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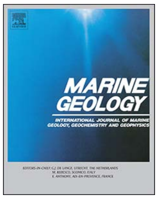

Invited review article

Mega-tsunami conglomerates and flank collapses of ocean island volcanoes

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ABSTRACT

Marine conglomerates at high elevation on the flanks of ocean islands are usually interpreted as evidence of mega-tsunamis generated by volcano flank collapses, although their origin is sometimes debated (elevated littorals vs. tsunami). In this review, we introduce case studies of well-documented examples of tsunami conglomerates in Hawaii (Pacific Ocean), the Canary and Cape Verde Islands (Atlantic Ocean), and Mauritius Island (Indian Ocean). Other less-documented marine conglomerates are also presented as tsunami candidates. Then, we build a comprehensive picture of the general characteristics of these conglomerates and the different methods that can be applied to date them. Different perspectives of research are proposed, especially on the use of tsunami conglomerates as proxies for better constraining numerical models of ocean island flank collapses and associated tsunamis. We also discuss the possible links between volcano growth, flank instability, and climate.

1. Introduction

Ocean islands experience rapid changes in morphology due to volcanism, subsidence or uplift, flank instability, and erosion (e.g. Menard, 1983, 1986; Mitchell, 1998, 2003; Keating and McGuire, 2000; Paris, 2002; Ramalho et al., 2013). Extreme-wave events such as storms and tsunamis are important agents of onshore-offshore sediment transport and play a key role in the evolution of volcanic islands (e.g. Johnson et al., 2017). Source mechanisms of tsunamis impacting volcanic islands are varied: local or distant earthquakes, flank instability, eruptive processes (pyroclastic flow, underwater explosion, caldera collapse, etc.), and nuclear explosions. Among all these mechanisms, only large flank collapses have the potential to generate mega-tsunamis. The term "mega-tsunami" is commonly and often arbitrarily used in the media, but Goff et al. (2014) proposed a definition based on a wave amplitude exceeding 50 m. Mega-tsunamis thus have a magnitude exceeding all published tsunami magnitude scales (e.g. Imamura, 1942; Iida, 1963; Soloviev, 1972; Abe, 1979; Hatori, 1986). The 1958 tsunami in Lituya Bay (Miller, 1960) can be considered as the only historical example of mega-tsunami, but the maximum runup of 524 m was spatially limited to the slope opposite to the landslide (30.6×10^6 m^3) and rapidly decreased down to 10 m at 12 km from the source. Volcanic edifices are particularly prone to flank instability due to rapid growth, structural discontinuities, hydrothermal alteration, magma intrusions, and seismicity (e.g. Siebert, 1984; Carracedo, 1996; Van Wyk de Vries and Francis, 1997; Keating and McGuire, 2000; Lagmay et al., 2000; Quidelleur et al., 2008). Slope instabilities at volcanoes range from rockfalls and small landslides ($< 10^6$ m^3) to large debris avalanches (up to the order of 10^3 km^3). Successive landslides of 17×10^6 m^3 and 5×10^6 m^3 on the flanks of Stromboli Island, December 2002, generated a local tsunami with a maximum runup of 8 m on the island itself, and limited effect on the coasts at a distance of > 200 km (Maramai

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et al., 2005). The volumes involved in the 1958 Lituya Bay and 2002 Stromboli landslides are two orders of magnitude lower than the largest historical volcano flank failures, such as Mount St Helens in 1980 (2.8 km^3: Voight et al., 1981), Ritter Island in 1888 (5 km^3: Cooke, 1981; Johnson, 1987), and Oshima-Oshima in 1741 (2.4 km^3: Satake and Kato, 2001). The 5 km^3 debris avalanche of Ritter Island in 1888 produced a large tsunami in all Bismarck Sea, with runups up to 15 m on the islands nearby, and 5 m at 500 km from the volcano (Cooke, 1981; Ward and Day, 2003). Mass wasting of ocean island volcanoes implies volumes of tens to hundreds of km^3, as evidenced by mass transport deposits offshore and collapse scars onshore (e.g. Moore et al., 1989; Holcomb and Searle, 1991; Normark et al., 1993; Carracedo et al., 1999; Day et al., 1999; Masson et al., 2002, 2008; Mitchell, 2003; Oehler et al., 2004; Paris et al., 2005). However, it is difficult to infer the mechanisms controlling these giant flank collapses and to evaluate tsunami hazards, because: (1) we lack observational or instrumental data on such low-frequency, high magnitude events, and (2) the geological record of such events is often incomplete and difficult to interpret.

Here we present a review on the present-day knowledge of high-elevation marine conglomerates on ocean island volcanoes, which are attributed to the impact of mega-tsunamis triggered by volcano flank collapses. The paper is organised as follows. We present a brief review on elevated marine deposits that were widely debated in the literature (tsunami deposits or uplifted littorals?). Pioneering works in Hawaii (Pacific Ocean) inspired later studies in the Canary and Cape Verde Islands (Atlantic Ocean), as well as in the Indian Ocean (Reunion Island and Mauritius). In the discussion, we address the main problems affecting the identification, interpretation, and dating of mega-tsunami conglomerates.

2. The Hawaiian debate: elevated marine deposits as evidence of tsunami or uplifted littorals?

The interpretation of elevated marine deposits on the southern flanks of Lāna'i and Moloka'i (Fig. 1) is a long debate in Hawaii's history of geology. The controversy started when Moore and Moore (1984) proposed that the so-called Hulopoe Gravel (Lāna'i), described by Stearns (1938, 1978) as an ancient littoral formation, was in fact deposited by a “giant wave”, i.e. a tsunami wave. The tsunami hypothesis relies both on geophysical and sedimentological data. Moore and Moore (1984) presented the Hulopoe Gravel as a single landward fining and thinning formation that originally blanketed the southern flanks of Lāna'i at altitudes up to 326 m a.p.s.l. (above present sea level; altitude measured by Stearns, 1938). Note that the term “conglomerate” should be used rather than “gravel”, since the deposits are cemented by calcrete. The great majority of the clasts are local basalts, but a marine origin is inferred from the presence of corals, beach-rock, and molluscs. Skeletons of corals and other reef organisms are not in growth position. Ten years later, Moore et al. (1994) described a similar marine conglomerate on the southern flank of Moloka'i. Moore and Moore (1984) also argued that the south-eastern Hawaiian Islands subside too fast for preserving deposits of past sea-level highstands. The origin of the Hulopoe Gravel is in fact one of the key aspects in the controversy concerning the vertical motion of the south-eastern Hawaiian Islands (Webster et al., 2010). Tide gage records and drowned reefs around these islands indicate both historical and long-term subsidence (Moore, 1971, 1987; Moore and Fornari, 1984; Moore and Campbell, 1987; Ludwig et al., 1991; Wessel, 1993; Moore et al., 1996; Smith et al., 2002).

However, the tsunami hypothesis has been revisited by several authors. Increasing age of coralline beach deposits with elevation on O'ahu and Moloka'I, together with observations of wave-cut notches and terraces are in favour of ancient uplifted shorelines (Brückner and Radtke, 1989; Grigg and Jones, 1997). Uplift of oceanic islands can be produced by lithospheric flexures (e.g. Watts and ten Brink, 1989; Grigg and Jones, 1997; Huppert et al., 2015), by isostatic compensation (rebound) following large collapses (e.g. Smith and Wessel, 2000), or even by intrusive processes (e.g. Ramalho et al., 2010a, 2010b, 2015a, 2017; Klügel et al., 2015). Detailed description of the lithofacies and biofacies of the Hulopoe Gravel allowed distinguishing individual subunits and assemblages of littoral to sublittoral fauna separated by erosional discontinuities and palaeosols (Rubin et al., 2000; Felton, 2002; Felton et al., 2006; Crook and Felton, 2008). The sequence of elevated marine deposits would then represent unconformity-bounded cycles of transgressive and regressive facies superimposed on a longer-time scale flexural uplift (Felton et al., 2006), even if reworking of the deposits by tsunami or hurricane cannot entirely be ruled out (Felton et al., 2006; Crook and Felton, 2008). However, the chronology of drowned reefs offshore Lāna'i does not support the uplift hypothesis (Moore and Campbell, 1987; Webster et al., 2006, 2007, 2010). The controversy is also fuelled by coeval dating of coral clasts from the Lāna'i and Moloka'i deposits (Moore and Moore, 1988, Moore et al., 1994; Rubin et al., 2000) and the Alika 2 and South Kona landslides (Lipman et al., 1988; McMurtry et al., 1999) coincident with MIS (marine isotopic stages) 5e and 7. It is thus tempting to correlate the onset of interglacials with reinforced instability of the islands, favouring large flank collapses and tsunamis (e.g. McMurtry et al., 2004a). The debate remains open, while the key outcrop at 326 m a.p.s.l. on the southern flank of Lāna'i was destroyed during the Second World War (Crook and Felton, 2008).

The marine fossiliferous conglomerate described by Stearns and McDonald (1946) on the western flank of Kohala volcano (northwest Hawaii), and later re-examined and dated 106–102 ka by McMurtry et al. (2004b), could finally represent the most convincing evidence of a mega-tsunami in Hawaii. The Kohala peninsula has been subsiding for the last 475 ka (Campbell, 1984; Ludwig et al., 1991). Considering the present-day maximum elevation of the conglomerate (61 m a.p.s.l.) and the subsidence rate, a tsunami runup > 400 m can be inferred (McMurtry et al., 2004b).

3. Canarian clues to the Hawaii mega-tsunami hypothesis

Unlike the Hawaiian Islands, the Canary Islands are not affected by long-term subsidence because plate motion over the mantle plume is slower and oceanic crust is more rigid (e.g. Carracedo et al., 1998). However, the growth of volcanic edifices on the flanks of each other over prolonged periods of time, from the shield building stages to rejuvenated stages, results in migrating lithospheric flexures and tilting of the islands, as evidenced by erosion rates (Menendez et al., 2008) and elevated Mio-Pliocene and Quaternary littoral deposits (Zazo et al., 2002, 2003; Meco et al., 2007). Three marine conglomerates do not fit into the framework of relative sea-level changes and vertical movements in the Canary Islands, and display unusual sedimentary and palaeontological characteristics. They are described below.

3.1. The Agaete tsunami conglomerates, Gran Canaria

The first evidence of mega-tsunami in the Canary Islands was provided by Perez-Torrado et al. (2002, 2006), who interpreted a fossiliferous conglomerate on the Agaete valley, north-western coast of Gran Canaria (Fig. 2), as a tsunami deposit. The Agaete conglomerate was previously interpreted as a single palaeolittoral (e.g. Denizot, 1934; Lecointre et al., 1967; Klug, 1968; Meco, 1989), but it is in fact attached to the slopes of the valley at elevations ranging between 41 and 188 m a.s.l. (Perez-Torrado et al., 2006). The present-day outcrops of conglomerate are the remnants of a large deposit that initially fossilised the relief of the entire valley (Figs. 2 and 3). Whatever the nature of the substratum (old lavas, soil, scree deposits), the basal contact is always erosive, showing rip-up clasts of soil up to 1 m large (see Fig. 4C in Perez-Torrado et al., 2006) and downward-injected clastic dykes (Fig. 4). The lithology of the clasts and the taphonomy of the fossiliferous content (bioclasts) point to a mixing of sublittoral, littoral,