Volcanic risk to marine infrastructure and shipping

Paul Cragg[1], Pete Rowley*[2], and Samuel Mitchell[2]
[1] Unafilliated
[2] School of Earth Sciences, University of Bristol, UK
* pete.rowley@bristol.ac.uk [corresponding author]

ORCiD (SA): 0000-0002-8322-5808
ORCiD (TA): 0000-0002-3224-5833

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Abstract

Exploration of volcanic risk over recent decades has helped garner a detailed understanding of the vulnerabilities and processes at work in the terrestrial setting, but relatively little is understood about volcanic risk at sea, despite our increasing reliance on surface shipping, energy and resource infrastructure, and submarine telecoms cables. This lack of understanding is rooted in (1) a lack of understanding of the marine volcanic processes themselves, (2) a lack of knowledge regarding how these processes interact with existing use and infrastructure at sea, and (3) no effective quantification of the degree of exposure and therefore vulnerability that different elements of our trade and industry experience to these different hazard processes.

Addressing these concerns must be a priority for the volcanological and maritime communities, as well as the users and stakeholders. This work aims to shine a light on some of the processes, interactions and major vulnerabilities which we are currently exposed to as a globally connected society. Some first order constraints are explored to provide context for the scale of the issues at hand. Finally, we suggest 6 initial goals for disaster risk reduction which require a full spectrum of research, policy and behavioural developments and improvements.

Introduction

Quantification of volcanic risk in the terrestrial environment has been an area of considerable research and progress in the last 50 years (Brown et al., 2015; S. C. Loughlin et al., 2015; Marzocchi & Woo, 2009). Exposure of populations living on or near active volcanoes to tephra fall, pyroclastic density current, lahars, and lava flow activity is well recognised, and experimental and numerical modelling approaches have been used to explore the extent of this exposure to different types and scales of volcanic activity. This risk assessment, however, rarely extends offshore, despite considerable known impacts already experienced around submarine, ocean island and near-shore volcanoes, and up to 1000's km from volcanic sources. Often as a result of specific events there have often been a flurry of papers exploring specific hazard processes, for example flank collapse generated tsunami (Cas et al., 2024; le Friant et al., 2009; Legros & Druitt, 2000; Milia et al., 2003), the propagation and entry of pyroclastic density currents (Andronico et al., 2021; Di Roberto et al., 2014; G. Giordano & De Astis, 2020) and pumice raft formation (S. E. Bryan et al., 2012; Iskandar et al., 2023).

The rapid development of subsea infrastructure, and the growth in international shipping has vastly increased exposure to less well studied marine volcanic hazards. Here we take a multi-stage approach to explore the issue of offshore volcanic risk. First, we briefly explore the exposure of shipping, and the magnitude of the industry presently at risk. We then discuss the volcanic hazard processes which may pose the greatest threat to shipping and infrastructure (Figure 1) before looking at specific vulnerabilities that ships have in relation to these processes. Finally, we suggest some priority areas for the natural hazard community to focus on based on our current understanding of frequency, range, and impact of different hazards.

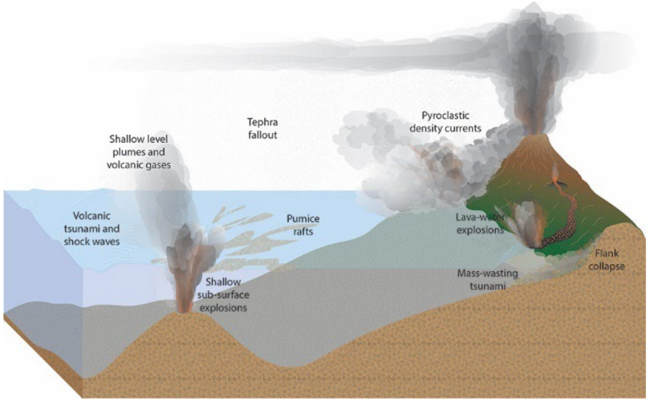

Figure 1. Schematic of the major volcanic hazards with the potential to impact the marine and submarine realm.

Exposure to risk

Approximately 90% of global trade today is reliant on marine shipping, with the volume forecast to more than double from its 2018 values by 2050 (Sardain et al., 2019). A large portion of the worlds' maritime trade passes within 100 km of active volcanic systems (Figure 2), and there is widespread documented evidence of ships being affected by eruptive phenomena throughout recent history, for example at the eruptions from Myojin-sho in 1792 (Morimoto & Ossaka, 1970), Krakatau in 1883 (Simkin & Fiske, 1983), Montagne Peleé in 1902 (Scarth, 2002; Tanguy, 1994; Zebrowski, 2002),(Johnson & Threlfall, 1985) and Rabaul Caldera in 1937 (Johnson & Threlfall, 1985). Impact to ships from marine volcanic hazards date back to at least 1650 BCE during the Late Bronze Age eruption of Santorini (Evans & McCoy, 2020; Karátson et al., 2020). In Simkin and Fiske (1983) there are nearly 100 ships mentioned regarding encounters with floating pumice and tephra fall. Shipping losses – while less common have most recently been as a result of the Hunga Tonga Hunga Ha'apai (HTHH) eruption in 2022, following which vessels were lost as far afield as Chile and Japan due to the far-reaching volcanic-induced tsunamis (McDonald, 2022; New Zealand Defense Force, 2022; Terry et al., 2022).

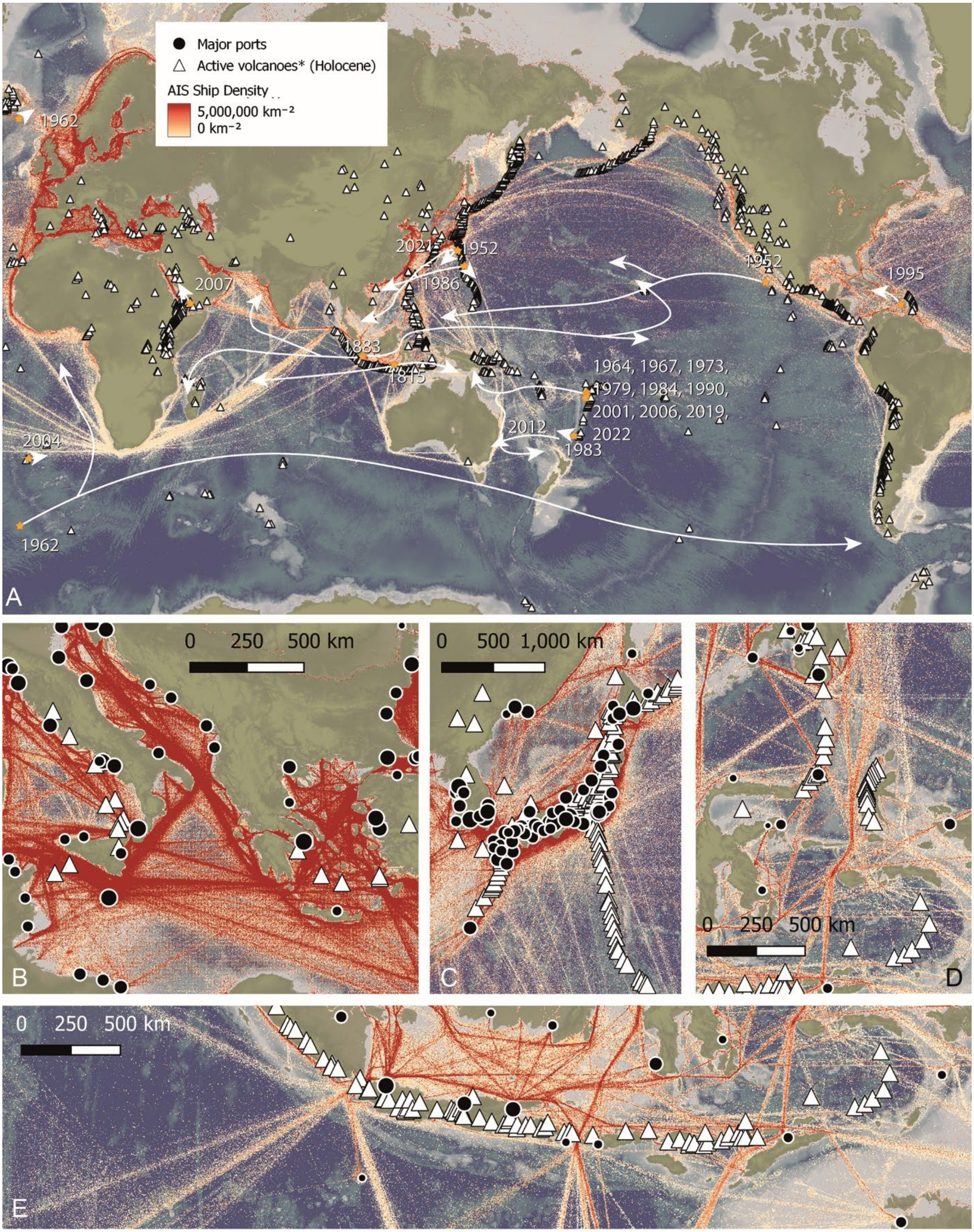
Major ports
Active volcanoes* (Holocene)
AIS Ship Density
5,000,000 km^{-2}
0 km^{-2}
1962
2021
1952
1986
2007
1952
1995
1883
1815
1964, 1967, 1973,
1979, 1984, 1990,
2001, 2006, 2019,
2022
2012
1983
2004
1962
A
0 250 500 km
B
0 500 1,000 km
C
0 250 500 km
D
0 250 500 km
E

Figure 2. (A) Global map of active volcanoes (white triangles), shipping density (orange-red), and observed pumice rafts (arrows and dates) over the last 200 years highlighting substantial overlaps in key areas including (B) the Mediterranean, (C) the Sea of Japan (D) the Molucca Sea, and E the Java, Flores and Savu Seas. The shipping density data (World Bank 2021) is derived from hourly Automatic Identification System (AIS) positions received between Jan 2015 and Feb 2021. The AIS positions may have been transmitted by both moving and stationary ships within each grid cell, therefore the density is analogous to the general intensity of shipping activity. Black circles indicate major ports (World Bank Data Catalogue, n.d.; World Port Index (WPI), n.d.), with relative scale related to volume of cargo handled.

The vulnerability of maritime trade and transport goes further than simply shipping routes, however, as a substantial number of ports also lie within range of many of the hazards identified in Table 1. Figure 2 subpanels B-E highlight the co-location of major ports in some of the worlds high traffic areas, which hints at the scale of potential vulnerability. A simple spatial analysis exploring how many Holocene volcanoes lie within 100km of each of the ports within the World Port Index database reveals that many have at least some exposure to local volcanism. Over 100 million Twenty-Foot Equivalent Units (TEU) of cargo capacity are exported annually from the ports with 3 or more volcanoes within 100 km, rising to over 300 million TEU when considering those close to a single Holocene volcano. These numbers only consider containerised transport.

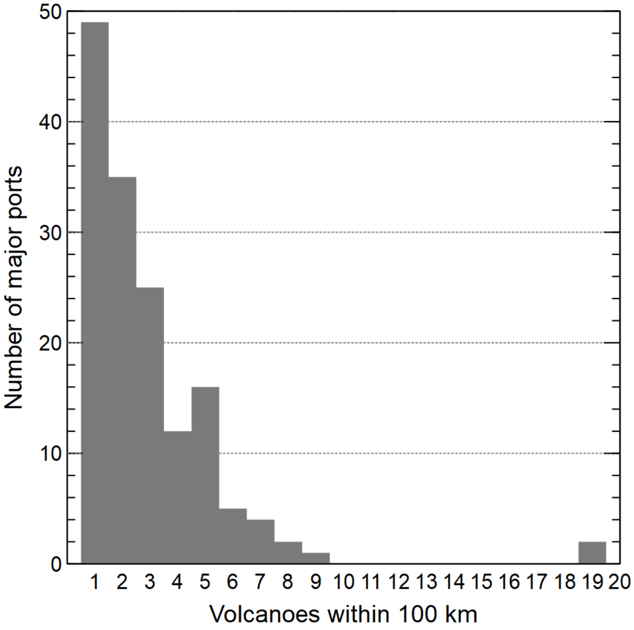

Figure 3. Evaluation of number of volcanoes within 100 km for all ports included in the World Port Index. 152 of the 856 listed ports (>15%) lie within 100 km of at least one Holocene volcano. 67 lie within 100 km of 3 or more volcanoes, while two volcanoes in El Salvadore are within 100 km of 19.

Beyond the direct threat to vessels, crews and passengers, the wider impacts of submarine or near-shore volcanic activity (Figure 1) may include navigation blockage and disruption, resulting in economic impacts at anything from local to global scales, depending on the degree and location of disruption. It is further important to note that the shipping industry is not solely comprised of commercial trade of goods, fuel etc, but also comprises tourism and leisure (cruise ships), research expeditions, private vessels, merchant and military vessels, and the global fishing/aquaculture industry. The distribution and density of these individual industries may vary due to location, distance to shore, trade routes, access to territorial waters, territorial disputes, culture, geopolitics, climate, local ecosystems, seasonal changes, or national affluence. This variety of factors make the assessment of volcanic risk to shipping a globally complex issue.

Hazard processes

Recorded losses have been attributed to a range of processes , including capsizing due to tsunami (Imamura et al., 2022), inundation by pyroclastic density currents (Guibert et al., 2018), and damage by tephra fall (Salgado et al., 2022, 2023). Submarine volcanism also frequently produces widespread and poorly monitored pumice rafts (Figure 1), which may be a hinderance to transit, or pose mechanical risks. The risks posed, and range of impact of these different hazards varies considerably (Table 1).

Table 1. A catalogue of identified volcanic hazards impacting the marine realm, summarising approximate range that the hazard may impact, and the risks to shipping thought to be associated with each. Note this does not include risks to submarine or coastally exposed vehicles, infrastructure or populations.

Type of volcanic hazard	Proximity to source	*Risks to shipping
Lava-water coastal explosions	~ 1 km	Ship destruction/severe damage; potential loss of life/critical injuries; large ballistics in hull side
Shallow sub-surface explosions	~ 1 km	Ship destruction/severe damage; potential loss of life/critical injuries; ship instability from wave action
Volcanic gases	Up to 10's km	Crew inhalation and respiration; possible metalwork corrosion from acidic vapours
Pyroclastic density currents	Up to 10's km	Ship destruction/severe damage; potential loss life/critical injuries; large ballistics in hull side
Terrestrial and submarine flank collapses	Up to 10's km	Ship destruction/severe damage; potential loss life/critical injuries; large ballistics in hull side

Tephra (ash/pumice) fallout	Up to 100’s km	Damage to electronic equipment; inhalation/respiration of fine ash; instability from wet tephra accumulation; navigation loss; radar attenuation
Volcanic plumes in atmosphere	Up to 100’s km	Disruption to navigation and position fixing; reduced visibility; radar attenuation
Oceanic pumice rafts	Up to 1000’s km	Loss of propulsion in engines; need to redirect shipping traffic; mechanical damage
Tsunamis and shockwaves	Up to 1000’s km	Wave damage; flooding; instability or capsizing; potential loss of life; pressure waves dangerous to hearing and health close to source

Pumice rafts pose perhaps the longest duration and widest dispersed threat. Our estimate of frequency of pumice raft forming events is very poor, as often these are only identified for scientific recording when the rafts encounter shorelines possibly months after eruption at remote submarine volcanoes (S. E. Bryan et al., 2012; Jutzeler et al., 2014; Redick, 2023) . Satellite observation is then used to back-calculate the tracks and ultimate sources of these rafts. Increasing efforts are being made to use and develop satellite based detection and tracking to mitigate the impacts of raft encounters (Iskandar et al., 2023; Whiteside et al., 2021; Zheng et al., 2022).

Raft encounters have not only impacted ships, but also coastal access and ports; the risks to shoreline infrastructure are documented (Asano & Nagayama, 2021). For example, the eruption of Fukutoku-Oka-no-Ba submarine volcano caused disruption to coastlines stretching from the Nansei islands to mainland Japan between October-November 2021; two months after the August eruption over 1000 km away (Chang et al., 2023; Yoshida et al., 2022) . Pumice rafts can also have important ecosystem impacts, both in terms of swamping coastal ecosystems, and as a transport mechanism for species across wide areas (S. E. Bryan et al., 2004; Ohno et al., 2022) .

Tephra (ash and lapilli) fall from eruption columns can be spread over very wide areas, although the distances over which substantial (1mm thick) deposits can be generated is much more restricted (in the order of 10’s to 100’s km from the vent). This still places many high intensity shipping routes within high exposure areas (Figure 4). Plumes from explosive volcanic eruptions can achieve heights from hundreds of meters to tens of kilometres, and disperse ash from local to global scales, respectively (Bonadonna & Costa, 2013). Following a number of aviation incidents with ash plume encounters significant work has been done to understand plume transport, and the effects of volcanic ash on aircraft (Alexander, 2013; Prata & Tupper, 2009). No such work has been completed exploring the impacts of ash ingestion or loading on ship structures and engines. We go on to explore some of these vulnerabilities in the next section.

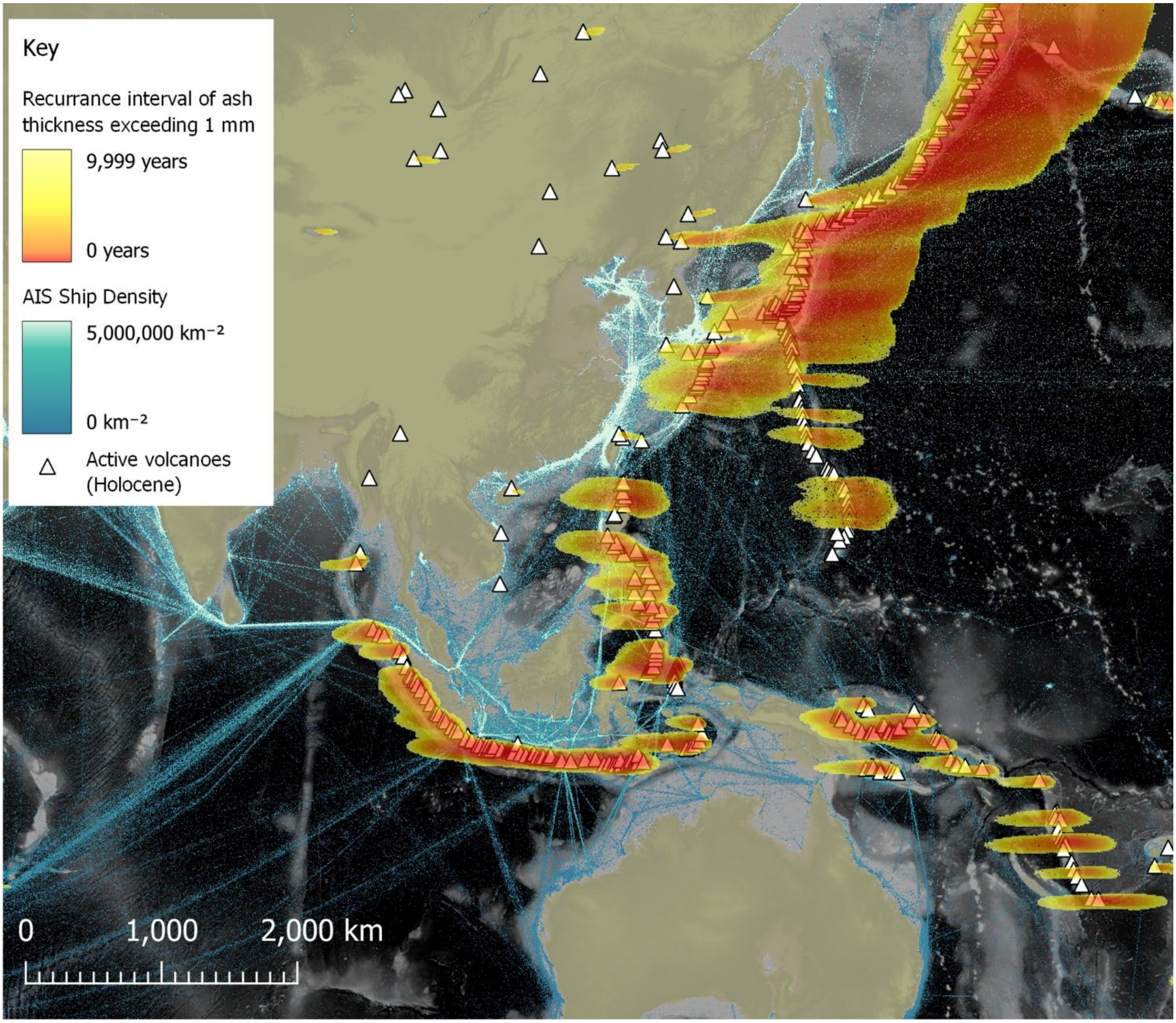

Figure 4. Shipping AIS data, overlaid with recurrence interval of ashfall exceeding 1 mm (Jenkins et al., 2015) for South East Asia. Holocene data from the Global Volcanism Programme (Smithsonian Institution, n.d.).

Pyroclastic density currents are a shorter-range hazard, with typical propagation distances of perhaps a few tens of kilometres (Freundt, 2003). However, on encountering water they pose a multiple hazard; the more dilute portions of these currents are able to propagate across the water surface, and therefore are able to directly impact surface shipping and infrastructure some considerable distance from the shoreline. This was the cause of vessel losses at St Pierre, Martinique in 1902 (Jaggar, 1949). The denser portions of the currents are able to enter the water as the flow encounters the shoreline. This has two separate products; the displacement can trigger tsunami (Bonaccorso et al., 2003; Bougouin et al., 2020; Lipiejko et al., 2022; Lynett et al., 2022), and the sediment mixes with water to generate submarine volcaniclastic density currents which can propagate for hundreds of kilometers offshore (Jutzeler et al., 2017; Trofimovs et al., 2012). Such currents pose a substantial risk to subsea infrastructure, and were responsible for the breaking of telecommunications cables most recently during the Hunga Tonga Hunga Ha´apai eruption in 2022 (Clare et al., 2023; Seabrook et al., 2023). However, the historical record of these processes causing cable breaks goes back as far as Krakatoa, 1883 (Simkin & Fiske, 1983), and Mt Pelée in 1902 (Chrétien & Brousse, 1989). There are at least 11 cases in the historical record where volcanic activity has resulted in submarine cable breaks CLARE ET AL IN REVIEW TBC.

Volcanogenic tsunami are also generated in the wake of mass wasting/flank collapse events (Bonaccorso et al., 2003; Giachetti et al., 2012) which, in the case of ocean island volcanoes, can lead to total edifice failure and explosive magma-water interactions as was observed at Krakatau in 1883 (Simkin & Fiske, 1983). These can generate tsunami greater in scale than those generated by ocean-entering PDCs, as these types of mass wasting generally introduce a larger volume of material to the water very rapidly. The frequency of these events is much lower than eruptive processes; a volcano may take many thousands of individual eruptions to build up, before a collapse removes a substantial proportion of its total mass. The frequency of flank collapse eruptions in subaerial volcanoes corroborates this, with the notable examples of Bezymianny, Russia (Shevchenko et al., 2020), Mt St Helens, USA (Sarna-Wojcicki et al., 1980), and Anak Krakatau, Indonesia (R. Williams et al., 2019) in the last century, in line with the estimated average of approximately 4 per century (McGuire, 2003).

Other, less explored hazards are more difficult to speak to with any certainty due to lack of event documentation or real-time detection. Ballistic bombs, for example, are generally only a risk within a few kilometres of a vent, but even so we have recorded encounters such as the tourist boat hit by a decimetre-scale rock ejected during the Kilauea eruption in 2018 (‘Kilauea Volcano’, 2018). Such ballistic ejecta need not be sourced from vents, but may be the result of lava bench collapse as subaerial lava flows encountering the shoreline. Still more esoteric, are the possible risks associated with volcanic gases in the water column or above the water, either from passive degassing, or from eruption driven gases and boiling processes. In such cases there is hypothetically a buoyancy risk, due to the decrease in fluid density (Denardo et al., 2001; Hueschen, 2010). To our knowledge there are no confirmed reports of such an event involving shipping, and given the very limited distance over which such a risk would exist we include it here only for completeness. However, there are recorded instances of the advection volcanic gases from submarine/emergent eruptions proving fatal to communities e.g. the 1650 AD eruption of Kolumbo, Santorini, that resulted in dozens of fatalities and livestock loss up to 10km from the eruption source (Fouqué, 1879; Nomikou et al., 2012) a potentially significant hazard for ship personnel if exposed with limited risk mitigation.

Vulnerability of shipping to volcanic hazards

Loss of propulsion

Nearly all marine engines rely upon seawater cooling systems to regulate their running temperatures. Older vessels are able to operate with 50% reductions in cooling water volume but newer vessels have lower design overheads, and experience issues at as little as 30% loss of volume of cooling water (Personal Communication, Rolls Royce Marine engineers, Ulsan Shipyard, South Korea. May 2003).

A typical main sea inlet grating for the cooling system restricts the diameter of ingested particles sucked up into the sea chest to about 15 mm across the minor axis but could be much greater than this along the major axis. Sand-mud grade particles would initially pass through the system, but may eventually start to coat the pipe work (Johnson & Threlfall, 1985) and cooling plates. Gravel-sized material (such as volcanic ash and lapilli) will quickly block the internal strainers. Depending on the piece of machinery in question, the coarse filter size in these strainers may be as little as 3 mm mesh. Separate intakes for the auxiliary machinery (generator motors, refrigeration plant, air conditioning etc), where fitted, will have finer filters and are likely to quickly become blocked. Keeping these clear will be an added burden to the ship's crew. It is likely that at least some machinery will have to be sacrificed so the main engine and generator motor cooling systems can be maintained.

Diesel engines require an airflow sufficient to ensure a flammable mixture within the combustion chamber. This air comes from the engine room atmosphere which, in turn, is provided by high-capacity ventilation fans. A fine (<1mm) mesh filter is generally installed at the air intake to remove solid particles before the air is exhausted into the engine room. If exposed to volcanic ejecta, this filter would soon become clogged with entrained tephra and would need to be removed and cleaned at regular intervals. Increasing tephra fall therefore poses increasing hazards to the crew on deck carrying this out. Marine diesel engines generally operate at temperatures below that required to melt primary volcanic material (>400°C), although localised hotspots may exist within cylinders, and some volcanic glasses may already become ductile and semi-molten at temperatures exceeding 400°C (D. Giordano et al., 2005). Some naval vessels are powered by gas turbines and these can suffer similar problems as experienced by aircraft (Shifler & Choi, 2018), which can lead to engine failure .

Hazards to stability

For a vessel to float upright, the centre of buoyancy (C_B), centre of gravity (C_G), keel (K), and the metacentre (C_M) must be in a vertical line on the centreline of the vessel, with $KC_M > KC_G > KC_B$ (Figure 5). In this case, she is said to have a positive metacentric height ($+C_GC_M$).

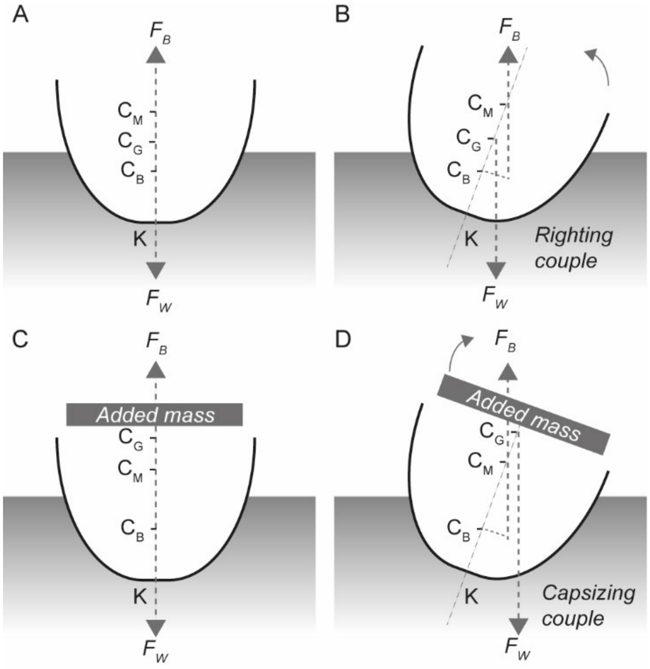

Figure 5. Generalised ship stability conditions for (A) stable upright,(B) self-righting, (C)over-loaded upright and (D) capsizing conditions, considering centres of buoyancy (C_B) and gravity (C_G), and metacentre (C_M) over the keel (K). Buoyancy force (F_B) and weight (F_W) vectors are indicated.

When a vessel is built, the position of her initial metacentre is determined by an inclining experiment and the height of the metacentre above the keel (KC_M) is tabulated for different draughts. To ensure all vessels are stable enough to meet all expected conditions during a voyage a minimum set of criteria are laid down by legislation, including the minimum C_GC_M that a vessel must have at all stages of her voyage. Where the C_GC_M is excessive the vessel will form a large righting lever when she is heeled over. As soon as the heeling force is removed the vessel will return to the upright violently. This can lead to injury to crew, damage to cargo and severe stressing of the ship's structure.

Where masses of unknown quantity (both total mass and location) are added to the vessel they must be allowed for when determining that the 'departure/arrival' and 'at sea' conditions for the ship meet the minimum legal requirements. These conditions are frequently encountered with excess water and ice loading. Excess water mass is generally limited by the catchment area and is allowed for both in the minimum criteria mentioned above and particular features within the ship's construction. Icing, however, is a different problem and much more like the situation that may arise from tephra accumulation.

Most vessels experience icing from meeting extreme temperature conditions in moderate to heavy weather. Water spray from the sea hits the cold steelwork of the vessel and deck cargo where it freezes, and ice accretion occurs. As well as accumulating on the deck and other horizontal surfaces, ice may also build up asymmetrically on vertical surfaces causing the vessel to list as well as loose stability. The International Maritime Organization lays down the minimum allowances required (IMO, 2022):

- All exposed horizontal surfaces are assumed to carry <30 kg m-2 of ice.
- Vertical surfaces are assumed to be the lateral area of both sides of the ship above the waterplane and carry less than 7.5 kg m-2 of ice.
- Other surfaces not included in the above are accounted for by increasing the total of 1 and 2 by 5% and the calculated moments (mass x Distance from Keel or Centreline) of these weights by 10%.
- In this condition the vessel must never become overloaded.

The magnitude of loading by tephra falls within a broad window of values; while accumulation in proximal areas during large eruptions may reach meters of thickness in a few hours (within km of source), this thins to centimetres then millimetres distally or during smaller eruption. Dry tephra density generally ranges between 800-2500 kg m-3, driven by solid densities in the region of 2200 - 2700 kg m-3, and vesiculation causing open pore space of 0 – 80% volume. This pore space is often well connected to the particle surfaces, so tephra will gain water mass in the presence of sea spray or rain, which can lead to even low bulk density tephra achieving bulk densities of over ~

2000 kg m-3 - twice that of ice (Spence et al., 2005; Williams et al., 2021). At these densities accumulation of just 15 mm of tephra will exceed the ice loading limit of 30 kg m-2. To put this in context, the 1980 eruption of Mt St Helens (VEI 5) deposited 15 mm of ash up to 450 km from the vent (Sarna-Wojcicki et al., 1980). With the tendency of tephra to easily drift in prevailing winds it is likely that any loading on a moving ship will be asymmetrical, which ice loading limit calculations are not suited to, and will likely underestimate stability risk in these conditions (Figure 5). As wetting occurs, the mechanical properties of the tephra change, so it becomes more cohesive and capable of sustaining larger steeper piles (Walding et al., 2023), enabling even greater loading capacity.

Position Fixing and Navigation

Marine navigation radar typically operate in either 'S' (10 cm) or 'X' (3 cm) bands. In recent years, radars in these bands have been used extensively to track tephra clouds from a volcanic eruption (Harris et al, 1981; Lacasse et al, 2004 (S. Bryan et al., 2017; Marzano et al., 2013)) due to its opacity to radar emissions. The sensitivity of X band radar to tephra (and particularly wet tephra) results in two separate issues; the first is that signal attenuation close to the ship prevents detection of obstacles at range, while the second is that the high reflectance of tephra in the atmosphere leads to signal cluttering. In other words, the effective radar range is reduced, and the signal to noise ratio is vastly impacted. These two effects are demonstrated in Figure 6 where images of an (A) unattenuated, (B) attenuated, and (C) cluttered signal from a ships navigation radar are shown.

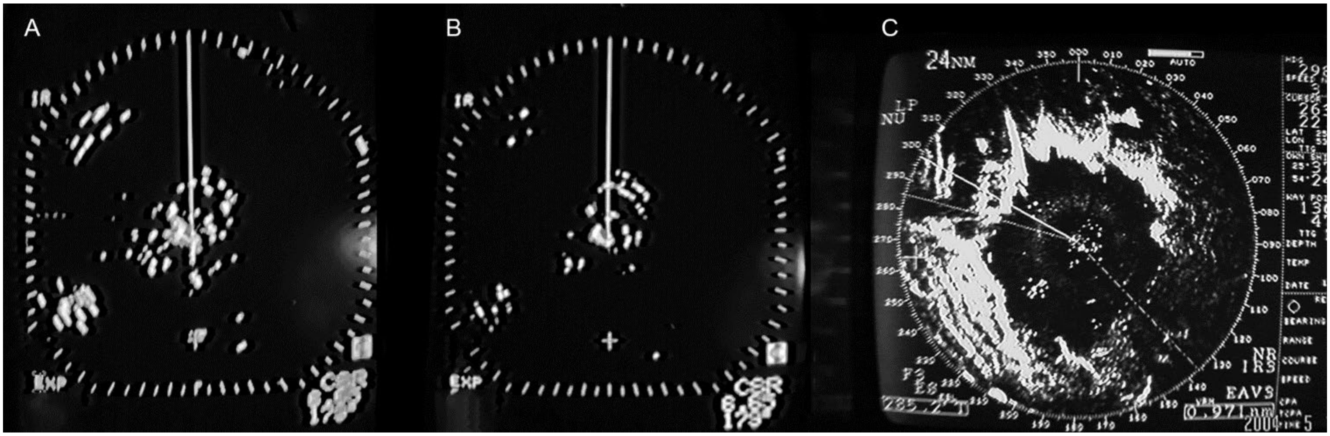

Figure 5. Photographs of ships navigation radar under different conditions. A demonstrates strong clear signal from nearby oil rigs. B is from the same setting and location, with the radar wrapped in a thin film containing volcanic ash with 30% moisture to generate attenuation. C is unattenuated, at a different time and location, demonstrating extensive noise as a result of a dust storm that has similar reflective properties to volcanic ash.

Electrical systems

The combination of moisture and tephra has been shown to cause serious problems to electrical distribution systems on land(Bebbington et al., 2008). Although vessels do not have an open distribution system, the wet environment and potential for tephra entrainment into switchboards and breaker panels is a hazard which should be explored. Radio aerials, especially those used for high frequency transmissions, can be similarly affected by shorting across insulators. Exposure of electrical systems and metallic structures on ships to volcanic ash is currently poorly constrained in impact assessments, but the acidic nature of tephra and volcanic gases may pose an additional threat to systems sensitive to acidic corrosion.

Hazards to Health

Respiration of volcanic ash has been shown, in general, to have little long-term effect on the health of a fit adult (Horwell & Baxter, 2006; Martin et al., 1986; Stewart et al., 2022). This is dependent upon the length of exposure and quantity of silica present in ash particles <4 μm. Irritation and bronchial tract problems are the most likely scenario following short term exposure to tephra particles <100 μm in size, but inhalation and absorption of particles <10, 4 and 1 μm can have different respiratory problems respectively (Stewart et al., 2022). PM-2.5 face masks can significantly reduce the risks from inhalation of volcanic ash, in the eventuality of prolonged exposure. For a vessel caught in an area of tephra fallout, any exposure to passengers or crew is likely to be short term, but ships do not routinely carry appropriate personal protective equipment (PPE) or these risks may not be recognised in safety standards set out by the International Maritime Organization (IMO) and the International Labour Organization (ILO).

Additionally, prolonged downwind exposure to volcanic gas (carbon dioxide, sulfur dioxide, and halogen species) may put ship personnel at significant health risk (Hansell & Oppenheimer, 2004; Horwell & Baxter, 2006). As aforementioned, most deaths associated with the marine-emergent eruption of Kolumbo volcano in 1650 AD, Greece, are attributed to exposure to noxious acidic gases blown over 7 km from the volcanic center (Fouqué, 1879). The interactions of hot lava/magma and cold seawater at the sea surface can create volcanic “laze” (lava-haze), where chlorine ions dissociate from the salt in seawater and attach to hydrogen ions to form dangerous hydrochloric gases and vapours (Resing & Sansone, 1999). However, the risks posed by volcanic gases may also be reduced through appropriate PPE usage

Routing and delays

The outcomes of the M/V Ever Given blockage of the Suez Canal in 2021 made clear the scale of financial risk when critical shipping lanes and routes are shut down or restricted (Lee & Wong, 2021) – a situation which could easily be replicated through volcanic activity in the wrong place. The Suez blockage event lasted just 6 days, yet disrupted supply chains globally, delaying shipments, imposing substantial route diversions, and costing the global economy $6-10 billion (Li, 2023). Pumice rafts are frequently observed to have lifetimes measured in months, even years (Bryan et al., 2012; Jutzeler et al., 2020) and there are numerous bottlenecks to major shipping lanes which not only pass within short distances of active volcanic centres (Figure 2), but also that have already seen pumice raft activity (e.g. the Sunda Strait, the Red Sea, the Torres Strait, and others - see Figure 2; Bryan et al., 2012). As documented previously, port closures have resulted from pumice rafts blocking access after numerous recent eruptions, such as at Fukutoko-Oka-Noba, 2021 (Salgado et al., 2023; Yoshida et al., 2022); such an event in a confined strait with more concentrated shipping may be highly costly both in terms of obstructed trade, and in repairs/maintenance of impacted vessels.

Vulnerability of marine infrastructure to volcanic processes

The growing exploitation of the shallow and deep marine environment for industry, tourism, and aquaculture represents a growing exposure to submarine hazards and risk. However, quantifying the vulnerability of these different infrastructure elements is strongly limited by our knowledge and understanding of the extent and dynamics of submarine volcanic hazards. The destruction of the communications cables surrounding HTHH in 2022 alerted us to the risks of rapid submarine volcaniclastic density currents, but to date we do not know whether these cables were destroyed through abrasion, tension, or simply burial. We have some estimates on deposit thickness in the areas of the cable breaks (up to 22 m on the cable), and flow velocities in the order of 100 m/s (Clare et al., 2023). While we understand the local deposit at HTHH, we have no grasp on the full extent of the deposits as they passed across into the wider ocean basin, or the wider propagation of the currents which formed them. We know from the literature that siliciclastic density currents are able to propagate across ocean-scale basins with subhorizontal bathymetry (Bouma & Stone, 2000; Frenz et al., 2009), but have no grasp of the extent to which either the volcaniclastic or siliciclastic density currents pose a threat to different types of engineering infrastructure.

Communications cables, oil and gas infrastructure, offshore renewable energy projects, and the growing development of deep-sea mining activity all occupy areas of the seafloor which are at potential risk of damage. However, we are not currently in a position as a community to provide any quantitative measures on frequency or magnitude of events, distributions, or the forces and damage these processes are capable of generating which might require engineering against. Furthermore, a large proportion of the shipping industry still relies on very limited shoreside communication and internet access, with bandwidth in some cases still being prohibited to some ship personnel. A lack of access to rapid information and updates in the event of sudden volcanic activity, which may not be translated through VHF-SRC radio channels, may escalate risk, and inhibit appropriate response. Increasing access to satellite internet constellations is already helping to reduce communications issues. Without immediate communication, seafarers are reliant on the guidance documentation that is provided to ships Captains. The Mariners Handbook (The United Kingdom Hydrographic Office, 2009), provides general information for seafarers on dealing with natural hazards they may face. It devotes less than a quarter of a page to volcanic eruptions and only deals with submarine eruptions; about the same amount of space discusses earthquakes while four pages are devoted to 'Tropical Revolving Storms'. This section is not mentioned in the Index under 'Volcano' but is indexed under 'Izu Shoto' (the volcanic chain of islands running South East from Honshu, Japan) or sub-indexed under 'Seabed'. Given the severity of possible outcomes outlined here, and the rapidity of volcanic hazard development, this bypassing of clarity and signage in the immediately available documentation on ship should raise some concern (e.g. Adams, 1979).

Suggested risk reduction actions

Improving training and onboard reference materials – Ensuring that IMO and ILO manuals and training are provided with guidance regarding how to respond to nearby volcanic activity, including training on appropriate PPE, ship management protocols, and awareness of hazards to the ship, personnel, and navigation.

Establishing of temporary exclusion and risk zones during eruption watches and warnings – Implementing pre-determined restrictive zones to maritime traffic, seen with the active submarine volcanoes Kick 'em Jenny (Lesser Antilles) (Kick `Em Jenny Yachting Information | The UWI Seismic Research Centre, n.d.) and Home Reef (Kingdom of Tonga). With limits on zone boundaries and implementation advised by local observatory scientists and probabilistic modelling of eruption scenarios.

Formalising new networks and communications to notify ships of potential hazards – There is currently only a limited system in place to routinely notify and advise maritime traffic to all nearby volcanic hazards. A system similar to the Volcanic Ash Advisory Centres (VAACs) for aviation traffic system could allow pre-emptive and more appropriate actions in response to developing volcanic crises.

Expansion of volcanic hazard and risk maps to offshore – Some hazards can be easily mapped offshore due to little change in the physics and processes controlling their distribution, e.g., ashfall and advection of volcanic gases. Other high-risk hazards, such as pyroclastic density currents (PDCs) and volcanic flank collapse - both subaerial and submarine (Furst et al., 2023), have poorly constrained interactions with water and this, alongside the resulting submarine volcaniclastic density currents require detailed experimentation and numerical modelling work to better constrain their behaviours. Modelling of potential tsunami wavefront heights, particularly closer to shoreline around near-shore ramps, are also imperative to ship safety and stability.

Identifying shipping lanes of increased risk and vulnerability – There are currently no studies that explicitly and quantitatively assess the hazards and risks to specific shipping lanes or area of high marine traffic through industry, fishing, aquaculture and/or tourism. This requires research that combine both global AIS datasets with known frequency, duration, and intensity of proximal volcanic systems. Certainly, an area worth of attention, where the data is available.

Improved knowledge of hazardous coastal/marine volcanic centers – Recent, high-impact eruptions have encouraged a surge of interest in shallow marine and marine-emergent volcanism. However, there are still many large knowledge gaps in this area of research, most critically, which volcanic centers are the most hazardous, where are they, and what is likelihood of activity? An improved global overview of hazardous marine volcanic centers by the volcanology and ocean exploration community is imperative to more adequately inform risk mitigation for shipping industries.

Conclusions

The risks posed to shipping around volcanic centres are varied, and generally poorly understood. When considering surface shipping and coastal infrastructure, the risk of a total loss to shipping is relatively low. However, the potential for delays, diversions and mechanical failures is probably high. Given the increasing dependence on global shipping freight and its growth, the time sensitivity of many deliveries, and the costs related to the running of shipping operations, volcanic activity should be a greater subject of concern.

Considerable work must be done in establishing baseline values for risk in the offshore setting, and in exploring the wider hazards not explored here. However, there is already sufficient knowledge in many areas for policy and available datasets to start addressing some of these hazards, in advance of a more substantial crisis.

Given the myriad hazards which may be associated with explosive eruptions, we suggest that a collaborative and meaningful effort is prioritised toward the establishment of a shipping-oriented alert system which runs similarly to, in parallel with, or as part of the Volcanic Ash Advisory Centres designated under the International Civil Aviation Organization. In addition, there are significant steps that can be taken in the volcanology and natural hazards scientific communities to progress research in the areas needed to better inform and validate the proposed policy and regulatory changes .

Author contributions

PC conceived the initial idea for this work together with initial literature review material, and conducted a number of experiments while at sea to evidence several arguments made herein (e.g. Figure 5). PR wrote the draft manuscript with regular discussion with SM, which all authors contributed to the editing and revision of. All authors contributed to data collation, figure design and preparation.

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Data availability

All data used for generating the GIS outputs is available through open source channels as referenced in the relevant figure captions.

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