Ls1 and Ls2 of the stratigraphic sequence (Fig. 7b) shows a drop in relative sea level during the interseismic uplift between the 1575 and 1737 earthquakes, when organic matter was accumulated (Ditzel 2019). This site is affected by dense vegetation cover composed mainly of reeds that retain moisture, and high tides that erode the front of the lower terrace. Loncoyén has high values for touristic and educational use due to

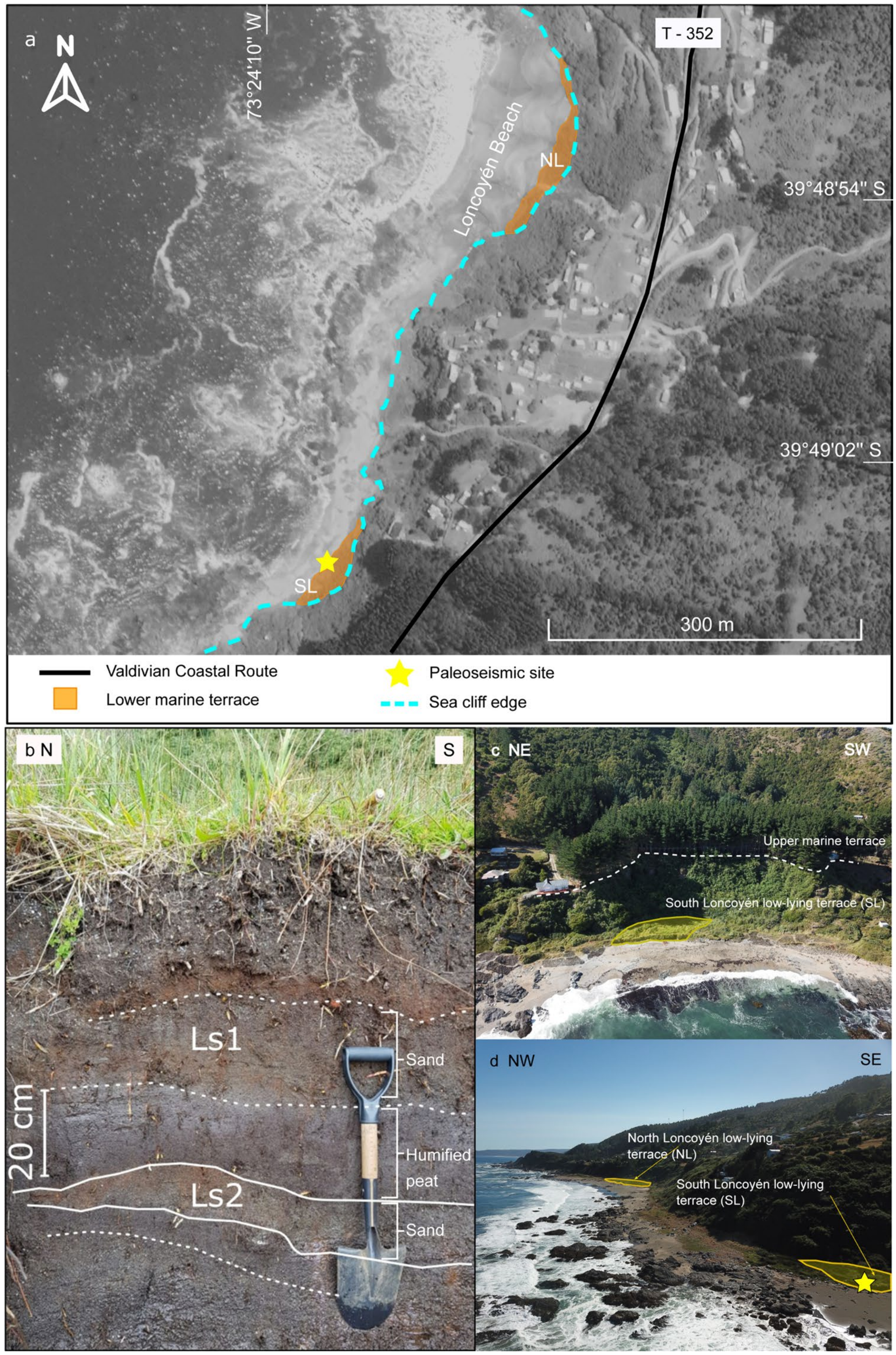

Fig. 7 Paleoseismic site of Loncoyén. a) Aerial image of Loncoyén paleoseismic site, Los Ríos Region. b) Profile of the lower terrace in South Loncoyén where dotted white lines indicate gradual contacts and solid white lines indicate sharp contacts. Ls1 and Ls2 corresponds to sand layers (modified from Ditzel (2019)). c) Marine terraces in South Loncoyén where dotted white line indicates the edge of the upper terrace of middle-upper Pleistocene age (Villalobos 2005) and the yellow shaded area indicates the surface of the lower Holocene terrace. d) Loncoyén beach that shows the lower terraces of North and South Loncoyén

its good accessibility, great natural scenic beauty, other elements of geodiversity and biodiversity (e.g. Valdivian Forest; see Mancera Island site) and elements of high historical and cultural value.

Mancera Island

Mancera Island is located in Corral Bay, in the Valdivia River estuary (Fig. 4f). It has a maximum extension of

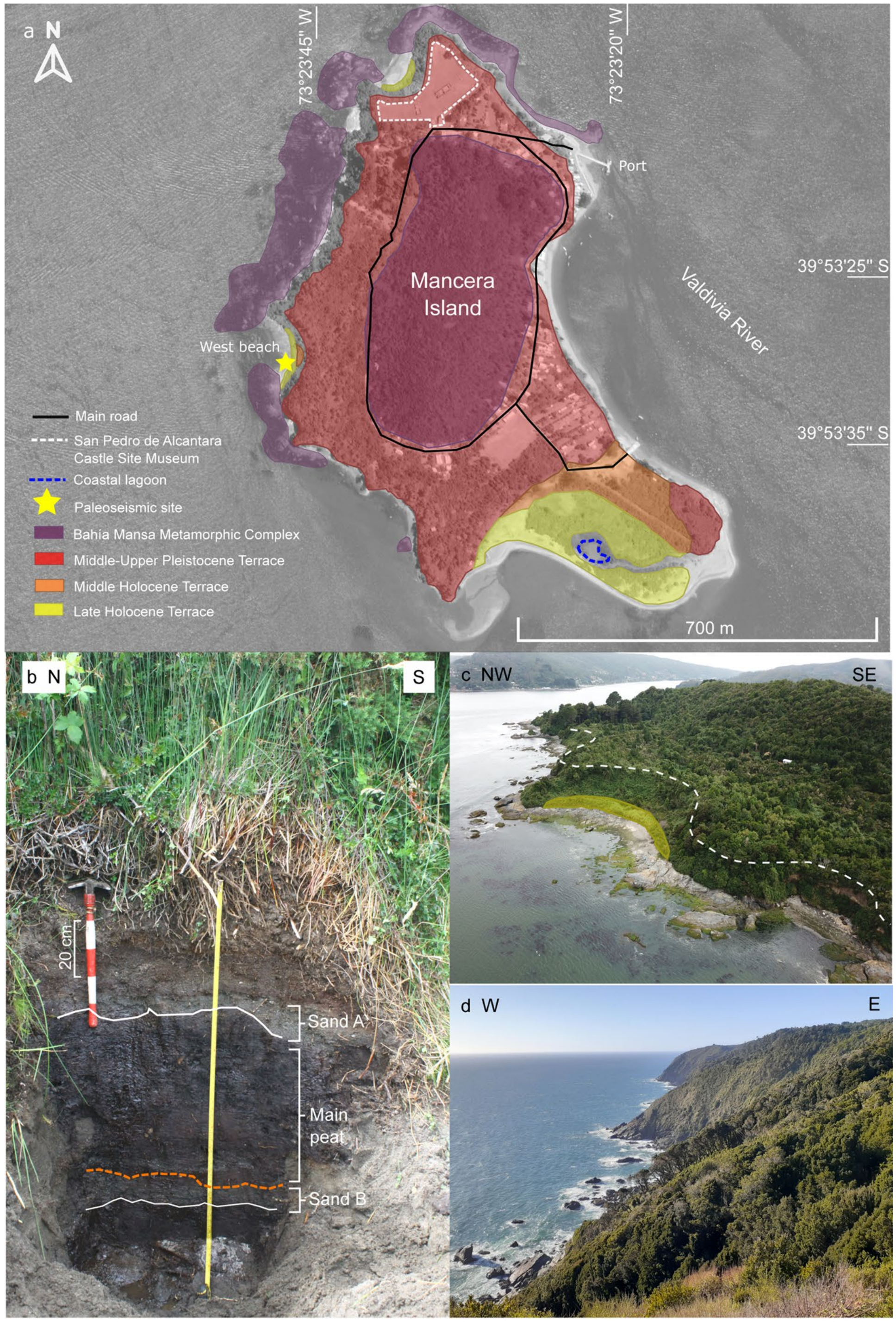

Fig. 8 Paleoseismic site of Mancera Island. a) Aerial image of Mancera Island in the Los Ríos Region, showing the location of the paleoseismic site. b) Stratigraphic profile of the paleoseismic site of Mancera Island, where solid white lines indicate sharp lower contact of sands A and B. Solid orange line indicates lower contact of the main peat. c) Western beach on Mancera Island where the white dotted line marks the upper terrace level, and the yellow shaded area indicates the surface of the lower terrace. d) Valdivian Rainforest in the Punta Curiñanco Protected Coastal Area

1.2 km and an area of 0.6 km^2, and in the center of the island there is a small hill that rises 90 m above sea level. A lower terrace is present on the west, northwest and southeast sides of the island; however, the proposed paleoseismic site includes only the lower terrace on the western side, which has an area of ~ 1,000 m^2 (Fig. 8a). The stratigraphic sequence of the Mancera Island lower terrace has similar characteristics to those of the Loncoyén site (Fig. 8b). The difference is that it presents evidence of only 2 earthquakes instead of 3, which correspond to those of 1960 and 1737 according to the radiocarbon dates calibrated for the main peat between the layers of sand (Ditzel 2019). This geosite has medium to low integrity; however, it contains the representative stratigraphic sequence of coseismic uplift and subsidence due to subduction earthquakes, which is the most important geological element. In this site, there is evidence of coseismic uplift related to the 1737 earthquake (Cisternas et al. 2017b; Ditzel 2019), that is very poorly documented on the southern shores. Mancera Island is the only site on the coast that presents 3 levels of marine terraces, relevant geodiversity elements of the seismic cycle which mark the last interglacial period of the late Pleistocene (upper terrace) (Fig. 8a, c) and the middle Holocene transgression (intermediate terrace) (Villalobos 2005). The island was declared a Historical Monument and a Typical Zone by the Council of National Monuments because it has a fort that is part of the "Spanish Viceroyalty Fort System" built in the seventeenth century in Corral Bay. Mancera Island and Loncoyén are located in areas surrounded by endemic transition zone forests called “Valdivian Rainforest” (Villagrán and Hinojosa 1997), a globally recognized ecoregion that contains about 50–70% of the richness of Chilean species, with a high concentration of endemic species. Near both sites there are protected areas for this ecosystem: Oncol Park and the Punta Curiñanco Protected Coastal Area (Fig. 8d).

Maullín

Maullín is an emblematic paleoseismic site known worldwide as a study site for ancient tsunami deposits (Cisternas et al. 2005). It is located 8 km from the coastline on a marsh of the Maullín River estuary that forms low-lying terraces (Fig. 4b, g; 9a). Here, there is a 1 m thick stratigraphic sequence with sedimentary layers related to 8 possible earthquake and tsunami events over the last 2,000 years (Cisternas et al. 2005). The upper part of this stratigraphic sequence, located benearth the current tidal marsh, only shows 4 events (Fig. 9b) and to see the complete sequence

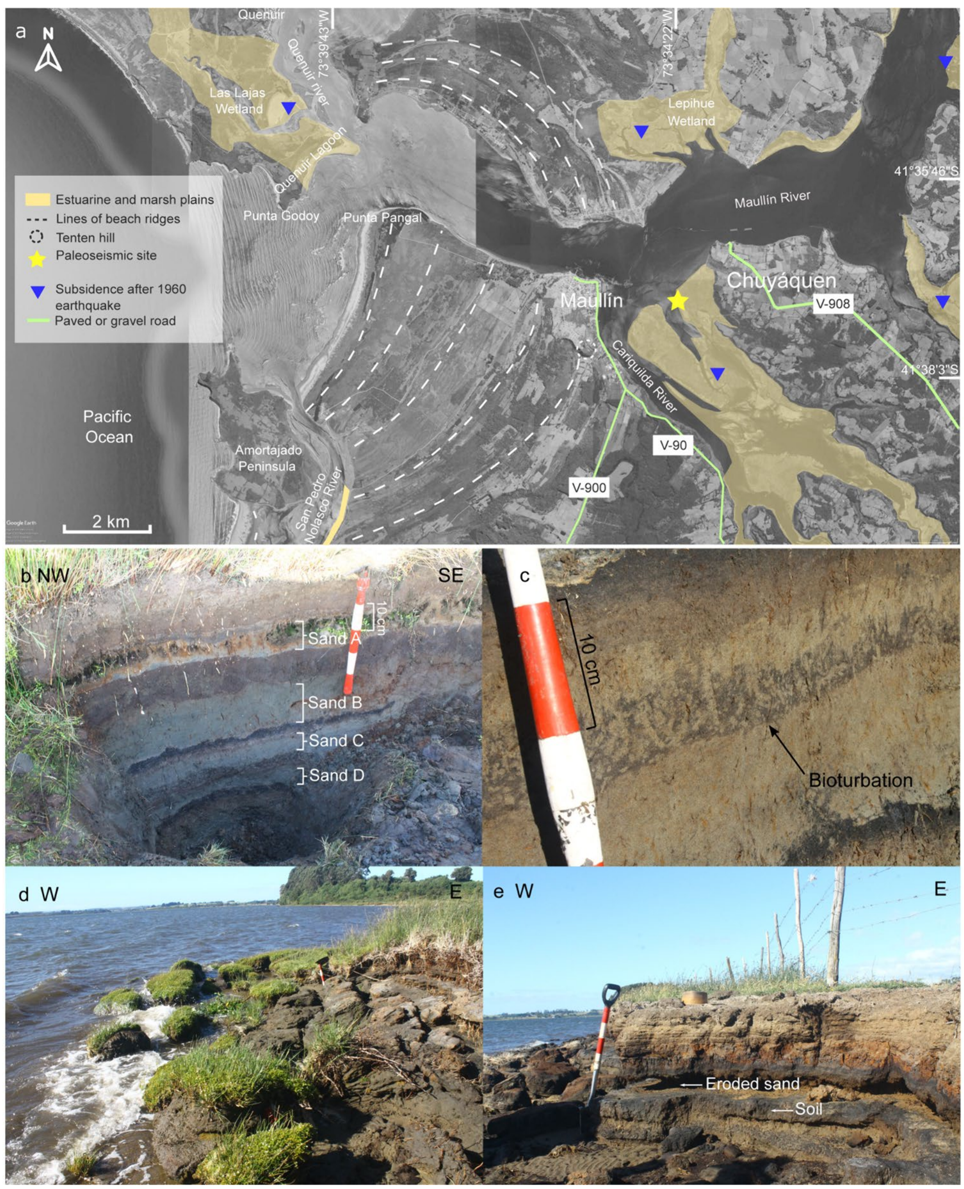

Fig. 9 Paleoseismic site of Maullín. a) Aerial image of Maullín paleoseismic site, Los Lagos Region. b) Stratigraphic units of the paleoseismic site of Maullín showing sharp and erosive contact of the layers related to tsunami deposits described by Cisternas et al. (2005). c) Evidence of bioturbation in one of the buried soils overlaid by sand. d) Natural degradation of the marsh with truncated soils due to wind and waves in Maullín River estuary. e) Natural degradation due to the waves in the estuary where it is possible to observe the erosion of the exposed layers left by tsunamis in Maullín estuary

a larger excavation or the use of cores is needed. An intercalation of sands and buried peat soils with deposits from 2 historical tsunamis (1960 and 1575) and older events from 1300 and 1100 AD can be observed in this sequence (Cisternas et al. 2005). The diatom assemblages allow the distinction of tsunami sediments from estuary floodplain sediments, as well as bioturbation (Fig. 9c) under sand deposits. Cisternas et al. (2005) emphasize that, within the interval of ~ 400 years between two mega-earthquakes (1575 and 1960), two smaller events occurred (1737 and 1837) that are not evidenced in the stratigraphy of the site but are recorded in historical documents. These authors propose that these events produced little or no evidence of subsidence or tsunami in the estuary and were precursors to the fault partly loaded with the accumulated plate motion that caused the 1960 earthquake. Maullín has elements of geodiversity very relevant to the seismic cycle, such as ancient beach ridges made up of coastal deposits (Upper Pleistocene – Holocene) that show a gradual increase in land elevation in relation to sea level, produced by the effect of deglaciation or tectonic movements on the coast (Antinao et al. 2000). These beach ridges (Atwater et al. 2013) are distinguished from the Maullín hills and Pleistocene glacial deposits and geomorphological structures (Antinao et al. 2000). In this site, the strong waves of the estuary rapidly truncate the marsh soils, and shallow sand layers are quickly eroded (Fig. 9d, e). There is also evidence of anthropogenic contamination due to waste and cattle that degrade the layer related to the 1960 tsunami. The Maullín River has an extended network of wetlands of different types (e.g., marshes, *hualves* that are seasonally flooded woodland, estuaries, rivers, etc.). The area has been identified by Birdlife International as an Important Bird Area (IBA) and was incorporated into the Western Hemisphere Shorebird Reserve Network (WHSRN). Due to its relevance for conservation, in 2019 the Maullín River Wetlands were declared as a Nature Sanctuary. It is an ideal place to carry out sustainable touristic and educational activities.

Chucalén

Chucalén is located in the Gulf of Quetalmahue (Fig. 4h), northern Chiloée Island, part of the Chiloé Archipelago which includes more than 40 islands. It is home to the indigenous community "Buta Lauquén Mapu". In the bay, a low-rise terrace is formed which reaches ~ 4 m above sea level and has an area of ~ 15,000 m^2 (Fig. 10a). The lower terrace of Chucalén shows 4 sedimentary layers related to earthquakes and tsunamis over the last 1000 years (Fig. 10b). These four events are clearly observed in a 1-m-thick sequence of fine sands and silt layers with erosive lower contacts within organic marsh soils (Fig. 10b, c). This sequence shows evidence of the great earthquakes of 1960 and 1575, and two previous events that Garrett et al. (2015) correlate with those from ~ 1,100 and ~ 1,300 AD identified by Cisternas et al. (2005) in Maullín, as well as by Moernaut et al. (2014) in lacustrine turbidites northeast of Valdivia. The Gulf of Quetalmahue provides a calm and protected environment that helps to conserve the stratigraphy of the Chucalén site. However, this place contains evidence of an increase in relative sea level during the last millennium, which suggests that Chucalén could be either sinking or stable (Garrett et al. 2015). This process, along with higher tides, leads to natural degradation of the site. This area is managed and protected under the category of Coastal Marine Spaces of Indigenous Peoples (ECMPOs) by the local community. This geosite is also located in an area of marsh-type coastal wetlands protected by Chiloé Wetlands Board for its sustainable management. It is important to mention that the Chiloé Archipelago has a relevant tangible and intangible cultural heritage distributed over more than 40 islands. Sixteen of Chiloé's 60 wooden churches were declared as World Heritage Sites by UNESCO in 2000 for their peculiar architecture and history. The mythological stories and cultural traditions are also a source of living intangible heritage in the archipelago. It is also a region with unique biodiversity elements such as peatbog-type wetlands whose origin is associated with the removal of ice caps in the last Pleistocene glaciation, and the presence of relics of Patagonian larch forests (*Fitzroya cupressoides*).

Cocotué

Cocotué is located on the Pacific coast of Chiloé Island, to the west of Ancud and south of Mar Brava beach (Fig. 4 h). The lower terrace of Cocotué is 500 m long and has a maximum height of 4 m above sea level at the center of the terrace (Fig. 11a). The selected profile is exposed in the central section of this terrace and is ~ 40 m long (Fig. 11c). Its stratigraphy consists of an intercalated sequence of yellowish sands and dark brown soils (Fig. 11b). Four main sharp lower contacts (A, B, C, and D) are visible, with contact C containing a distinct layer with pumice pebbles (Fig. 11d) (Cisternas et al. 2017b). There are also diamictic deposits that locally interrupt the sand layers above the contact with soil, which form colluvial fans composed of clay, silt, sand, and gravel coming from the sea cliff (Fig. 11a). In addition, Cisternas et al. (2017b) describe four less distinctive and discontinuous contacts of sand and soils. The sedimentary layers of this geosite show records of the historical earthquakes of 1960 and 1575, along with the only currently identified sedimentary record of the earthquake and tsunami of 1837 (not recognizable in Fig. 11b) and those of 1300 and 1100 AD (Cisternas et al. 2017b). Between contacts D and B there is evidence for three smaller events recorded in lacustrine sediments studied by Moernaut et al. (2014),

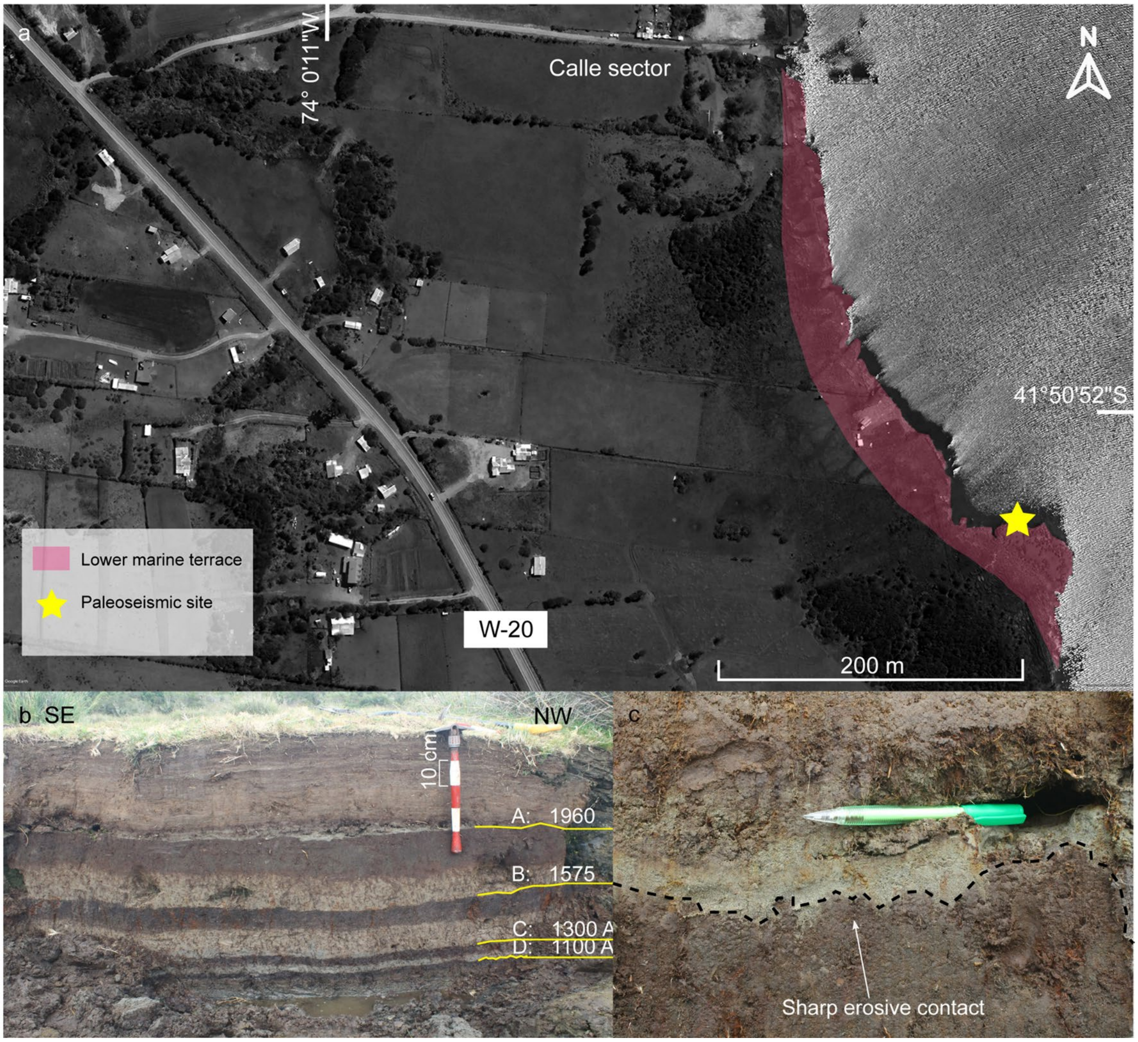

Fig. 10 Paleoseismic site of Chucalén a) Aerial image of Chucalén paleoseismic site, Los Lagos Region. b) Section of the stratigraphic profile of the constructional terrace of Chucalén where solid yellow line indicates the sharp lower contacts produced by the earthquake and tsunami events studied by Garrett et al. (2015). c) Dashed line indicates the sharp erosive lower contact of sand layer A of the Chucalén stratigraphic profile

giving a recurrence between AD 1300 and 1575 of 85 years (Cisternas et al. 2017b). These events could possibly have been earthquakes and tsunamis that occurred in the southern portion of the Valdivia segment or nearby. Consequently, the shortest average recurrence interval for southern Chile is found at this site. The sedimentary record suggests that landslides and volcanic eruptions are possibly associated with seismic movements; however, the volcanic origin of pumice pebbles is not known. This geosite is very well preserved because it is far from the erosive effect of the highest tides. It has excellent and safe accessibility for educational and touristic activities. Also, it has a high diversity of geological elements such as sedimentary rocks outcropping in the sea cliff that are associated with glaciations of the Pleistocene and volcanic activity of the Upper Oligocene – Lower Miocene (Antinao et al. 2000). To the north of Cocotué beach there are dunes and coastal wetlands, fragile ecosystems that are protected by the Chiloé Wetlands Worktable. Presently, this area is threatened by the installation of the "Chiloé Wind Farm" project, which could harm the conservation of this geosite as well as the ecosystems and routes of migratory birds that inhabit the island.

Results of quantitative assessment of paleoseismic sites

The results of the quantitative assessment of selected and characterized sites of paleoseismological interest (Tirúa, Queule, Loncoyén, Mancera Island, Maullín, Chucalén and Cocotué) are presented in Table 1, Tables S1-S4, and Fig. 12. Values between 1 and 4 points were obtained for each parameter of the quantitative assessment for scientific

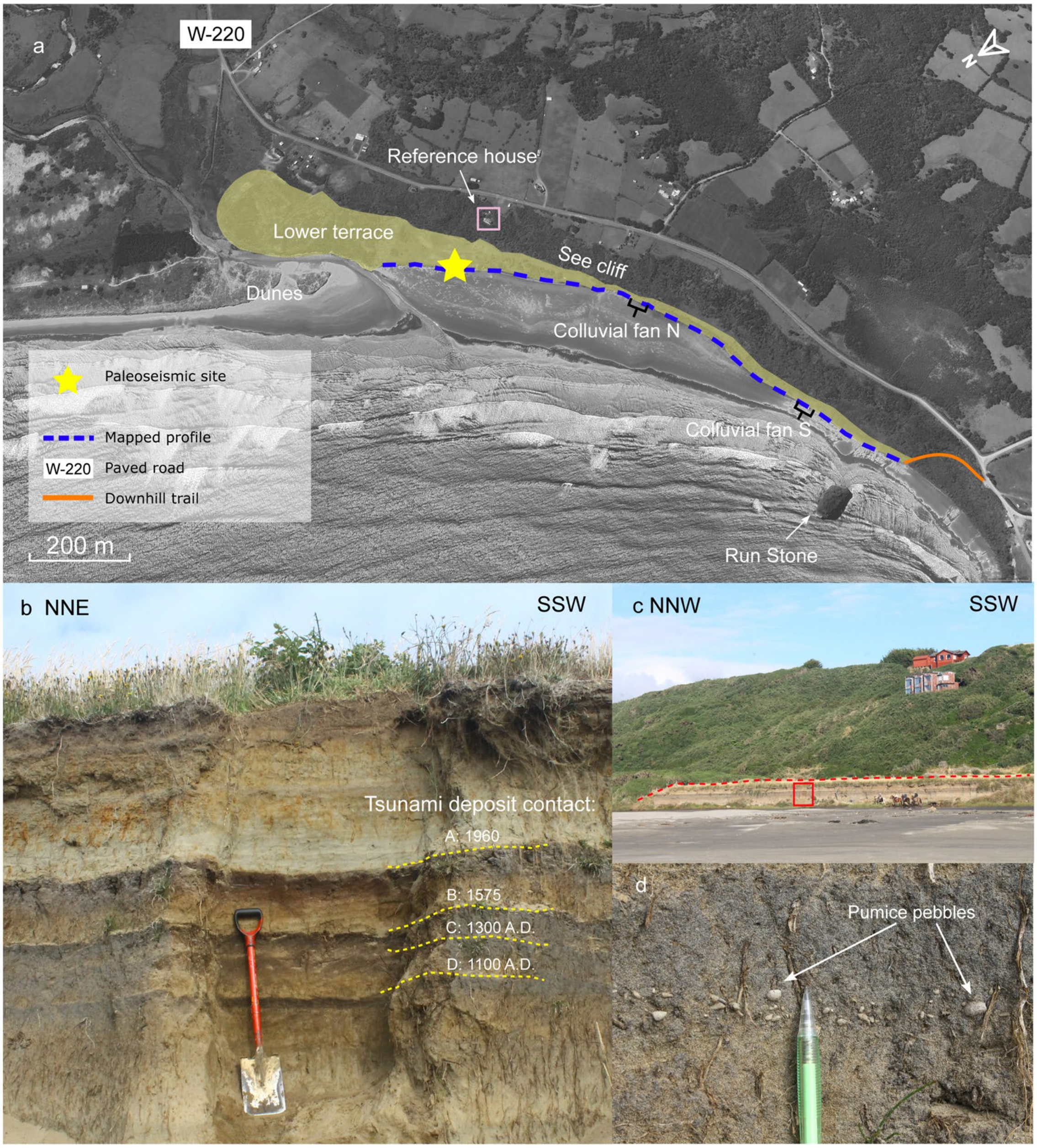

Fig. 11 Paleoseismic site of Cocotué a) Aerial image of Cocotué paleoseismic site, Los Lagos Region. b) Section of the stratigraphic profile of the lower Cocotué marine terrace where the dotted yellow line indicates the sharp lower contacts produced by the 4 earthquakes and tsunami events described by Cisternas et al. (2017a, b). c) Lower terrace of Cocotué shown by the dotted red line, and the location of the stratigraphic profile shown by the red square. d) Pumice pebbles found at contact C of the Cocotué stratigraphic profile (Cisternas et al. 2017b)

(SV), touristic (TV) and educational (EV) value and degradation risk (DR). In this work, values for SV, EV, TV, and DR of ≥ 3 points are considered high, between < 3 and ≥ 2 points are moderate, and < 2 are considered low values. All sites have SV ≥ 2 and are therefore considered as geosites according to Brilha (2016).

Five of the paleoseismic sites have high scientific value. Cocotué has the highest score (3.7 points), whereas Mancera Island has the minimum score of 2 points. The geosites with higher EV are Loncoyén and Cocotué with 3.1 points. Most of the paleoseismic sites have high TV, with five sites scoring ≥ 3 points. Regarding degradation risk, the quantitative values obtained show that two of the seven geosites have high DR values (≥ 3 points) and the rest have moderate values. None of these paleoseismic sites have low DR values.

Table 1 Summary of the numerical results of scientific (SV), touristic (TV), and educational (EV) values and the degradation risk (DR) for the seven characterized sites of paleoseismic interest. High values (≥3 points) are shown with bold numbers. The maximum score is 4 and the lowest is 1. Complementary information is presented in the supplementary material (Tables S1-S4)

Value	SITES						
	Tirúa	Queule	Loncoyén	Mancera island	Maullín	Chucalén	Cocotué
Scientific Value (SV)	**3.30**	**3.00**	2.90	2.00	**3.35**	**3.30**	**3.70**
Educational Value (EV)	2.80	2.45	**3.10**	2.85	2.80	2.80	**3.10**
Touristic Value (TV)	2.55	2.55	**3.00**	**3.10**	**3.00**	**3.15**	**3.30**
Degradation Risk (DR)	**3.00**	2.35	**3.30**	2.75	2.65	2.25	2.45

Discussion

Scientific relevance of the assessed paleoseismic sites

A final list of seven paleoseismic sites with moderate to high intrinsic scientific values (SV; 2.00–3.70) was obtained (Table 1, Fig. 12). This is consistent with the fact that these sites have contributed to the knowledge of large subduction earthquakes at a regional and global scale. The integrity of the main geological elements is well conserved in all geosites. Based on their high SV they are considered to be part of the geological heritage associated with late Holocene earthquakes and tsunamis that occurred on the coast of south-central Chile. In particular, the Maullín geosite is positioned as an international benchmark for paleoseismology (Cisternas et al. 2005, 2017b; Nelson et al. 2006; Satake and Atwater 2007; Moreno et al. 2009; Scholz and Campos 2012; Melnick et al. 2012; Ely et al. 2014; Moernaut et al. 2014; Garrett et al. 2015; Ruiz and Madariaga 2018). Contrary, the Mancera Island geosite obtained the lowest SV (2) since it is the least representative of the main geological elements compared to other geosites (Table S1).

These sites have been used by scientists to understand the behavior and geometry of megathrust earthquakes that induce vertical displacement of the continental margin, which is relatively constant over millennia (Ely et al. 2014). Paleoseismological data from a single site contribute to the knowledge of a given locality and can provide insights about the behavior of subduction zones in other parts of the world. The integration of different studies and methodologies improves the understanding of the processes related to the ruptures of seismotectonic segments (Garrett et al. 2015).

Each paleoseismic site has features that makes it unique in terms of its location within the Valdivia segment. For example, the Tirúa geosite has a unique location on the boundary of two seismotectonic segments and is highly representative of the seismic and tsunami events that characterize both segments. The Queule geosite shows a geological hiatus of approximately 5,000 years where there is no evidence of earthquakes or tsunamis. Finally, Chucalén and Cocotué on Chiloé Island are excellent examples of constructional marine terraces with exposed profiles where the layers left by ancient tsunamis associated with earthquakes interbedded with marsh soils can be observed clearly. In addition, all the geosites present evidence of the 1960 Valdivia mega-earthquake and provide information on great subduction zone earthquakes in terms of their depth, recurrence, geometry, and slip distribution. Consequently, it is important that these sites of high SV, which are not easily identified, are recognized by the scientific and local communities, and protected against natural and anthropogenic degradation.

Educational and touristic use potential of the paleoseismic sites

Most of the paleoseismic sites selected in the present study show high use values, especially their values for tourism (2.55–3.30), with 5 of 7 geosites scoring ≥ 3 points. These are Cocotué, Chucalén, Mancera Island, Maullín and Loncoyén. Loncoyén and Cocotué geosites also obtained high scores for EV (Fig. 12). Regarding education about geological risk, sites associated with natural disasters play two roles (Migoń and Pijet-Migoń 2019). Geosites related to earthquakes provide information about the forces of nature, their frequency and magnitude, their location at the interface of converging plates, and the consequences to the natural environment and human communities. Paleoseismic sites record evidence of those instantaneous and destructive events. Also, they contribute to a better understanding of risk exposure (Migoń and Pijet-Migoń 2019), taking on a fundamental educational role for coastal communities and the development of human settlements through observation of past events.

High-quality experiences for students and community members in nature help them better understand ecosystems and environmental issues and allow them to interact with their community. Most of the geosites considered in this study have a high potential for use in educational activities since they are safe and easy to access. According to the Chilean National Education Curriculum, they are especially useful for students and teachers of fourth grade (9 years-old

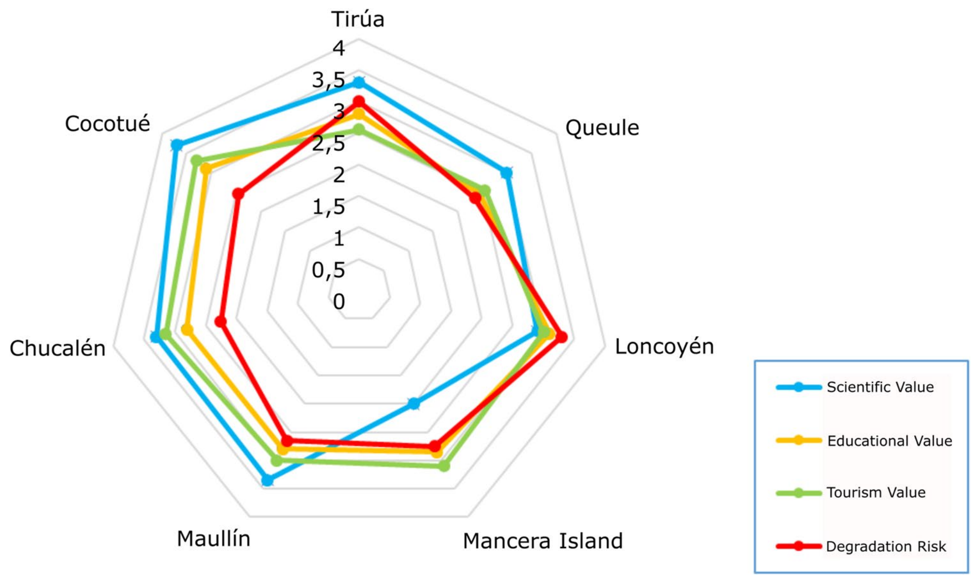

Fig. 12 Radial diagram that shows the final values for the scientific (SV), touristic (TV), and educational (EV) values and the degradation risk (DR) of the 7 assessed paleoseismic sites. The different values (blue, yellow, green, and red color dot) obtained for each site range from 2 to 3.7 points

children), at which level issues associated with the seismic cycle and knowledge about Earth systems are addressed. To support the achievement of learning objectives, interdisciplinary outdoor activities may be considered, together with specialization workshops for teachers, videos or documentaries, and the implementation of interpretative panels at geosites, museums, and interpretative centers. Moreover, these educational initiatives can promote the conservation of these geosites.

Additionally, geotourism can be used as a tool for the education and the development of a territory, based on the principles of environmental sustainability (Bentivenga et al. 2019). Geotourism contributes to local economies through an integral environmental and cultural interpretation of the main geological features of certain areas (Brilha et al. 2018). The selected paleoseismic sites have great potential for the development of geotourism due to complementary elements: aesthetic (e.g. landscapes of Maullín, Chiloé, and Mancera Island); cultural (e.g. Spanish forts near Valdivia and Chiloé, Mancera Island as a Historical Monument and Typical Zone, historic photographic record and narratives associated with the 1960 and 2010 earthquakes); ecological (e.g. marsh environment in bays and estuaries, and Valdivian rainforest); and geological (e.g. Pleistocene glaciations). The two geosites of Chiloé Island are very close to each other and present various elements of natural (e.g. marshes, peat bogs, natural monuments, marine reserves) and cultural heritage (e.g. system of Chiloé forts), and other tourist attractions (e.g. viewpoints of great scenic beauty).

It has been demonstrated that scientific studies not only improve education but also provide useful information for the management of territories and for people working in the area (Bentivenga et al. 2019). Also, the development of basic infrastructure is required for tourism activities, together with small-scale interventions in controlled places like park ranger houses, and the permanent monitoring of natural heritage and some restriction of uses (Worboys et al. 2005). Moreover, each paleoseismic site has certain requirements. It is essential to guarantee a pleasant experience for the tourists by ensuring good accessibility and tourist safety. Ideally, a geosite must be clean of anthropogenic waste, have nearby basic services and its maximum capacity must be respected (De la Maza and De Gregorio 2019). Ensuring that these factors are addressed contributes to the protection of geosites, by considering the social context and benefits to inhabitants, sustainable management, and a quality recreational experience for tourists that support local economies.

Conservation of the paleoseismic heritage sites

The selected paleoseismic sites show a moderate to high degradation risk (2.25–3.00). This indicates a high fragility due mainly to their active geomorphological environment. Most of these sites are composed of small geological elements that are exposed to natural erosion from tides in bays and estuaries, but also to anthropogenic degradation. Some of them are located in private farmland used by livestock, which erode the most superficial deposits left by tsunamis, aquaculture areas, or artisanal fishing. Consequently, the management of these geosites is relatively complex and dynamic. Another relevant condition is that only Mancera Island, Maullín and Chucalén are in some way legally protected. The paleoseismic sites with highest DR are Tirúa and Loncoyén. This is in part because these two sites lack legal protection and are near places where human activities can cause degradation. Moreover, the geological heritage values that all these sites represent are unknown by most of the local population and authorities. Therefore, the conservation of these sites is a great challenge.

To ensure the protection of these places, it is recommended to prioritize Loncoyén, Tirúa, Mancera Island and Maullín, which yielded the four highest DR scores. The combination of a high SV with a high DR implies the need for an urgent action plan for geoconservation (Brilha 2016). This includes the definition and establishment of different types of legal protection for those paleoseismic sites that are not presently protected by law.

The current view of conservation considers the human being an integral part of nature. This includes the relationships that exist between biotic and abiotic elements of ecosystems, as well as the images, symbols, and cultural values that arise beyond biophysical nature (Rozzi 2019). Most of the selected paleoseismic sites are directly associated with other elements of natural heritage (e.g., wetlands, marshes, shorebird reserves) and cultural heritage (e.g., intangible heritage, Historical Monuments, historical records). The geosites on the coasts of Valdivia, Maullín, Chucalén and Cocotué stand out in this regard because of the seventeenth century Spanish historic fort system of the Valdivian coast including Mancera Island declared as a Historical Monument and Typical Zone, the Valdivian endemic rainforest ecoregion, Maullín River Nature Sanctuary, and the material and immaterial cultural heritage of the Chiloé Archipelago. Making visible the interaction between these elements to the public can improve local communities' sense of belonging and their empowerment and participation in conservation. In addition, from a cultural perspective, earthquakes are part of the natural diversity of Chile as repetitive events mark historical contexts and ways of life. It is important to note that all geosites present evidence of the great 1960 Valdivia earthquake.

Within natural environments, the relationships between different inhabitants (including humans) make up ecosystems with flows of nutrients, energy, and ecological interactions (Rozzi 2019). Four of the seven geosites correspond to tidal marsh that exist due to effects of the seismic cycle. Also, earthquakes have an impact on the environment in which they occur. The abrupt vertical changes in these geosites can be too fast for some habitats and species to adapt (Gordon 2019), and can also produce changes in the spatial distribution of landforms with uplift or subsidence in marshes and wetlands. Thanks to this, the marshes conserve physical characteristics and natural processes that sustain biodiversity, as in the geosite of Maullín, a migratory bird reserve. Another example is Chucalén, which is managed by a coastal indigenous community and provides important ecosystem services. In addition, these geosites could be considered case studies for development solutions and adaptation to emerging climate change impacts such as the relative rise in sea level (e.g., Chucalén; Garrett et al. 2015) and the effects of future earthquakes and tsunamis. Also, the conservation of these natural areas contributes to improvements in the mental, physical, and spiritual health of people who inhabit and visit these places (MacKinnon and Londoño 2016, Gordon 2019).

Conclusions

Seven localities on the coast of south-central Chile were identified and characterized as paleoseismic heritage sites. From north to south these are: Tirúa, Queule, Loncoyén, Mancera Island, Maullín, Chucalén and Cocotué. Except for Mancera Island and Loncoyén, these geosites have high scientific values relevant for the study of the seismic cycle in Chile, particularly of the Valdivia segment. They contain exceptional records of the vertical elevation changes on the Chilean coast caused by subduction earthquakes as well as during interseismic periods, with sedimentary deposits left by ancient tsunamis that occurred during the late Holocene (< 1.5 ka). They are unique in their representation of important geological processes including major subduction earthquakes, such as the events of 1575 and 1960 (the largest earthquake measured by humanity), the latter showing evidence at all geosites. Consequently, all these sites have high historical value. Moderate and deep-focus earthquakes like the event of 1737 are evidenced in Loncoyén and Mancera Island, while the local event of 1837 is only recorded in the stratigraphy of Cocotué. The events from the paleoseismic record of 1100 and 1300 AD can be identified in the central zone of the Valdivia segment. All the geosites included in this inventory are part of the geological heritage of Chile, specifically for paleoseismology, and their relevance is both national and international.

These geosites are important for the understanding and characterization of the behavior of subduction zone earthquakes. There are scientific studies that support their association with earthquakes and tsunamis, and Tirúa, Maullín, Chucalén and Cocotué are included in publications in high impact international journals. They have good integrity; however their risk of degradation ranges from moderate to high, including two geosites (Tirúa and Loncoyén) that urgently require the implementation of management strategies to protect their elements through public geoconservation policies and actions. Three geosites have some type of legal protection: Mancera Island as a Historical Monument and Tourist Zone; Maullín, which is a Nature Sanctuary, an Important Bird Area (IBA) recognized by Birdlife International and was incorporated into the Western Hemisphere Shorebird Reserve Network (WHSRN); and Chucalén, which is part of the Coastal Marine Spaces of Indigenous Peoples (ECMPOs) managed by the local community with sustainable practices. Even taking these protections into account, it is necessary to promote their effective conservation and raise awareness of their value among the community and pertinent authorities. Future sustainable scientific, educational and tourist activities should be carried out by linking the paleoseismic heritage sites and other relevant geological, ecological, and cultural elements, thereby contributing to the reconnection and integration of human beings with natural systems. This implies a more complete and holistic conservation strategy for the future.

These paleoseismic sites are ideal places to educate about the geological hazards associated with earthquakes and tsunamis that occur on the Chilean coast by involving the communities that inhabit these places, as they are resilients with these geological events that occur frequently in this country. Moreover, the selected sites have moderate to high potential touristic value and can contribute to the sustainable economic development of local communities.

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Data Availability The authors confirm that the data supporting the findings and conclusions of this study are available within the article and its supplementary materials.

Declarations

Conflicts of interests/Competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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