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Abstract

Extreme geophysical events such as asteroid impacts and giant landslides can generate mega-tsunamis with wave heights considerably higher than those observed for other forms of tsunamis. In this paper, we review recent advances in the study of mega-tsunamis in the geological record, focusing on well-documented examples that have captured particular attention over the past decade. We provide up-to-date background on the source mechanisms of tsunami generation during asteroid impacts and ocean-island landslides, which are the largest landslides on Earth. We also discuss the main sources of uncertainty for modelling such mega-tsunamis, and for addressing associated hazards.

Introduction

The 2011 Tohoku-oki and 2004 Indian Ocean tsunamis were occasionally described as "mega-tsunamis", not only in the media but also in peer-reviewed literature (e.g. Lekkas et al., 2013), probably because they were the largest ones observed in the modern era (Goff et al., 2014). However, there is evidence in the geological record for rare but extreme events, with wave heights considerably larger than those observed during the 2011 and 2004 tsunamis (e.g. Moore and Moore, 1984; Bourgeois et al., 1988).

As a background to this discrepancy, it is important to recognize the fundamental difference in viewpoints between geologists, other scientists and the public regarding hazards. For instance, as commonly observed in risk assessment (Fig. 1), event probability decreases with an increase in hazard intensity (e.g., Kawata, 2003). Engineers and government agencies have to set thresholds of design force to enable infrastructure to be built for protection against hazards. However, although the frequency is low, some events are larger than this design force and as such, the protection that has been constructed can fail. For such overwhelming hazards, engineers and government agencies have to estimate a maximum size that they can reasonably prepare for reducing damage. Sometimes, people misunderstand this and assume that this maximum hazard is actually the real maximum, but larger hazards can still occur although at such a low frequency that we consider them negligible in a human lifetime. These hazards are beyond the limit of modern-style disaster prevention countermeasures so that when they do occur they are most definitely “unexpected (or “*souteigai*” in Japanese) hazards” (Goff et al., 2014). The 2011 Tohoku-oki and the 2004 Indian Ocean tsunamis were examples of these kinds of unexpectedly large events. Depending on the people who study these larger hazards, they use various terms such as “maximum”, “unexpected” and “mega” events.

In contrast, geologists who study the Earth’s history usually investigate extreme hazards such as asteroid impacts, large igneous provinces, snowball earth, etc. Without doubt, these events are hazards with global impacts and are far beyond the normal-style risk assessment (Fig. 1); these hazards can lead even to mass extinctions. Compared with these extreme hazards, “normal” hazards which occur over intervals of 100s to 1000s of years (e.g., large earthquakes and tsunamis) are quite frequent and relatively small events from a geological point of view. Sometimes these events are below the resolution and detection limits of geological research. Indeed, even recent large events such as the 2011 Tohoku-oki and the 2004 Indian Ocean tsunamis are probably only just large enough that sedimentary evidence for them will be preserved in strata over geological timescales. Also, geologically speaking, the occurrence of these events is not unexpected.

The discrepancy is in terms of the human perspective. While risk assessment is carried out from the human perspective (datum on the left-hand side of the horizontal axis in Figure 1), geologists study it from the point-of-view of deep time (datum on right-hand side of the horizontal axis in Figure 1). This is essentially why geologists generally consider that neither the 2011 Tohoku-oki nor the 2004 Indian Ocean tsunamis should be called “mega-tsunamis” since they know that there have been far larger events (or they consider that evidence for larger events is still undiscovered) that deserve to be called as such; “Mega” defines the largest events we know about at the moment.

Goff et al. (2014) proposed that the term “mega-tsunami” should be reserved for tsunamis with an initial wave amplitude exceeding 50 m at their sources, thus excluding all tsunamis generated by historical earthquakes. Paris et al. (2018) adopted the following definition: mega-tsunamis have a magnitude exceeding all published tsunami magnitude scales. Whatever the definition, among all the possible source mechanisms of tsunamis, only large landslides and asteroid impacts have the potential to generate mega-tsunamis.

With a maximum runup of 524 m, the 1958 tsunami in Lituya Bay (Miller, 1960) could be considered as the only historical example of a mega-tsunami. However, this exceptional runup was caused by the restriction due to the slope just opposite the source landslide (30.6×10^6 m^3) and values of runup rapidly decreased down to 10 m at 12 km from the source. By comparison, the December 2018 Anak Krakatau volcano flank collapse had a volume three times larger (> 0.1 km^3: Gouhier and Paris, 2019) than the Lituya Bay landslide, and an initial leading positive water displacement of 50 to 80 m (Grilli et al., 2019; Paris et al., 2019). Following the definition proposed by Goff et al. (2014), the 2018 Anak Krakatau tsunami could thus enter the mega-tsunami category, but the wave heights observed on the coasts of Sumatra and Java (40-60 km away from the volcano) were lower than 7 m (Takabatake et al., 2019; Muhari et al., 2019), which falls far from the maximum wave heights of the 2004 Indian Ocean (Lavigne et al., 2009) and 2011 Tohoku-oki tsunamis (Mori et al., 2012). Volumes of the 1958 Lituya Bay and 2018 Anak Krakatau landslides are at least one order of magnitude lower than the largest historical volcano flank failures that generated tsunamis, i.e. 1888 Ritter Island (5 km^3: Cooke, 1981; Johnson, 1987), and 1741 Oshima-Oshima (2.4 km^3: Satake and Kato, 2001). Mass transport deposits on the seafloor and giant collapse scars on the flanks of ocean islands with volumes of tens to hundreds of km^3 support the existence of even larger events in the geological record (e.g. Moore et al., 1989; Carracedo et al., 1999; Oehler et al., 2004; Masson et al., 2002, 2008).

The sizes of the clasts moved upward by a tsunami can be compared between modern, historical, and geological events. Coastal boulders with a mass of ~50 to 700 tonnes have been transported by modern and historical events such as the tsunamis in the Indian Ocean in 2004 (85 tonne, Sumatra: Paris et al., 2009), Tohoku-oki in 2011 (690 tonne, Tanohata: Iwai et al., 2019), Krakatau in 1883 (200 tonne, Java: Verbeek, 1886), and Meiwa in 1771 (216 tonne, Ishigaki Island: Goto et al., 2010), but all were deposited on the coastal lowland. Tsunami waves caused by ocean island flank collapses have the potential to carry clasts that are considerably heavier and higher above sea level. In the Cape Verde Islands, Ramalho et al.

(2015) reported boulders up to 700 tonnes, which were quarried from the edge of a palaeocliff (presently at 160-190 m above present sea level (a.p.s.l.)) and transported upwards to 220 m a.p.s.l. The likely cause was a mega-tsunami generated by a massive flank collapse of Fogo volcano at ca. 70 ka (Day et al., 1999; Masson et al., 2008; Paris et al., 2011; Ramalho et al., 2015). However, the largest known tsunami boulders have been found on Tongatapu Island, Tonga (1600 tonnes: Frohlich et al., 2009) and Shimoji Island, Japan (2500 tonnes: Goto et al., 2010).

In this paper, we briefly provide some background on pioneering studies of the sedimentary signatures of mega-tsunamis generated by ocean island flank collapse and asteroid impact, and we discuss the main conclusions and perspectives that must be drawn from studies of the last decade. For a detailed review of the characteristics of mega-tsunami conglomerates on ocean islands, we refer to Paris et al. (2018).

Marine conglomerates at high elevation on the flanks of ocean islands

Debated evidence of mega-tsunamis in Hawaii…

The origin of elevated marine conglomerates on the flanks of the Hawaiian Islands has long been debated since Moore and Moore (1984) revisited the Hulope Gravel (southern LānaʻI, up to 326 m a.p.s.l.), previously presented as an ancient littoral deposit (Stearns, 1938), and concluded that it was actually laid down by a tsunami. Similar fossiliferous conglomerates in MolokaʻI (Moore et al., 1994) and Big Island (McMurtry et al., 2004) later contributed to the controversy. The different arguments in favour or against the tsunami hypothesis have been widely discussed (e.g. Grigg and Jones, 1997; Felton et al., 2006; Crook and Felton, 2008) and we refer to Paris et al. (2018) for a comprehensive review. The interpretation of the conglomerates also needs to account for the history of vertical motion of the Hawaiian Islands, and the dating of coral clasts in their deposits. In short, voluminous landslide and slump deposits on the seafloor around Hawaii (e.g. Moore et al., 1989; Normark et al., 1993), reefs drowned by long-term subsidence (e.g. Moore and Fornari, 1984; Webster et al., 2007), and coeval ages of coral clasts from different islands (Rubin et al., 2000; McMurtry et al., 2004) strongly support the hypothesis of mega-tsunamis related to flank failures.

... later supported by unequivocal evidence in the Canary and Cape Verde Islands

In parallel to studies in Hawaii, another “unusual” marine deposit was interpreted as being caused by a mega-tsunami in the Canary Islands. In the Agaete Valley (western Gran Canaria), Perez-Torrado et al. (2006) described a fossiliferous conglomerate attached to the slopes at elevations ranging between 41 and 188 m a.p.s.l., a stratigraphical position that does not fit into the framework of relative sea-level changes and uplift of Gran Canaria Island (Meco et al., 2007), i.e., it cannot easily be interpreted as a paleo-beach deposit. Perez-Torrado et al. (2006) thus concluded that it was most likely created by a tsunami caused by a massive collapse, with the Güímar event on the eastern flank of Tenerife Island being the best candidate.

During the last decade, mega-tsunami deposits were also found in the Cape Verde Islands (Paris et al., 2011; Ramalho et al., 2015; Madeira et al., 2020), which is not surprising considering the number of massive flank collapses that have affected these islands (Masson et al., 2008), including the Late Pleistocene Fogo collapse (Day et al., 1999). On northern Santiago Island, mega-tsunami evidence is provided by fossiliferous conglomerates and boulders at elevations up to 100 m and 220 m a.s.l. respectively (Paris et al., 2011; Ramalho et al., 2015). The Santiago conglomerates share many sedimentological characteristics with their Hawaiian and Canarian counterparts: complex but diffuse internal organisation with a poor lateral continuity of the subunits, poor sorting, landward and seaward imbrication of the clasts, heterogeneous composition of locally derived volcanic rocks and mixed taxa of shallow and deep-water fossils (never in life position, often fragmented) (Fig. 2), an erosive base with rip-up clasts of the underlying substratum, and downward-injected veins of conglomerates (clastic dykes) inside the palaeosol (Paris et al., 2011). The megaclasts reported by Ramalho et al. (2015) were transported upwards from a cliff edge presently at 160-190 m a.p.s.l. (Fig. 2) to elevations up to 220 m a.p.s.l. (equivalent to a runup of 270 m above coeval seal-level) and 650 m from their source. The largest megaclast measured 9.4×6.8×3.8 m and had an estimated mass of 700 tonnes. ^{3}He exposure ages of the megaclasts range between 65 and 84 ka, with an arithmetic mean age of 73 ka (Ramalho et al., 2015), which is concordant with the age of the last massive flank collapse of Fogo Island volcano ca.

70 ka (Foeken et al., 2009; Cornu et al., 2017), and with the age of another tsunami conglomerate recently identified on Maio Island (Madeira et al., 2020).

Quaternary deposits are particularly well preserved in the Cape Verde Islands, making them useful for identifying tsunami deposits within a complex framework of elevated marine terraces, littoral deposits, and alluvial fans (e.g. Madeira et al., 2020). For a detailed review of the sedimentological criteria used for distinguishing mega-tsunami conglomerates from other coastal deposits, we refer to Perez-Torrado et al. (2006) and Paris et al. (2011, 2018), but many of the criteria listed by Paris et al. (2018) in their Table 1 are not specific to tsunamis. Paris et al. (2018) identified three specific criteria: (1) the succession of landward and seaward clast imbrication; (2) the increasing abundance of terrestrial material upward and landward; (3) and the mixed and unusually rich fauna, ranging from terrestrial to circa-littoral species (Fig. 2). Following these criteria, a number of mega-tsunami conglomerates have been identified, not only in the Canary Islands (Meco, 2008; Paris et al., 2017) or the Cape Verde Islands (Madeira et al., 2020), but also on Mauritius(Paris et al., 2013). In Maio, Madeira et al. (2020) reported four distinct tsunamis occurring over the last 500 kyrs, including the Fogo tsunami previously identified on Santiago by Paris et al. (2011) and Ramalho et al. (2015). The runup on Maio was in excess of 60 m above coeval sea level at 120 km from Fogo volcano, compared to a runup of 270 m on Santiago at 70 km from Fogo.

Other candidate islands?

With more than 40 flank failures identified over the last 2 Ma (Labazuy, 1996; Oehler et al., 2004), Réunion Island represent a significant source of mega-tsunamis in the Indian Ocean. However, there is so far only one published study on mega-tsunami deposits related to the impact of a Réunion Island flank collapse on the southern coast of Mauritius Island, where Paris et al. (2013) reported reef megaclasts and a tsunami conglomerate at elevations up to 40 m. The maximum age of the tsunami is given by a ^{14}C age of 4425 ± 35 BP on a coral branch, which is concordant with that of the last flank collapse on the eastern flank of Piton de la Fournaise volcano on Réunion Island (Labazuy, 1996; Oehler et al., 2004). The humid climate of Mauritius and Réunion Islands does not allow tsunami deposits to be as well preserved as in the Canary and Cape Verde Islands, but other mega-tsunami evidence might yet be discovered in Rodrigues Island or Madagascar.

In the Atlantic Ocean, studies in the Cape Verde and Canary Islands should be extended to the Azores (Andrade et al., 2006), where large-scale mass wasting has been documented, especially on the southern flank of Pico Island (e.g. Mitchell et al., 2011; Costa et al., 2015). However, there is so far no report of mega-tsunami deposits that could be related to flank collapses in the Azores. The same is true for the southern Pacific Islands. Quaternary flank collapses in the Society and Marquesas Islands (e.g. Clouard et al., 2001; Clément et al., 2002; Hildenbrand et al., 2006) might have generated mega-tsunamis whose traces are yet to be identified. Blahüt et al. (2019) recently created a worldwide database of "giant landslides on volcanic islands" (https://www.irsm.cas.cz/ext/giantlandslides/index.php) which can provide a general framework for completing the catalogue of mega-tsunamis.

Multistage flank collapses

Following the seminal work of Perez-Torrado et al. (2006), Madeira et al. (2011) described new sections in the Agaete Valley (Gran Canaria) and they found two other tsunami conglomerates below the one described by Perez-Torrado et al. (2006). This succession of three tsunami deposits in the same valley not only illustrates the recurrence of massive flank collapses in the Canary Islands, but it also raises the following question: do ocean island mega-failures collapse in one-go or retrogressively as multistage events separated by short periods of time? Answering this question is of fundamental importance for evaluating the mega-tsunami threat.

Giachetti et al. (2011) demonstrated that a multistage scenario of collapse (rather than in one go) generates a tsunami large enough to explain the maximum inundation distance inferred from the spatial distribution of tsunami deposits in the Agaete valley. Hunt et al. (2010, 2013) used the sequences of distal turbidites to illustrate the multistage nature of the majority of the Canary Islands flank collapses, including the Güímar collapse that produced the Agaete mega-tsunami. On the northern flank of Tenerife, the Icod collapse is recorded offshore by three debris lobes that were successively emplaced (Watts and Masson, 2001) and a stacked sequence of seven turbidites (Hunt et al., 2011). The compositions of the successive turbidites and their subunits vary from basaltic lavas of the submarine flank to phonolitic-trachytic lavas of the subaerial edifice, recording how successive failures removed different parts of the edifice (Hunt et al., 2011).

Based on the structure of the tsunami deposits in Santiago (Cape Verde) and available geophysical data offshore, whether the Fogo collapse was multistage or not is far from evident (Masson et al., 2008; Paris et al., 2011). However, as for the Agaete Valley in Gran Canaria (Perez-Torrado et al., 2006; Madeira et al., 2011), numerical simulations show that tsunami runup resulting from a multistage failure can reproduce the spatial distribution of mega-tsunami deposits reported by Paris et al. (2011) and Ramalho et al. (2015), whereas massive collapses (in one-go) may over-estimate the runup (Paris et al., 2018).

Links between volcanic activity, flank instability, and mega-tsunami

Causal links between some ocean island flank collapses and major explosive eruptions was unclear until new evidence of a mega-tsunami combined with explosive activity was demonstrated by Paris et al. (2017) in Tenerife. Indeed, the Icod collapse on the northern flank of Tenerife was highly debated because its genesis was coeval with a major caldera-forming volcanic eruption (El Abrigo eruption and the Las Cañadas caldera: Marti et al., 1994; Ancochea et al., 1999; Edgar et al., 2007). The Icod collapse was a multistage retrogressive event that mobilised a volume of ~200 km^3 from both the submarine and subaerial flanks of the island (Watts and Masson, 1995, 2001; Hunt et al., 2011). Paris et al. (2017) recently proposed a scenario that links the successive flank collapses with the Abrigo eruption and two major tsunamis at ca. 170 ka. Paris et al. (2017) used the composition of tsunami deposits on the northwestern coast of Tenerife (at altitudes up to 132 m a.p.s.l.) to propose the following scenario: an initial tsunami was generated during the submarine stage of the retrogressive failure and before the onset of the Abrigo eruption, whereas a second and larger tsunami immediately followed the debris avalanche of the subaerial edifice and formation of the caldera. This original scenario of coupled flank collapse and explosive eruption seems to be recurrent for the central volcanic edifice of Tenerife (Hunt et al., 2018), and it represents a new type of volcano-tectonic event on ocean islands.

Numerical modelling of ocean island mega-tsunamis: learning from historical examples of landslide tsunamis

Landslides and their resultant tsunamis could be an extreme hazard with potentially several tens to hundreds of meters of local tsunami run-up height. Recent developments in numerical simulation can help us to estimate the impact and affected areas of such events, although it is a challenging exercise (e.g. Løvholt et al., 2015; Yavari-Ramshe & Ataie-Ashtiani, 2016). The choice of parameters for numerical simulations of mega-tsunamis generated by large-scale flank collapses of ocean islands is difficult because there is no instrumental or observational data available. This is particularly well illustrated by the debate on the potential impact of a tsunami generated by a large-scale collapse of the western flank of La Palma, Canary Islands (e.g. Ward and Day, 2001; Løvholt et al., 2008; Abadie et al., 2012; Tehranirad et al., 2015).

The main factors used to determine the initial size of a landslide-induced tsunami are the volume of landslide mass, water depth, velocity of movement, landslide scenario (in one-go or multistage) and the types of landslide that are classified by movements such as rotational landslide, debris flow or avalanche (USGS, 2006), and conditions (submarine or subaerial). Compared to earthquake-induced tsunamis, landslide tsunamis can cause locally extreme run-ups with a high wave energy caused by the relatively short wave periods that are generated (Muhari et al., 2018). However, short period waves are likely to be significantly attenuated over a short distance (Friz et al., 2004; Heidarzadeh & Satake, 2015; Heidarzadeh & Satake, 2017). To simulate landslide-induced tsunamis, it is necessary to develop models of both landslide movement and the short-period tsunami waves. To explain the physics of landslide-induced tsunamis, three types of models have been proposed.

The first type of model generates the tsunami waves by inputting an initial waveform estimated by analytical, empirical or observational landform changes (e.g. Tappin et al., 2014; Grilli and Watts 2005; Satake and Kato, 2001). This method is commonly used for preliminary assessments because the model is easy and simple to use (e.g. Okamura et al., 2018). The model can also be used for the calculation of tsunamis caused by landform deformation such as caldera collapse (e.g. Ulvrova et al., 2016). However, it is difficult to estimate the interactive process between landslide movement and the resulting tsunami wave.

The second type is a two-layer model of depth-averaged equations representing the tsunami (water mass) and the landslide (soil mass) in upper and lower layers, respectively (e.g. Imamura et al., 2001; Kawamata et al., 2005). This approach was applied to simulating massive flank collapses and their resulting mega-tsunamis in Reunion Island (Kelfoun et al., 2010), Tenerife (Giachetti et al., 2012; Paris et al., 2017), and Fogo (Paris et al., 2011). Since this type of model considers the landslide as a fluid, it is adequate for simulating the tsunami caused by a debris flow or debris avalanche. As examples, Ioki et al. (2019) simulated the

1741 tsunami caused by the sector collapse of the Oshima-oshima volcano in Japan using the two-layer model with a Coulomb viscosity model to reproduce both the distribution of landslide deposits and historical tsunami wave heights. Yanagisawa et al. (2018) simulated the 1792 tsunami caused by sector collapse of Unzen Mayuyama volcano in Japan using a two-layer model. Their model predicted that a wave amplitude greater than 50 m would occur soon after tsunami generation. These modelling results were well validated by historical information of tsunami sediments (Imamura & Matsumoto, 1998; Tsuji et al., 2002; 2017). We suggest that the two-layer approach should accurately model extremely large landslide tsunamis.

The third type is a 3-dimentional (3D) model used to simulate landslide-generated impulse waves. Mader (2002) simulated the 1958 Lituya Bay tsunami using the Navier-Stokes equations for compressible fluid flow. The calculated maximum wave height in the bay was about 250 m above sea level, which ran up to a height of 580 m, agreeing well with the observed runup of 524 m (Miller, 1960). Franco et al. (2020) simulated this tsunami using the Computational Fluid Dynamics (CFD) software Flow-3D, which computes the movement of two fluids having a different density. Recently, methods that do not use gridding, such as Smoothed Particle Hydrodynamics (SPH), perform well in simulating the complex multi-phase flow of a landslide-generated tsunami (Xenakis et al., 2017). There is also a hybrid using 2D and 3D models for landslide and water movement, respectively, which can accurately simulate waves with short periods with a reducing computational load for the landslide movement calculation (Ma et al., 2015; Grilli et al., 2019).

Although modelling is indeed useful, accuracy of the initial parameters of the landslide remains controversial because these are usually difficult to observe directly or to infer from geological data (e.g. geometry of the landslide scar, characteristics of the landslide deposits). For the 1741, 1792 and 1958 events, observations and inundation data are used to validate the model including, for example, the topography before and after sector collapses, the extent of the landslide deposit and erosional area, historical tsunami heights, and tsunami deposits; and it was therefore possible to infer the landslide parameters using these data. Since mega-tsunamis are a low frequency hazard we only have rare opportunities to collect sufficient evidence to determine most of the necessary parameters. With this in mind, Sassa et al. (2016) enhanced the landslide parameters for the 1792 sector collapse of Unzen Mayuyama volcano by conducting ring shear stress tests on soil from the landslide material. Although these results are important as a fundamental dataset, the scaling of experimental results to in situ prototype remains an issue. Therefore, it is important to collect as much accurate information as possible, not only from experimental data but also from studies of recent events, such as the 2018 Anak Krakatau tsunami (Grilli et al., 2019; Muhari et al., 2019; Paris et al., 2019). Although this recent landslide tsunami was not mega, the simulation of such events is useful for developing reliable models that can be later applied to the study of potential megatsunamis.

Asteroid impacts and mega-tsunamis

Asteroid impacts are extreme phenomena that infrequently punctuate Earth's history. They can drastically change Earth's environment and climate and can lead to mass extinctions (Alvarez et al., 1980; Schulte et al., 2010). Since major parts of the Earth's surface are covered by oceans (~70%), many past (and future) impact events will have occurred in the oceans and potentially generated mega-tsunamis. However, oceanic impact craters are difficult to identify, so there are few examples recorded (they represent only ~20% of all known impact craters, e.g., Jansa, 1993; Ormö and Lindström, 2000; Dypvik and Jansa, 2003). Many of them are undoubtedly waiting to be discovered (e.g., Nozaki et al., 2019), although some oceanic impact craters may well have been eroded away or subducted into the mantle over time. When seeking evidence for oceanic events, tsunami deposits with associated traces of the impact are extremely useful (e.g., Gersonde et al., 1997).

Impact-induced mega-tsunamis can also occur on other planets and satellites if water or other liquids exist on their surfaces. Within our solar system, Mars is of the greatest interest since it has been suggested to have had a putative ocean in its past (Ormö et al., 2004; Iijima et al., 2014; Costard et al., 2017, 2019). While the presence of an ocean on Mars is still under debate (e.g., Parker et al., 1993; Tanaka, 1997), the identification of Martian oceanic impact craters and tsunami deposits has the potential to assist further discussion about the ocean's possible existence, its depth and lifespan. On this point, the understanding of the oceanic impact process on Earth can provide crucial information for the identification of similar features on other planets and satellites.

Among oceanic impacts on Earth, that caused by the Chicxulub asteroid, which struck the Yucatàn Peninsula, Mexico, ca. 66 Ma, is currently the largest known impact. The paleontological evidence of it defines the Cretaceous/Paleogene (K/Pg) boundary and the impact is now widely accepted as the major trigger of a mass extinction at this time (Schulte et al., 2010). The K/Pg boundary tsunami deposits have been studied for more than 30 years since Bourgeois et al. (1988). Also, the Eltanin asteroid at 2.51 Ma (Kyte et al., 1988; Goff et al., 2012) is another interesting example of an oceanic impact event that was recognized in the absence of an impact crater. The research histories of the Chicxulub and Eltanin events and the resultant tsunami deposits are interesting examples that may serve to guide future work in identifying undiscovered oceanic impacts and resultant generation of mega-tsunamis.

The K/Pg boundary tsunami deposits

Since it was first proposed by Alvarez et al. (1980), there have been numerous discussions about the K/Pg impact and extinction event. The most serious weaknesses of the impact hypothesis in the 1980s was the lack of conclusive evidence of an impact crater. The K/Pg boundary deposits, which were reported during the 1980s mostly around Europe and North America, are usually a few mms to cms in thickness (e.g., Alvarez et al., 1980; Smit et al., 1980). During the late 1980s, Bourgeois et al. (1988) reported meter thick tsunami deposits on the K/Pg boundary at the Brazos River in Texas, USA. It is interesting to note that this impact tsunami work was being reported at almost exactly the same time as the first scientific papers about Holocene paleotsunami deposits were being reported in the Pacific Northwest, USA (Atwater, 1987), Japan (Minoura et al., 1987) and Europe (Dawson et al., 1988). The presence of impact-induced tsunami deposits around the Gulf of Mexico indicated that the impact must have occurred close to the Gulf coast (e.g., Hildebrand and Boynton, 1990; Maurrasse and Sen, 1991). Finally in 1991, Hildebrand et al. (1991) identified the Chicxulub crater on the northern flank of the Yucatàn Peninsula. The impact site was on the Yucatàn carbonate platform and was interpreted as having occurred in relatively shallow water (~200 m, Matsui et al., 2002).

After the discovery of the Chicxulub crater, during the 1990s and 2000s, numerous K/Pg boundary offshore deposits were reported around the Gulf of Mexico (Maurrasse and Sen, 1991; Alvarez et al., 1992; Smit et al., 1992, 1996; Smit, 1999) and the proto-Caribbean Sea (e.g., Takayama et al., 2000). These offshore deposits have similar sedimentary features that can be characterized by some of following: 1) basal erosional contact, 2) large rip-up clasts or coarse basal spherule layer, 3) multiple sets of bi-directional cross laminations that indicate repeated reversal of flow directions, 4) massive but monotonous upward fining units with slight variations in grain size and/or composition, 4) they are a meter to few hundred meters thick, and 5) there is an abundance of organic matter such as wood (e.g., Smit et al., 1992, 1996; Smit, 1999; Tada et al., 2003; Schulte et al., 2012). Based primarily on these characteristics, these offshore deposits have been interpreted as having a tsunami origin (e.g., Smit, 1999). On the other hand, other researchers have suggested that these deposits can alternatively be interpreted as impact-induced turbidites or submarine landslide deposits (Bohor et al., 1996; Bralower et al., 1998) or the combination of lower gravity flow deposit and upper thick tsunami deposit (Kiyokawa et al., 2002; Tada et al., 2003; Goto et al., 2008).

Since there are very few reports of modern tsunami deposits in the deep ocean, but they seem likely to have been emplaced, the differentiation between tsunami deposits and turbidites remains an important issue for paleotsunami researchers. Indeed, submarine tsunami deposits formed by recent events have only been reported since the 2000s (e.g., Noda et al., 2007), although some possible Holocene ones were reported in the Mediterranean Sea (Kastens and Cita, 1981; Cita et al., 1996). Note that the potential offshore K/Pg tsunami deposits were studied and interpreted without any modern analogues. Following the recent 2011 Tohoku-oki tsunami, there were some reports concerning deposits formed in 100-6000 m water depth (Ikehara et al., 2014; McHugh et al., 2016). Interestingly, some of these deposits are interpreted as being a combination of a lower turbidite triggered by the earthquake or tsunami and an upper tsunami deposit (Ikehara et al., 2014; Usami et al., 2017) with peaks of Cs concentration, like the iridium anomaly of the K/Pg boundary deposits, released from the damaged Fukushima Daiichi Nuclear Power Plant (Ikehara et al., 2014). This interpretation is similar to those of the K/Pg boundary reported in the proto-Caribbean sea (Takayama et al., 2000) although the 2011 deposits are significantly thinner.

More recently, DePalma et al. (2019) reported an onshore K/Pg surge deposit in North Dakota, USA. The site is located ~3000 km away from the impact site near the narrow seaway that connected to the Gulf of Mexico during the Cretaceous (DePalma et al., 2019). They proposed that the deposit was formed not by the tsunami generated by the impact but by an impact-induced seismic seiche similar to those observed in Norway following the 2011 Tohoku-oki event (Bondevik et al., 2013).

K/Pg tsunami generation mechanisms

Another important discussion concerns how the tsunami was generated by the Chicxulub impact. Bralower et al. (1998) suggested that the tsunami could have been generated by an impact induced landslide. Matsui et al. (2002) suggested mainly three generation mechanisms of the K/Pg impact-induced tsunami: 1) a rim wave formed from the collapse of the large splash caused by the impact, 2) impact-induced landslide, and 3) ocean water flowing into (resurge) and flowing out from the crater. Tsunamis could have been generated by all of these processes simultaneously with differing intensities and waveforms. For instance, Matsui et al. (2002) suggested that the rim wave might have had only a small impact along the Gulf coast. This is because a rim wave is characterized by a high wave amplitude with a short wave period at the impact site. The tsunami may be very large around the proximal impact site but it is unstable and dissipates quickly. An impact-induced landslide also has the potential to generate a large tsunami that is unidirectional. Namely, if the submarine landslide were generated off the northern flank of the impact crater (Bralower et al., 1998), a large tsunami would have been preferentially propagated northwards.

The resurge process may induce the movement of a significant volume of ocean water (Matsui et al., 2002). If this was indeed generated during the Chicxulub impact, wave periods tend to be long (10 h according to Matsui et al., 2002) and stable, propagating through the ocean and becoming very large along the coast. Matsui et al. (2002) estimated that the maximum run-up height around the Gulf of Mexico could have reached as high as 300 m and this could explain the ocean-wide distribution of tsunami deposits in the Gulf of Mexico and proto-Caribbean Sea.

The resurge should rework fallback ejecta inside the crater and so the process is testable using core samples from the site. Goto et al. (2004) and Smit et al. (2004) studied the ICDP YAX-1 cores recovered 65 km from the crater centre (near the crater rim) and found sedimentary features with influence of flow such as climbing ripples and repeated upward fining and coarsening units; they suggested that resurge did indeed occur following the Chicxulub impact. However, others have suggested that a large portion of the inferred resurge deposit can be interpreted as fallback ejecta (e.g., Wittmann et al., 2007). Also, if the crater rim rose high above sea level then it may have prevented ocean water flowing into the crater (Bahlburg et al., 2010). Since the water depth of the impact site was considered to be shallow, numerical modeling results indicate that only a low energy resurge might have occurred locally (Bahlburg et al., 2010). On the other hand, the resurge process might have been stronger than previously thought according to the recent studies. Gulick et al. (2008, 2019) suggested that water depths around the impact site would have been much deeper than previously thought. In 2016, IODP Expedition 364 recovered continuous cores at the peak ring inside the crater (45.6 km from the crater centre). Gulick et al. (2019) studied the sedimentology of these cores and based on the presence of laminations and variations in grain size, suggested that resurge deposits were also present. The presence of inferred resurge deposits at the two separate sites near the crater centre and rim suggests that this process was large and occurred at a crater-wide scale.

The tsunami generation process of the Chicxulub impact is still under discussion and more research including numerical modeling for sediment transport should be carried out in the future.

The Eltanin impact event

While it was originally thought that the Eltanin asteroid impact occurred around 2.15 Ma, its date has subsequently moved back to 2.51+0.07 Ma, contemporaneous with the Pliocene–Pleistocene boundary at 2.58 Ma (Goff et al., 2012). Unlike Chicxulub, this was a deep ocean (4–5 km) impact that struck in the Southern Ocean some 1500 km SSW of Chile. Furthermore, unlike Chicxulub there is no seafloor crater with the impact being identified through traces of intense erosion and the presence of meteoritic material in sedimentary rocks collected 500 km apart (Gersonde et al., 1997). The absence of a physical crater and the distribution of meteoric material have allowed researchers to estimate the asteroid diameter at between 1 and 4 km. However, there is considerable debate concerning this diameter, which has significant implications for numerical modelling of any resultant tsunami (e.g. Korycansky & Lynett, 2005; Ward & Asphaug, 2002; Weiss et al., 2006; 2015). There are significant disparities between most of the model outputs, but recently Weiss et al. (2015) have produced the most comprehensive study using an assumed diameter of a mere 750 m. This resulted in wave amplitudes between 8 and 10 m in southern Chile to less than a meter in northern Chile. Needless to say, if a larger diameter is used, amplitudes are larger. These results have been used to suggest that much of the proposed physical evidence for a circum-South Pacific tsunami generated by the impact is incorrect. The size of the modelled wave means that it could not transport much of the material found in the proposed coarse-grained tsunami deposits.

The geological evidence is compelling, however, so the problem lies mainly with the modelling of asteroid impact tsunamis. Modelling waves produced by large sized impactors becomes increasingly complex and as such it is simpler to work with a smaller diameter (Goff et al., 2012). Numerous arguments have been made for the inferred size of the Eltanin asteroid but ultimately it seems most reasonable to place it somewhere between 1 and 4 km and as such we are still unclear about the possible maximum size of the tsunami wave amplitude along the Chilean and other South Pacific coastlines.

Possible Eltanin impact related deposits have been reported around the Pacific Ocean from as far north as Japan and as far south as Antarctica, with the densest concentration being along the Chilean coast, largely associated with either the Ranquil or Pisco Formations (Goff et al., 2012). Some of these deposits have been dismissed as tsunamites through both numerical modelling and geological reassessment, the most notable being those at Hornitos where the tsunamite was reinterpreted as a debrite (Spiske et al., 2014). Most recently though, Le Roux (2015) has questioned this reinterpretation stating that it may well still be a tsunami deposit but that it could be 5.3-7.2 Ma old and therefore not related to the Eltanin asteroid impact.

Geological evidence for the Eltanin tsunami from other sites range from boulder deposits and associated bonebeds of marine fauna, to coarse bioclastic sands, soft sediment deformation features, rip-up clasts, unconformable contacts and deeply channelled erosional features (Goff et al., 2012). This evidence generally mirrors that used to positively identify modern tsunami deposits, but of particular note are the unusual bonebed deposits noted by Gersonde et al. (1997) from Peru and Chile. These bonebeds contain the skeletons of rorqual whales, sperm whales, seals, aquatic sloths, walrus-whales, predatory bony fish and many other species (Pyenson et al., 2014). The end of the Pliocene was marked by an extinction event among marine megafauna (mammals, seabirds, turtles and sharks) with 36% of Pliocene genera disappearing including apex predators such as *Carcharocles megalodon* (the megashark) the largest shark that ever lived (Pimiento and Clements, 2014; Pimiento et al., 2017). It also marks the last appearance date of numerous marine microfossils (Berger, 2011). This prominent die-off of marine species may well be linked to severe acoustic trauma or shock waves associated with a deep ocean asteroid impact (e.g. Ketten, 1995). The contemporaneous combination of bonebeds and sedimentary evidence make a compelling case for an Eltanin tsunami that was larger than current modelling scenarios suggest.

Like Chicxulub, the tsunami generation process of the Eltanin impact is still under discussion and more research, particularly with respect to combined bonebed-possible tsunami deposit sequences, should be carried out in the future.

Hazard assessment

Assessing hazards related to mega-tsunamis generated by volcano flank collapse or asteroid impact amounts to a reconciliation between the human and geological perspectives. Considering the low frequency of such events and the high cost of monitoring, one could conclude that the implementation of any form of prevention strategy is not cost-effective. However, whether or not this is the case, it is the role of geologists to improve society's awareness of such extreme hazards.

Addressing mega-tsunami hazards related to volcano flank instability could start with an adequate monitoring strategy and a regional collaboration between both the volcano observatories and the tsunami warning systems. The monitoring of active volcanoes such as Kilauea in Hawaii and the Piton de la Fournaise in Reunion Island now offers the possibility to detect small flank displacements (e.g. using GNSS and InSAR), but the scientific community lacks milestones to anticipate large-scale flank collapses of ocean islands. The major eruption of Piton de la Fournaise volcano in April 2007 was associated with a large (up to 1.4 m horizontally) seaward motion of its eastern flank along a detachment fault (Froger et al., 2015). Although no collapse occurred, it illustrates the relevancy of InSAR for an early detection of ground motion on volcanoes. Earth observation programs such as Copernicus now give access to worldwide data from satellites, including radar imaging that can be rapidly post-processed to produce interferograms. The second step is the definition of scenarios to be used in probabilistic tsunami hazard assessment (PTHA) and Tsunami Early Warning Systems (TEWS). Given the uncertainty of the collapse mechanisms, numerical models could yield unrealistic results and any conclusions concerning hazard assessment should be viewed with caution.

Similar uncertainties weigh on the assessment of tsunamis generated by asteroid impacts. For instance, Ward and Asphaug (2003) assumed an oceanic impact of a 1950DA asteroid with 1.1 km diameter and found that the east coast of the United States would be inundated by a tsunami over 100 m high if it struck the Atlantic Ocean. Wünnemann et al. (2007) performed numerical modelling of the tsunami generation process from an small asteroid impact, which predicted that the rim wave decays quickly so that it can't be treated as a long wave. Gisler et al. (2011) suggested that even a relatively large asteroid with <500 m diameter hit the ocean at a depth of <5 km depth, tsunamis would quickly dissipate and around adjacent shorelines the wave height would be smaller than the 2004 Indian Ocean tsunami. These results suggest that large tsunamis with long wavelengths may not be generated when the impact site is deep and/or the impactor is small. Also, if the impact site is shallow and a high crater rim is formed, then large tsunamis may not be generated as well. Future investigations of the most effective conditions for maximizing the size of impact tsunamis need to be carried out (Goto et al., 2013).

For hazard assessment, probabilistic analysis with information on potential impact size and frequency is important (Ward and Asphaug, 2000). According to Chapman and Morrison (1994), the recurrence interval over which an asteroid with a 100 m diameter hits the Earth is about 10^3-10^4 years and with a 1000 m diameter it is about 10^5-10^6 years. While an asteroid with a diameter of a few hundred meters may break up in the atmosphere so that the impact frequency of small asteroids may well be lower, this effect is less likely for large asteroids (Bland and Artemieva, 2003, 2006). Bland and Artemieva (2006) estimated that an asteroid with a 200 m diameter, which may generate a hazardous tsunami, will hit the Earth's surface every ~10^5 years, which is a far lower frequency than Ward and Asphaug (2000)'s estimated (3000-4000 year interval for a 220 m diameter impactor).

Goto et al. (2013) carried out a preliminary evaluation of the tsunami hazard for the Japanese coast from the impact of a 500 m diameter asteroid hitting 5000-m-deep ocean. In this case, the impact tsunami was characterized by short wavelengths with high amplitudes. The amplitude reached nearly 80 m in the deep ocean, decaying quickly to only a few meters when it reached 50 m water depth. They proposed that the tsunami broke on the continental shelf far away from the shoreline so that it was considerably attenuated prior to striking the coast. Importance of wave breaking is known as the "Van Dorn effect" (Melosh, 2003) and is important for tsunami hazard assessment of coastal communities.

Conclusions: the future hazard of mega-tsunamis

There is a risk of mega-tsunamis generated by ocean island flank collapses or asteroid impacts in the future. Although they occur with a very low frequency compared to earthquake-induced tsunamis, they can potentially be a significantly large hazard. It is extremely difficult to assess and mitigate the risks associated with such high-magnitude but low-frequency hazards. Mega-tsunamis are treated as geophysical curiosities rather than true threats, probably because their recurrence interval far surpasses that of political and economic development strategies. However, both the 2004 Indian Ocean and 2011 Tohoku-oki earthquakes raised awareness of global disasters and their associated cascading risks. In this context, addressing future mega-tsunami hazards requires international collaboration.

To end on a positive note, García-Olivares et al. (2017) used a combination of geological and mtDNA data to demonstrate that ocean island flank collapses may be drivers of island colonization, and subsequent lineages of diversification. Extreme geophysical events can thus have positive biotic consequences that balance out their catastrophic repercussions.

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Figure captions

Fig. 1 – Tsunami size versus event probability (modified after Kawata, 2003), as seen from two different perspectives: disaster management, and geology.

Fig. 2 – Offshore to inland sediment transport during a mega-tsunami (here the source of the tsunami is a massive flank collapse from an oceanic island). A: the flank collapse from the source island produces a submarine debris avalanche with a volume of tens to hundreds of km^3, and the mega-tsunami starts propagating in the ocean until it strikes another island (runup island); B: tsunami starts mobilising sediment on the shelf, including boulders; C: as the inundation progresses, sediment from different sources are mixed until a maximum altitude is reached (runup); D: tsunami backwash implies a re-mixing of the sediments deposited during the uprush inundation; E: idealized cross-sections of sedimentary deposits resulting from a mega-tsunami generated by an ocean island flank collapse. Colours correspond to successive sediment sources from left (offshore) to right (inland).

Fig. 3 – Sediment transport processes acting during an impact tsunami. A: The impact of the asteroid with the water body (ocean, lake, etc.) normally generates a crater that corresponds to the initial stage of the tsunami, as noted for explosion-generated tsunamis. B: The water crater then collapses and waves start propagating radially around the impact, while a large plume of ejecta is formed. C: While tsunami is propagating, seismic wave associated with the impact may trigger debris flows on submarine slopes. Ejecta are transported by density currents (collapsing plume) over the surface of the ocean, and then reworked as submarine suspension clouds. Wave ripples are formed in deep-water by the passage of the tsunami (e.g. Hassler and Simonson, 2001). D: Tsunami breaks on the shelf and erodes the substrate. Sediments deposited during inundation have a mixed marine – continental composition, including ejecta from the impact. E: A second generation of submarine debris flows is generated during the backwash of the tsunami, and oscillations produces compositional variations of the

deep-sea sedimentary sequences (e.g. Goto et al., 2008). For more details on stages D and E we refer to figure 1.