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REGULAR PAPER

Revisiting the role of high-energy Pacific events in the environmental and cultural history of Easter Island (Rapa Nui)

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Pacific islands are spread over thousands of kilometres of the Pacific Basin and are characterised by similar ecological features but very diverse geologic origins, from steep volcanoes to flat coral atolls. Several climatic phases have been shared across the region within the last 1,000 years. Numerous and abrupt societal and cultural changes during the same period have been described for islands separated by thousands of kilometres. Conspicuous societal changes have been exclusively attributed to the main climatic patterns (changes in precipitation and temperature). The possible role of tsunamis and the occurrence of large volcanic eruptions as regional societal modulators, however, have traditionally received little attention from archaeologists, mainly due to the difficulty of recognising them in the sedimentary and geomorphological records. We explore the potential influence of the most important high-energy events in the Pacific on Polynesian societal changes, with a special focus on Easter Island. For example, the extreme Samalas eruption in AD 1257 may have been an indirect driver of the sudden population decline, land degradation and decreased food resources on many Pacific islands between AD 1250 and 1300, and the Kuwae eruption in AD 1450 may have triggered the synchronous end of long voyaging expeditions across the Pacific. Important palaeo-tsunamis have had unquestionable impacts on coastal and seafaring societies. A direct effect of the main eruptions of the last millennia (AD 1257 and 1453) on Easter Island has not yet been identified by any record, but we have calculated the likelihood of destructive tsunamis with an estimated period of recurrence for large events of less than a century. This insight is new and needs to be taken into account to complement what we already know about Easter Island's cultural history and archaeological sites, especially those in vulnerable coastal locations.

KEYWORDS
Easter Island, historic volcanic eruptions, lacustrine record, palaeo-tsunamis, Polynesian societies

1 | INTRODUCTION

Polynesia, Melanesia and Micronesia consist of more than 1,000 islands spread over the Pacific Ocean. They define a scattered and unique landscape where native inhabitants have shared similar traits, including language, beliefs and excellent sailing skills (Figure 1). The islands are characterised by similar ecological features but different geologic settings and topographies.

Large climatic changes have been recorded during the last millennia across the Pacific (Allen, 2006; Nunn, 2007). The Mediaeval Warm Period (MWP) was characterised by a rising sea level in the Pacific Basin from AD 750 to 1250 and climate varied little inter-annually, but with periods of drought along the eastern Pacific (Figure 2). The climatic shift that occurred from AD 1250 has been regarded as the most dramatic of the past 5,000 years (Mayewski et al., 2004; Miller et al., 2012; Nunn, 2000). This transition to the Little Ice Age (LIA) preceded the lower sea levels and cooler global temperatures that lasted until AD 1750. The onset of the LIA caused large and worldwide climatic changes (Miller et al., 2012), and there is evidence of lower sea levels of up to 1.8 m in most parts of the Pacific Basin (Nunn & Peltier, 2001). Changes in sea level can change coastal environments and therefore resources, and the shape and size of islands. The onset of the LIA was also characterised by a decrease in global temperature (Miller et al., 2012). Together with these climatic disruptions, the increase in storm frequency in the central Pacific (Toomey et al., 2013) has been attributed to an increase in El Niño Southern Oscillation events (cold ENSO events since circa AD 1300; Rein et al., 2004).

The changing climatic conditions between AD 1250 and 1350 may have caused profound societal crises. Nunn (2000, 2007) and Nunn et al. (2007) have conducted extensive interdisciplinary studies, gathering archaeological, climatic and palaeoecological records to explain complex societal disruption. Similar societal changes sometimes occurred on islands thousands of kilometres apart within a restricted period. The principal examples consist of (1) dietary changes, (2) sudden

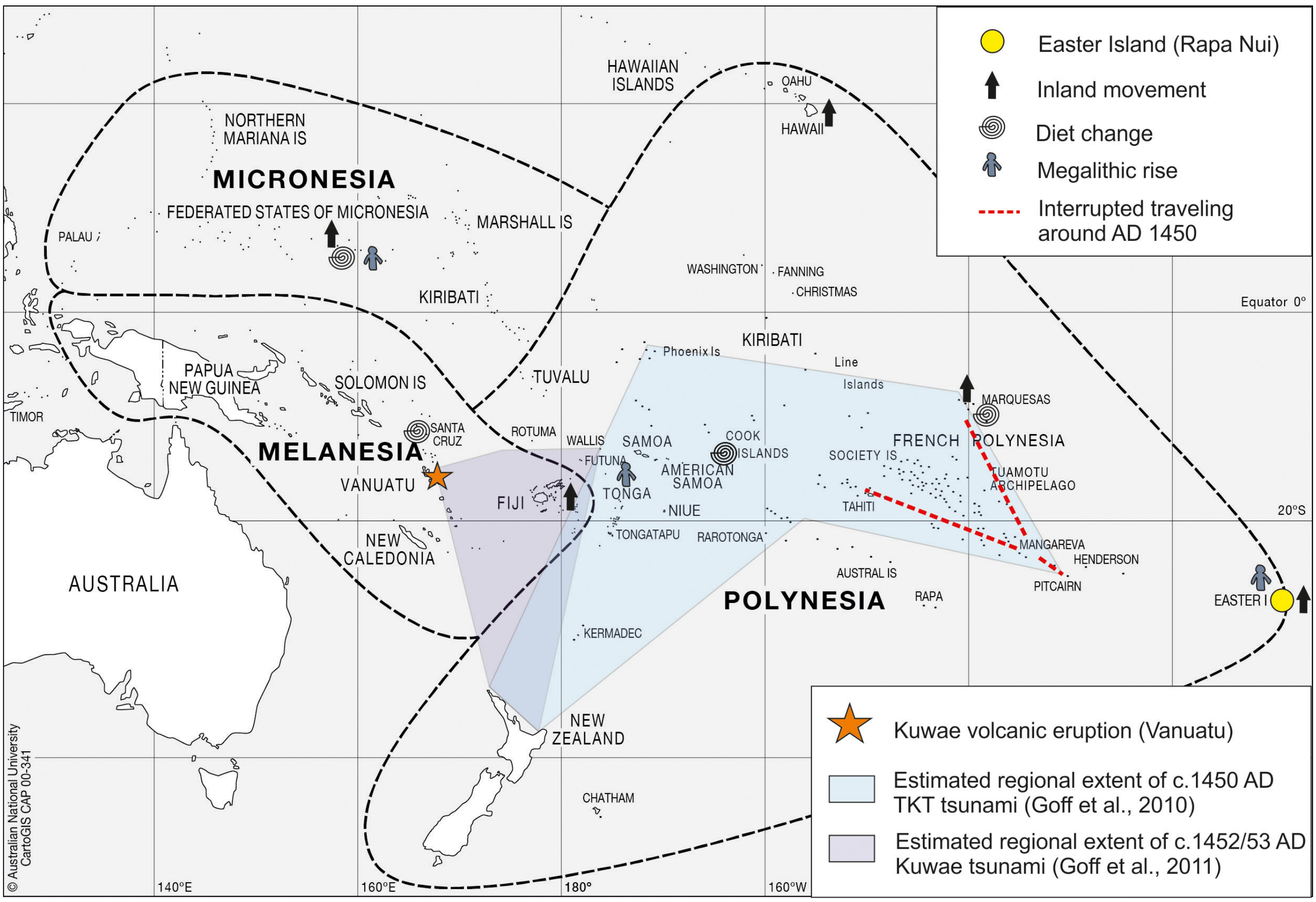

FIGURE 1 Map of the Pacific Ocean islands. Easter Island is at the easternmost edge of Polynesia. Main cultural changes recorded during the 1300 event and the Little Ace Age are detailed, together with the effect of the ENSO phases on precipitation and the deduced reach of the 1450 Tonga-Kermadec (TKT) and 1452 Kuwae tsunamis.

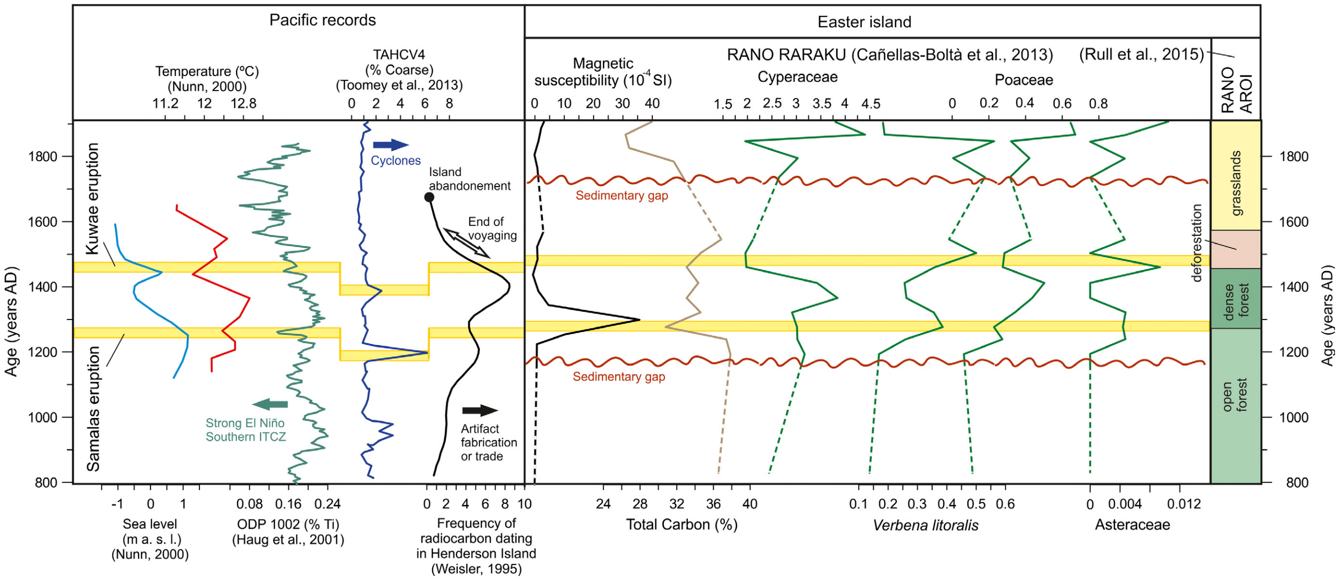

FIGURE 2 Summary of the main climatic trends in the Pacific Ocean between AD 800 and 1800 (Nunn, 2000; Haug et al., 2001; Toomey, et al., 2013) and a record of trade among islands from Henderson Island (Weisler, 1995). The main pollen taxa from Rano Raraku (Cañellas-Boltà et al., 2013) for the same period and the main landscape phases recorded in Rano Aroi (Rull et al., 2015) are also included.

land degradation, (3) inland movement of coastal settlements, and (4) interruption of long-distance trade among archipelagos (Figure 1). Allen (2006) has nevertheless questioned the reliability of this widespread societal disruption because of the spatial climatic heterogeneity of the Pacific Ocean.

Little information, however, is available for the effects of abrupt high-energy events during the last millennia on the ancient inhabitants of ancient Pacific Island Countries (PICs), which is relevant given the elevated geohazard risk across the region. The Pacific Basin is surrounded by the most tectonically active plate boundaries, the "ring of fire", the main source of earthquakes and volcanic eruptions in the world. Explosive eruptions have occurred during the last 1,000 years, especially in Southeast Asia, perturbing climatic conditions and disrupting societies as distant as Europe. Tsunamis and volcanic eruptions are also important when studying human environmental and climatic interactions because their effects can push stable societies into crisis.

Archaeological and paleoenvironmental studies have provided, for the moment, little information on the impacts of high-energy events on the widespread, isolated island systems. In this paper, we intend to highlight the remaining questions of the effects of volcanoes and earthquakes on old PIC societies, with a special focus on the vulnerability of Easter Island. Despite the fact that high-energy events have been occurring in the Pacific Basin since earlier times (Goff, Lamarche, et al., 2011; Goff, Chagué-Goff, et al., 2011), we have chosen the temporal window of the last 1,000 years because it includes several well known eruptions, tsunamis and climatic changes, and many islands were already inhabited or were about to be colonised. This period represents an excellent opportunity for determining the impacts of these events on the relation between humans and the environment.

2 | VOLCANIC ERUPTIONS AND CLIMATE IN THE PACIFIC BASIN

The Pacific Basin is surrounded by 452 volcanoes, more than 75% of the world's active volcanic systems (Simkin, 1993). Volcanic eruptions have been among the most disruptive short-term events in human history, as active triggers of global climatic and social changes (LeGrande & Anchukaitis, 2015). Some of the largest eruptions in the last 1,000 years were in the Java and Tonga trenches: AD 1257 (Samalas, in the island of Lombock, Indonesia), AD 1453 (Kuwae), AD 1665 (Long Island; Blong et al., 2017), AD 1815 (Tambora) and AD 1883 (Krakatoa) (Table 1). The consequences for Pacific societies of the first two are challenging to estimate because of the difficulty of reconstructing history given the lack of written chronicles. However, what we know for the Tambora and Krakatoa eruptions offers a good source of evidence for inferring what could have happened in former eruptions. The main regional impact of the Krakatoa eruption was a tsunami

TABLE 1 Details of the main circum-Pacific south Hemisphere volcanic eruptions of the last millennia

Volcano	Coordinates	Year	VEI[a]	Intensity (kg/s)[b]	DRE (km^3)[c]	Tsunami	References
Samalas	8.40°S, 116.41°E	1257–1258	7	12	>40	?[d]	Castellano et al. (2005), Lavigne et al. (2013), Vidal et al. (2015)
Kuwae	16.83°S 168.54°E	1452–1453		6.9–7.2	30–60	Yes	Gao et al. (2006; Goff, Lamarche, et al., 2011)
Long Island	5.35°S 147.12°E	1655	6	?[d]	11	?[d]	Blong et al. (2017), Hoffmann et al. (2008)
Tambora	8.25°S, 118.0°E	1815	7	11.4	>33	Yes	Cole-Dai et al. (2009), Oppenheimer (2003), Self et al. (2004)
Krakatoa	6.10°S, 105.41°E	1883	6	10.7	12.5	Yes	Paris et al. (2014), Simkin & Fiske (1983)
Pinatubo	15.13°N, 120.35°E	1991	6	11.6	5	No	Hansen et al. (1996), Schoeberl et al. (1993)

[a]VEI, volcanic explosivity index, is a relative measure of the explosiveness of volcanic eruptions from 0 to 8.
[b]Intensity is the rate of mass eruption.
[c]DRE, dense-rock equivalent, is an estimate of the volume of magma emitted during the volcanic eruption.
[d]Unknown.

that devastated the coast of the Sunda Strait and killed 40,000 people (Paris et al., 2014). The injection of 3×10^{13} g of total aerosols into the stratosphere decreased the mean global temperature by 1.2°C (Deirmendjian, 1973) and produced unusual sunsets worldwide for the next three years (Simkin & Fiske, 1983). The Tambora eruption in 1815 was even more explosive. The effects were devastating for the surrounding islands, and thousands of people died from starvation and illness (water pollution, cholera) in the region (Oppenheimer, 2003). The massive injection of sulphate aerosols into the stratosphere led to a global cooling of 1–1.5°C (Self et al., 2004) with impacts on global agricultural production (Cole-Dai et al., 2009), and the worst famine throughout Europe in more than a century (Oppenheimer, 2003). In spite of the clear record of unexpected weather in summer 1816, such dramatic consequences in Europe can only be explained within a historical contingency of ongoing social calamity (Veale & Endfield, 2016).

The tropical eruption at Pinatubo in 1991 was closely monitored by the SAGE II satellite. The most optically dense portions of the cloud produced by this explosion were concentrated from 10°S to 30°N (McCormick & Veiga, 1992). Strong stratospheric winds distributed these aerosol particles widely in the following years, causing a global cooling of *c*. 0.5°C (Hansen et al., 1996).

2.1 | The Samalas AD1257 eruption

The Samalas explosion (AD 1257) was the largest stratospheric volatile release during the Holocene. The sulphate concentration that reached Antarctica was four times higher than that of Tambora. The associated global cooling could have been 50%–200% more than from the 1991 Pinatubo eruption (LeGrande & Anchukaitis, 2015). Climatic impacts were global, for example, heavy rains during summer and autumn throughout Europe that ruined crops, causing severe famine.

Miller et al. (2012) suggested that the Samalas eruption may have played a key role in triggering the LIA. These authors used a transient climatic model simulation to demonstrate that explosive volcanism could produce cold summers and that cooling could be maintained by sea-ice oceanic feedbacks long after the volcanic aerosols had been removed. The onset of the LIA can thus be linked to an unusual period (50 years) of large eruptions that started with the AD 1257 Samalas eruption (Miller et al., 2012).

The probability of strong ENSO episodes during the cold season doubles after a large volcanic eruption at low latitudes, due to the negative shortwave surface radiative forcing from the injection of aerosols into the lower tropical stratosphere. Cole-Dai et al. (2009) reported that the AD 1257 eruption likely favoured the occurrence of El Niño events in the midst of prevailing La Niña-like conditions. Consequences have also been reported in the West Pacific. Consistently, the onset of a different drainage phase at the Kuk Swamp in Papua New Guinea has been attributed to the onset of El Niño droughts after the Samalas eruption (Bayliss-Smith et al., 2017).

The massive injection of aerosols into the stratosphere, however, could have had other consequences over the central Pacific, as did the Pinatubo eruption. Large ozone depletion (Schoeberl et al., 1993) allowed more UVB to reach the ground (Self, 2006). The depletion at mid-latitudes (e.g., in the Hawaiian archipelago) reached 20%. Moreover, pollution of the lower atmosphere with acidic aerosols could induce respiratory illness thousands of kilometres from the eruption (Self, 2006), as well as groundwater contamination and serious disruption of coral growth.

The most extreme impacts of the Samalas eruption probably lasted a few years, but its occurrence during the onset of the long-term environmental changes that characterised the LIA could have had large impacts on the societal disruption described for the 1250–1350 period. Large areas could have been under the influence of polluted rainwater and unexpected rainfall patterns for years after the eruption, ruining crops and coastal resources, but also under the influence of unusually cold temperatures that could last for decades. The main obstacle to understanding the consequences of the Samalas eruption to Pacific populations is the lack of accurate dates for most of the agricultural, dietary or settlement changes. Important changes nonetheless occurred throughout the Pacific Basin during the century after this period, although the specific influence of the Samalas eruption will need to be further assessed in the future.

Several indicators of societal disruption across the Pacific Basin between AD 1250 and 1300 have been described. A sudden reduction of population occurred in Nuku Hiva (Marquesas Islands; Weisler, 1995), and societal crises in Mangareva and the Pitcairn islands were precipitated by land degradation (Nunn, 2007). The shift from coastal to hilltop settlements was also a major indicator of societal disruption on high Pacific Islands. The consumption of marine food changed after AD 1250 on other islands, such as Kapingamarangi Atoll (Federated States of Micronesia) (700 BP; Leach & Ward, 1981), Aitutaki (Cook Islands) and Guam. The populations of commensal species probably introduced deliberately by humans (such as dog, rat or chicken) fell abruptly in the Marquesas Islands during the 1250–1350 period and then partially recovered (Nunn, 2007). The building of megalithic monuments around the time of the 1250–1350 period represents such a short-term adaptation, in this case an appeal to a divine power. Examples are the monuments on Easter Island (Bahn & Flenley, 1992), Pohnpei in Micronesia and some Tongan islands.

3 | IMPACTS OF TSUNAMIS

The devastating effects of tsunamis have been considered as too local to be important for the history of PICs (Anderson, 2009). Goff et al. (2012), however, claimed that palaeotsunamis have received too little attention in archaeological studies because the inhabitants were coastal people and fishers who relied on boats for their livelihoods. Recent tsunamis, such as the South Pacific Tsunami in 2009, have shown how vulnerable these islands can be to such events (Goff, Lamarche, et al., 2011).

Myths that are part of the cultural heritage of PICs represent the recollections of these catastrophic events. Tales of diluvia and floods are among the most common myths in the region (Nunn & Pastorizo, 2007), for example, the devastating tsunami recalled in Pukapuka oral traditions (Cook Islands) or the Manihiki and Rakahanga (Cook Islands) myth that refers to the sea as a "sheeting mass" (Gill, 1916). The coral boulders 15 m in diameter and weighing 1,600 tonnes found 10 m a.s.l. in Tonga deposited by a Holocene tsunami were described by local oral tradition as giant stones thrown from the sea by the god Maui (Frohlich et al., 2009).

Tsunamis can have an immense erosive power. Extreme wave events can break beach barriers, move tons of sand to infill coastal lagoons or erode an entire beach (Ramalho et al., 2013). Tsunamigenic deposits are characterised by boulder-strewn gravel with megaclasts and finer sedimentation in topographic lows (Ramalho et al., 2013), with low islands being particularly vulnerable (Woodroffe, 2008).

Examples of rocky coastlines of volcanic islands strongly impacted by tsunamis include the Kohala and Kīlauea shores in Hawaii or the shore of Gran Canaria (McMurtry et al., 2004; Noormets et al., 2002; Pérez-Torrado et al., 2006; Ramalho et al., 2013). Some old tsunamis have already been well described for the regions of Tahiti (Sinoto, 1979) or New Zealand (McFadgen, 2007), but most remain undiscovered. Goff, Chagué-Goff, et al. (2011) proposed more than 22 possible PIC palaeotsunamis from archaeological, geochemical, palaeoecological, geomorphological and sedimentological features. Some were equivocal and on islands where archaeologists certified a sudden abandonment of coastal settlements, such as the Marquesas Islands (Aswani & Allen, 2009). Others, though, are very conclusive, such as the large palaeotsunamis in Hawaii dated between 1430 and 1665. Remarkable examples are two tsunamis whose inferred reaches are shown in Figure 1; that caused by the AD 1452–1453 Kuwae eruption which reached Fiji and the New Zealand coast (Goff, Chagué-Goff, et al., 2011, 2012), and the AD 1450 Tonga-Kermadec trench tsunami inferred from its effects from Pitcairn to New Zealand, separated by more than 5,400 km (Goff et al., 2012).

Archaeological evidence suggests that open-sea voyaging suddenly collapsed in the mid-fifteenth century (Goff et al., 2012). Accurately dating the cessation of inter-island communication is difficult (Nunn et al., 2007), but the Vanuatu-Tonga trade tradition was likely suddenly interrupted in AD 1450, as was the regular exchange between Henderson Island and other islands (Weisler, 1995) (Figure 1). The trade connection in eastern Polynesia among the Society Islands, Marquesas Islands and the Pitcairn group pivoted around Mangareva. The withdrawal of one of the nodes of these trading routes around AD 1450 likely led to the collapse of the entire commercial tradition (Weisler, 2002). Goff et al. (2012) suggested that the coincidence of the AD 1450 Tonga-Kermadec and AD 1452 Kuwae tsunamis with this interruption of inter-island trade may indicate a causal relationship. Tsunamis could have been responsible for the damage of belongings, such as huts and canoes, but also for the loss of knowledge arising from high death rates in the population (Goff et al., 2012). These circumstances, together with climatic instability during the LIA, may account for the ubiquitous and long-term changes.

The incidence of tsunamis, together with other societal and environmental changes, could have encouraged humans to move from main coastal settlements towards inland areas and caves. The development of ridge-top settlements across the Pacific Ocean may have been partly due to the recurrence of tsunami events that killed islanders and destroyed goods along the coast. Inland movements are a main characteristic of the early LIA and have been described for Chuuk and Yap (Micronesia) and Kaua'i and O'ahu (Hawaii). A wholesale movement of people inland around 1450 has been described on islands within the estimated ranges of the 1450 and 1452–1453 tsunamis (Goff et al., 2012), such as in Marquesas or in Lau and Viti Levu (Fiji) where the clearance of upslope vegetation indicated a communal movement (Nunn, 2007).

The nature of this geohazard is localised in space and time. This lack of ubiquity and the difficulty of recognising and dating the geomorphological tsunamigenic imprints are the main reasons why they have not yet been extensively studied (Anderson, 2009), and are considered as minor sources of cultural changes in the Pacific Basin. The impact of a tsunami, however, can be catastrophic for a single island or archipelago because of the size and topography of Polynesian islands and the seafaring lifestyle. The remaining enigma of the mystery islands (inhabited and then abandoned) has been associated with abandonment due to changes in sea level and water accessibility. For these islands, the hypothesis of the impact of tsunamis should be considered and contrasted with the available archaeological and palaeoenvironmental information. The following section considers this for the case of Easter Island.

4 | EASTER ISLAND

Easter Island (Rapa Nui) is a volcanic island at the easternmost edge of Polynesia and more than 3,000 km from South America (Figure 1). Pioneer palynological studies in sedimentary lake records were conducted in the island in the early 1980s, and were used to relate landscape evolution with societal and cultural changes (Flenley & King, 1984). According to their theory, the first settlers arrived between AD 800 and 1200 from east Polynesia and deforested the island, causing an ecological catastrophe leading to a cultural collapse (Flenley & Bahn, 2003). Another theory proposes a later arrival, between AD 1200 and 1300 (Wilmshurst et al., 2011). However, recent studies on lacustrine sequences revealed stratigraphic discontinuities in the sedimentation (Sáez et al., 2009) and suggest that the first signals of anthropogenic disturbance occurred at 450 BC, associated with the appearance of an American human-dispersed weed (Cañellas-Boltà et al., 2013). There is a general consensus that the island underwent important changes in landscape. However, the age and nature of deforestation has been a controversial issue. This controversy, together with the latest archaeological discoveries (Lipo et al., 2016), indicate that societal changes were thus transitions or transformations rather than a collapse (Rull, 2016a, 2016b). Recent revisions have proposed holistic approaches that combine climatic, ecological and cultural changes to understand the history of the local community and landscape (Rull et al., 2016). Current revisions, however, have not incorporated the possible impact of eruptions or tsunamis on the island, despite the main ancient settlements having been located in coastal areas of Easter Island. To address this question, we contextualise the latest discoveries on the island's environmental reconstructions with what we know, from a regional perspective, of the principal geohazards that could have affected this remote enclave.

4.1 | Tracking the regional volcanic signal

Studies of the sediments on the island present a chronology precise enough to permit a detailed analysis of the last 1,000 years. The RAR-08 core of lacustrine sediments from Rano Raraku (Cañellas-Boltà et al., 2013) and the ARO 08-02 core of peat from the Rano Aroi mire (Margalef et al., 2013; Rull et al., 2015) are some examples. Direct effects of the eruptions described in Section 2 on "Volcanic eruptions and climate in the Pacific Basin" are not feasible due to the enormous distance from the emitting focus. We may, however, be able to recognise indirect impacts on Easter Island.

The sequences of the RAR-08 core depict an important magnetic susceptibility peak at *c*. AD 1280, which could be interpreted as an important influx of detritic material to the centre of the wetland basin. Similar processes in former times have been associated with episodes of higher precipitation (Sáez et al., 2009). The age of this intense pluvial event and the associated age uncertainty of this core section (±29 years) allow correlation with the Samalas eruption and its global impact. This correlation would be consistent with the studies demonstrating that tropical and intense eruptions can be precursors of changes to storm frequency and rainfall patterns, and that ENSO intensity abruptly increased after the Samalas eruption (Cole-Dai et al., 2009; Rein et al., 2004). The definitive attribution of this terrigenous sediment peak as a consequence of the Samalas eruption can nevertheless only be achieved by more radiocarbon dating to reduce the present uncertainties of the chronological model.

The Rano Raraku sedimentary record also indicates that the deforestation around the lake started much earlier than has been traditionally established (Cañellas-Boltà et al., 2013), with a strong intensification *c*. AD 1200 culminating around AD 1450. Documented evidence suggests that agricultural activity continued until AD 1320 and 1440 (Horrocks et al., 2012). The 1250–1350 period and the initial phase of the LIA are characterised in the Raraku basin by a decrease in palm abundance and a gradual increase in herbaceous species such as Poaceae and *Verbena litoralis*, together with an increase in charcoal remains (Cañellas-Boltà et al., 2013). Focusing on a narrower temporal scale, however, indicates coherent fluctuations between the vegetal cover and the occurrence of the AD 1257 Samalas and the AD 1450 Kuwae volcanic eruptions. The main tendencies of the vegetal cover in this period were interrupted by two changes in the relative abundance of pollen taxa, with less Poaceae and Palmae pollen and more *V. litoralis* pollen, suggesting a disturbed site (Cañellas-Boltà et al., 2013). The abundance of wetland taxa (Cyperaceae) also decreased, a trend coinciding with the higher influx of clastic material (Figure 2). Heavy rains suggested by the magnetic susceptibility could have limited the expansion of shore vegetation and floating mats as a result of the arrival of large detrital inputs. The Rano Aroi basin on the highest part of the island evolved differently. Rull et al. (2016) described a change in the pollen zones around AD 1250, apparently driven by natural causes, because human activity was not prevalent in the area at that time. The deforestation around Rano Aroi began in AD 1550 and ended in AD 1650, but the area was likely occupied only by marginal populations (Rull, 2016a, 2016b). On the other hand, Horrocks et al. (2015) suggests a period of deforestation between AD 1240 and 1610. The authors conclude that Rano Aroi was occupied after AD 1670, later and shorter than at lowland sites, which is consistent with Rull et al.'s (2015) proposal.

The premise that the available sedimentary records for Easter Island have captured indirect impacts of the main global eruptions from the past cannot be rejected. These vegetal changes were synchronous with regional cooling and lower sea levels (Nunn, 2000) (Figure 2). Periods in which the intertropical convergence zone migrated southward (Haug et al., 2001) and cyclones were more frequent (Toomey et al., 2013) have been described in areas under the influence of the South Pacific convergence zone (Margalef et al., 2014). The nature and resolution of our Easter Island evidence, however, do not imply causality from chronological correlations with regional observations. Whether or not Rapa Nui's ecological and cultural changes are a consequence of these main eruptions cannot be fully addressed with the available evidence and will require further multidisciplinary research. The geochemical and chronological study of coral growth could contribute to this open question. Interest in the growth of coral has also been expressed in a recent review (Rull, 2016a, 2016b).

4.2 | Easter Island and the risk of tsunamis

Easter Island is 3,500 km from South America and therefore vulnerable to tsunamis generated on the circum-Pacific subduction zones, especially those in South America. In the last century, Rapa Nui was affected by tsunamis generated in the Alaska trench in 1946 (Okal et al., 2002) and along the coast of Chile in 1960 and 2010 (Fritz et al., 2011). The M_W 8.1 event in Chile in 1995 generated a flood of decimetres (Guibourg et al., 1997). The last demonstration of the vulnerability of Easter Island to tsunamis from distant sources was on 16 September 2015, when a tsunami reached the island after the Illapel-Coquimbo earthquake (M_W 8.4 magnitude). Local witnesses reported some damage to old stone walls near the coast.

Waves at least 6 m high arrived at the island during the largest tsunami documented, after the 1960 Valdivia earthquake (M_W 9.5 magnitude). Many *ahu*[1] from the southeast coast were impacted and flooded (Cortez et al., 2009; SHOA, 2000), and around 50 tons of *moais* were moved more than 60 m inland (Domínguez, 1961). Photographs from a few days before and after the tsunami were taken by Lorenzo Domínguez, a Chilean artist (Figure 3). Marine abrasion debris distribution allowed reconstruction of the run-up limit, close to 1 km inland (Cortez et al., 2009).

Recent reviews show how dated archaeological evidence (Mulrooney, 2013) and the vast majority of the *hare paenga* (boat-shaped house) distribution (Seager Thomas, 2014) suggest that human activity during the last millennia mostly

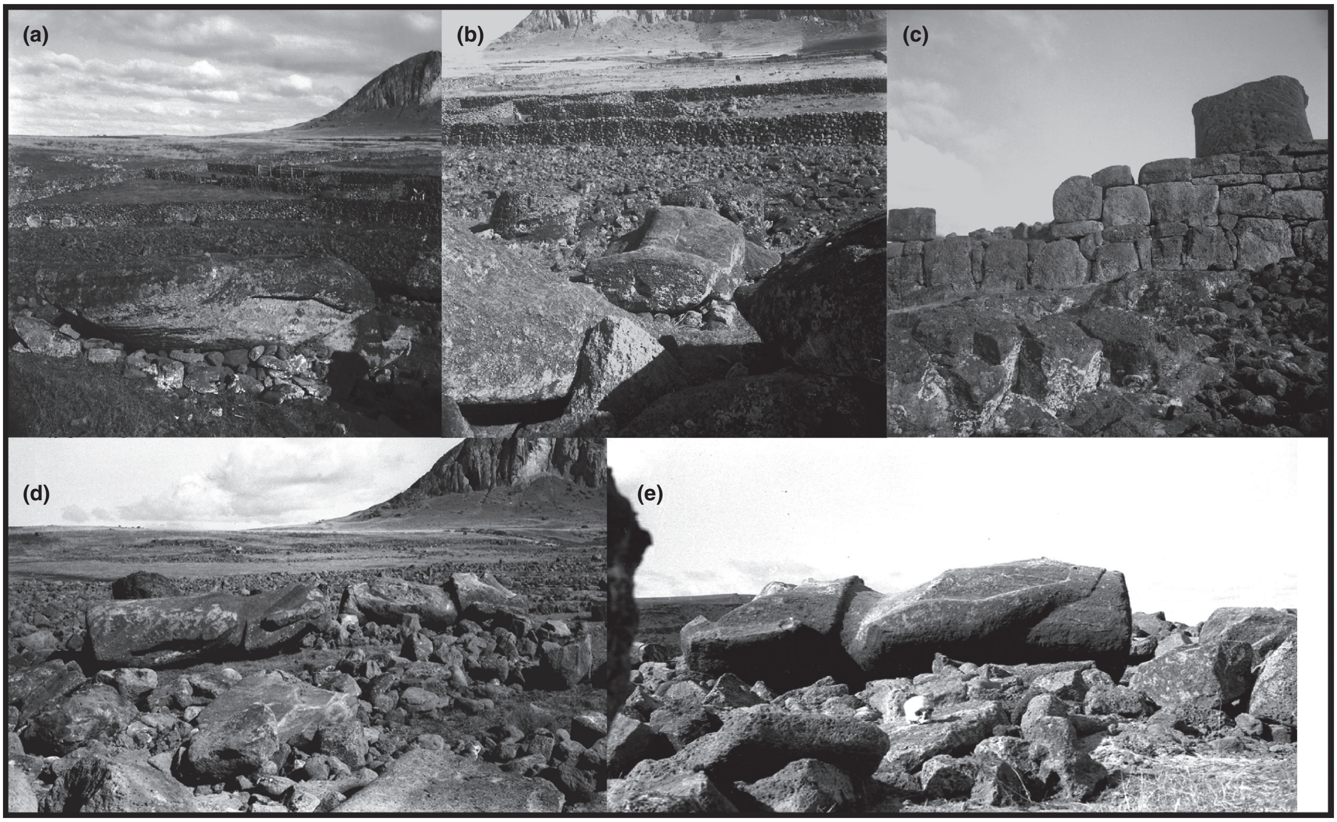

FIGURE 3 Images taken by the chilean artist Lorenzo Domínguez (Domínguez, 1961) before (a–c) and after (d, e) the Valdivia earthquake (reproduced with permission). The 50 ton moais were transported 60 m inland. Several stone walls at the base of Raraku crater were completely ruined, exposing several human bones (e).

occurred in coastal areas. Inland landscapes were mainly occupied for agricultural purposes (Puleston et al., 2017), although a few residential remains were also found in inland areas (Mulrooney, 2013).

To estimate the frequency of tsunamis that could have affected Easter Island in the past, we have simulated a series of tsunamis and conducted a seismo-tectonic analysis. Not all Pacific subduction zones have the capacity to generate tsunamis that could endanger Easter Island due to the direction of the waves generated by tsunamis, the maximum wave heights perpendicular to the generating source and the dissipation of energy with distance (see for example Kajiura, 1970). The subduction zones with the greatest potential to produce damaging tsunamis at Easter island are Tonga-Kermadec, Marianas, Japan, Alaska, Mexico, Central America, Peru and Chile (red in Figure 4). We developed a number of tsunami simulations using COMCOT (Liu et al., 1995) to obtain the wave propagation, taking into account the circum-Pacific subduction characteristics (Berryman et al., 2015), and estimated the tsunami inundation in our models using the Synolakis (1987) formulation for comparing our results with observed run-ups.

Our numerical model was based on the linear shallow-water equations resolved on a finite difference scheme with three nested grids with increasing resolutions of 10′, 2′ and 30″. We simulated the 1946 Alaskan earthquake (Okal & Hebert, 2007) and the 1960 (Barrientos & Ward, 1990) and 2010 (Lorito et al., 2011) Chilean earthquake as controls. For the Chilean earthquakes, the run-ups at Hanga Roa were 2.7 m for the M_W 8.8 2010 earthquake and over 6 m for the M_W 9.5 1960 earthquake, and our simulations produced run-ups of 2.8 and 6.8 m, respectively, correlating well with the observations. Our estimated run-up for the 1946 Alaskan earthquake was not consistent with the evidence (1.4 m compared with the observed 8.6 m run-up; Okal et al., 2002), perhaps due to the large uncertainties about the tsunami source: a submarine landslide or complex ruptures may have been involved. Our results were nevertheless consistent with the Alaskan subduction; the 1964 M_W 9.2 Alaskan earthquake in Prince William Sound, which produced tsunami run-ups of several metres in Hawaii, did not damage Easter Island, as our results showed.

We modelled worst-case scenarios and a M_W 8.5 magnitude event for each of the subduction zones mentioned above (the source dimensions for the events were modelled in agreement with Berryman et al. [2015]). The propagation of a tsunami wave can be considered a linear phenomenon in deep water, so we can obtain a correlation between the estimated

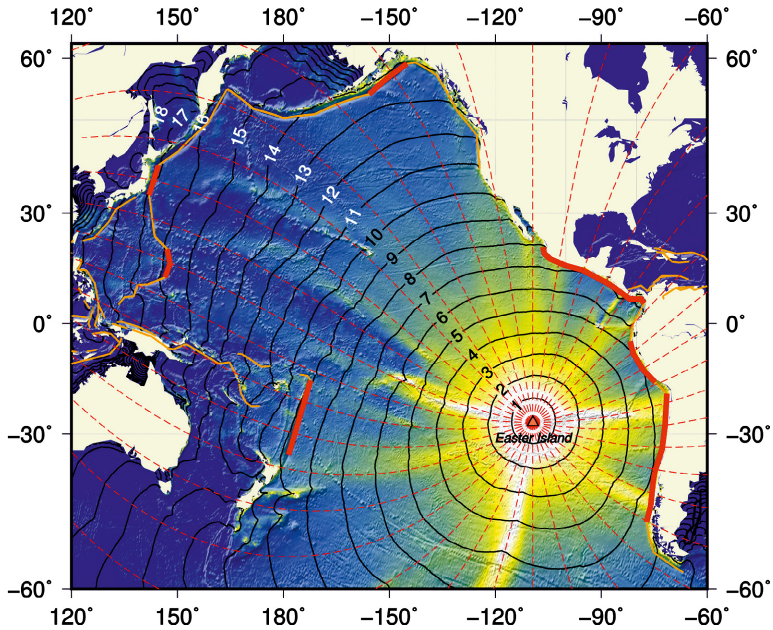

FIGURE 4 Inverse tsunami propagation map from Easter Island. The colour shade shows the tsunami wave elevation attenuation; the clearer the colour, the higher the wave. The isolines show reverse tsunami travel times in hours (for example a tsunami generated in Tonga-Kermadec will reach Easter Island in 9 h). In red are marked the subduction segments with the greater capacity to generate tsunamis for Easter island. Red dashed lines show rectilinear trajectories from Easter Island.

run-up height and the corresponding earthquake magnitude. We can then establish the minimum earthquake magnitude needed to produce tsunamis that could damage Easter Island for each circum-Pacific subduction segment.

The period of recurrence for an earthquake magnitude in each subduction zone can be expressed as (Cosentino et al., 1977):

$$\lambda_{Mi} = \exp(\alpha - \beta_{Mi}), \tag{1}$$

where $\alpha = a \times \ln(10)$, $\beta = b \times \ln(10)$ and a and b are the parameters of the Gutenberg–Richter law (Gutenberg & Richter, 1941). The recurrence interval is defined as the inverse of the annual rate of exceedance: $T = 1/\lambda_{Mi}$. We used the values of b estimated by Berryman et al. (2015). The values of a are obtained from the worst case event average slip and plate subduction velocity calculated as (Cosentino et al., 1977):

$$a = (\ln 1/T_{\max} + \beta_{M\max})/\ln(10) \tag{2}$$

The recurrence interval for Easter Island of tsunamis generated by earthquakes, T_{EI}, is analogous to $1/\lambda_{EI}$:

$$\lambda_{EI} = \sum_{1}^{nsub} \lambda_{M_{\min},\, nsub} \tag{3}$$

Our results indicate that events similar to the Chilean 2010 tsunami could reach Easter Island every 15–20 years, mainly from Chile but also from Peru, Mexico, Japan and Tonga–Kermadec. More devastating tsunamis, generated mainly in South America, such as the 1960 Chilean tsunami, had recurrence intervals of 50–60 years, in agreement with the results of Nakamura (1986) for the Eastern Pacific.

At least 50 tsunamis may have reached Easter Island during the last 1,000 years, including high-magnitude events, such as the 1960 earthquake or the 1575 earthquake in southern Chile (Goff, Lamarche, et al., 2011), but also others such as the 1604 earthquake in northern Chile (Goff et al., 2010) or the 1586, 1409 and 1449 earthquakes in Peru (Bilek, 2009; Vargas et al., 2005). No signs of these potential tsunamis have yet been found in lacustrine records. However, some pioneer studies proposed that some semi-pyramidal *Ahu*, made of ancient recycled *Ahu* remains and fragments of marine material – probably dragged from water by tsunamis – indicate the impact of more than one tsunami event (Cortez et al., 2009). Identification of tsunamigenic sedimentological features in transitional marine-terrestrial environments requires a challenging and interdisciplinary approach (Rubin et al., 2017; Scheffers & Kelletat, 2003), which has not yet been developed for the island and would need to be taken into account in future projections.

5 | CONCLUSIONS

The Pacific Basin is the main region of volcanic activity, earthquakes and tsunamis, but the impact of these high-energy events has traditionally been overlooked as a driver of environmental and cultural changes in the reconstruction of PIC history. This oversight may be due to the difficulty of recognising their imprints in sedimentary records and landscapes, but also to the difficulty of dating the events with sufficient accuracy.

No direct effects of the main eruptions of the last millennia (AD 1257 and 1453) have yet been identified on Easter Island. Records for Rano Raraku and Rano Aroi, however, may eventually identify indirect effects of these volcanic episodes associated with changes to the regional climate, e.g., temperature, but also to changes in sea level and ENSO dynamics across the Pacific Basin. The likelihood of destructive tsunamis hitting the island during the last millennia has been demonstrated, with an estimated recurrence interval for large events of less than a century. This estimate is a new insight that needs to be taken into account when analysing Rapa Nui cultural history and archaeological sites, especially those at the more vulnerable coastal locations.

The reconstruction of the histories of ancient Pacific societies is an extraordinarily complex exercise due to the lack of written chronicles and the evident fragmentation of the large territory. This endeavour has made outstanding advances during the last 20 years despite these difficulties. Several enigmas, however, remain, despite several satisfactory attempts to provide regional correlations (Nunn, 2007). The nature and significance of the 1250–1350 period, a time with many climatic, environmental and cultural changes, or the reasons for the sudden cessation in trade among distant islands around 1450, though, have not yet been clarified. The geohazards outlined above (volcanoes and tsunamis) may have contributed to these unsolved questions, but further research is needed for clarification.

New records with better resolution and an efficient integration of the existing data that identify the landscape and cultural changes of the last millennia are required to determine the impact of past high-energy events on PICs. The currently available data are very diverse in theme and format, which complicates their collection and correlation. An open-access database for Pacific Island records for the sharing of data of different natures would be very useful to the scientific community. The first steps have been provided for Easter Island in the radiocarbon databases from archaeological sites (Mulrooney, 2013) and in sedimentary records (Rull, 2016b). An online, accessible Pacific Island database practically and simply organised would facilitate real interactive synergies for coordinating the frontiers of present knowledge.

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ENDNOTE

[1] The *ahu* are stone pedestals on which the *moai* stand, there are around 300 of these ceremonial platforms, mainly situated along the coastline. The *moai* are the well known monolithic figures carved from volcanic rock. These sculptures are between 2 and 10 m high.

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