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Perspective

# The Contributions of Marine Sediment Cores to Volcanic Hazard Assessments: Present Examples and Future Perspectives

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**Abstract:** The rigorous assessment of volcanic hazards relies on setting contemporary monitoring observations within an accurate, longer-term geological context. Revealing that geological context requires the detailed fieldwork, mapping and laboratory analysis of the erupted materials. However, many of the world's most dangerous volcanic systems are located on or near coasts (e.g., the Phlegraean Fields and Vesuvius in Italy), islands (e.g., the volcanic archipelagos of the Pacific, southeast Asia, and Eastern Caribbean), or underwater (e.g., the recently erupting Hunga Tonga–Hunga Ha'apai volcano), meaning that much of their erupted material is deposited on the sea bed. The only way to sample this material directly is with seafloor sediment cores. This perspectives paper outlines how marine sediment cores are a vital yet underused resource for assessing volcanic hazards by: (1) outlining the spatio-temporal scope of the marine volcanic record and its main deposit types, (2) providing existing examples where marine sediments have contributed to volcanic hazard assessments; (3) highlighting the Sunda Arc, Indonesia as an example location where marine sediment cores are yet to contribute to hazard assessments, and (4) proposing that marine sediment cores can contribute to our understanding of very large eruptions that have a global impact. Overall, this perspectives paper aims to promote the utility of marine sediment cores in future volcanic hazard assessments, while also providing some basic information to assist researchers who are considering integrating marine sediment cores into their volcanological research.

**Keywords:** volcanic hazard; marine sediment core; tephra; volcanic ash



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## 1. Marine Sediment Cores and Volcanic Hazard Assessments

### 1.1. Volcanic Hazard Assessments

Assessments of volcanic hazards require the integration of data from active monitoring systems such as gas emissions, geodetic height, and seismic data (short-term hazard assessments), with an understanding of the long-term behaviour of a volcanic system (Figure 1). This understanding comes both from historical accounts (when available) and field and laboratory studies of the erupted products. Historical accounts, while often detailed, only cover the last few hundred to thousand years at best, and many dormant volcanoes have not erupted at all in that timeframe. Fieldwork on terrestrial outcrops of eruptive products can extend the record of eruptions back hundreds of thousands of years, but these are often fragmentary, eroded, or covered in dense vegetation (equatorial regions) or ice (glaciated regions).

For island and coastal volcanoes, these issues are augmented by much of the erupted material from explosive eruptions being deposited in the sea. However, marine sediment cores act as archives for these eruptive products, offering an opportunity to reveal a very long history of volcanic activity (perhaps 100,000s of years or more [1]). The volcanogenic deposits and their host sediment can be analysed in the laboratory to inform on the magma chemistry, eruption size [2], and date (Table 1), and therefore provide insights into a volcano's range of eruption styles, their magnitudes, and their eruptive frequency. They can also offer the chance to assess the past activity of a volcano with respect to major changes in the structure or morphology of the volcanic edifice, such as those associated with a caldera or sector collapse [1,3] or external environmental change such as sea-level change [4,5].

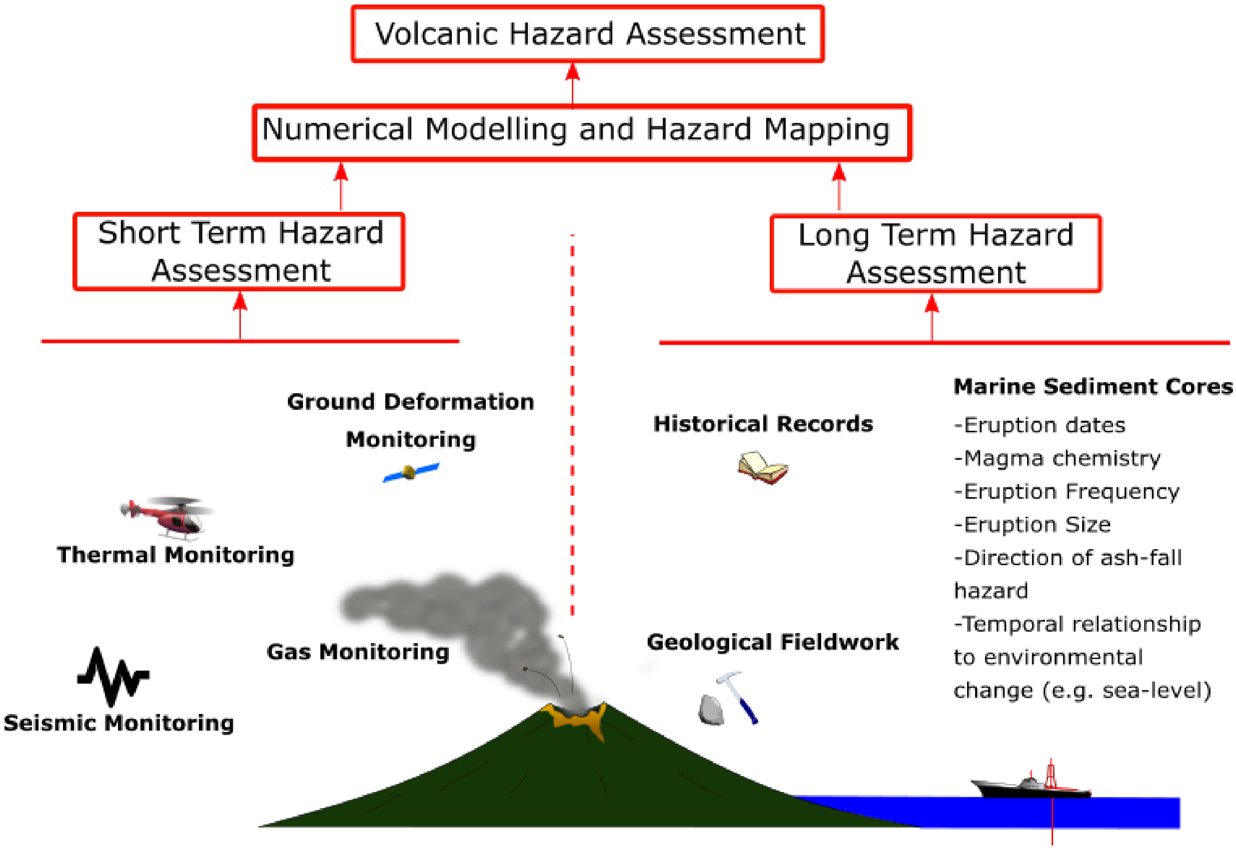


**Figure 1.** Schematic representation of the sources of information contributing to a volcanic hazard assessment for an island or coastal volcano, with the details of the types of information which can be provided by marine sediment cores.

### 1.2. *The Spatial and Temporal Scope of Volcanic Deposits in the Marine Sediment Record*

Ocean sediment cores present records of explosive activity from coastal and island volcanoes on timescales of 100 s to 100,000 s of years. The limit on the timescale is determined only by the length of the sediment core. Perhaps the best compilation of ash deposits in marine sediments is give by the VOLCORE database [6]. The authors compiled and described a global database of 34,696 known visible ash layers in ocean sediment cores; the oldest deposits are 150 million years old, but the majority of deposits are Quaternary or Pleistocene (66%). It should be noted that while this impressive database is the best compilation of the spatial and temporal distribution of marine ash layers available, it only includes cores taken by the large international drilling projects: the Deep-Sea Drilling Project, Ocean Drilling Program, and International Ocean Discovery Program. There have been many smaller-scale sediment core projects using shallower coring systems and smaller national science research vessels, in addition to industry-funded programmes. The use of smaller drilling platforms and more varied coring methods can provide access to waters that are too shallow for large vessels and deep drilling techniques. If added to Figure 2, these cores would improve the sampling density closer to the volcanic coasts and islands. However, their temporal extent is generally much shorter than that covered by the coring projects in Figure 2, and they are unlikely to capture evidence of eruptive events prior to the Quaternary.

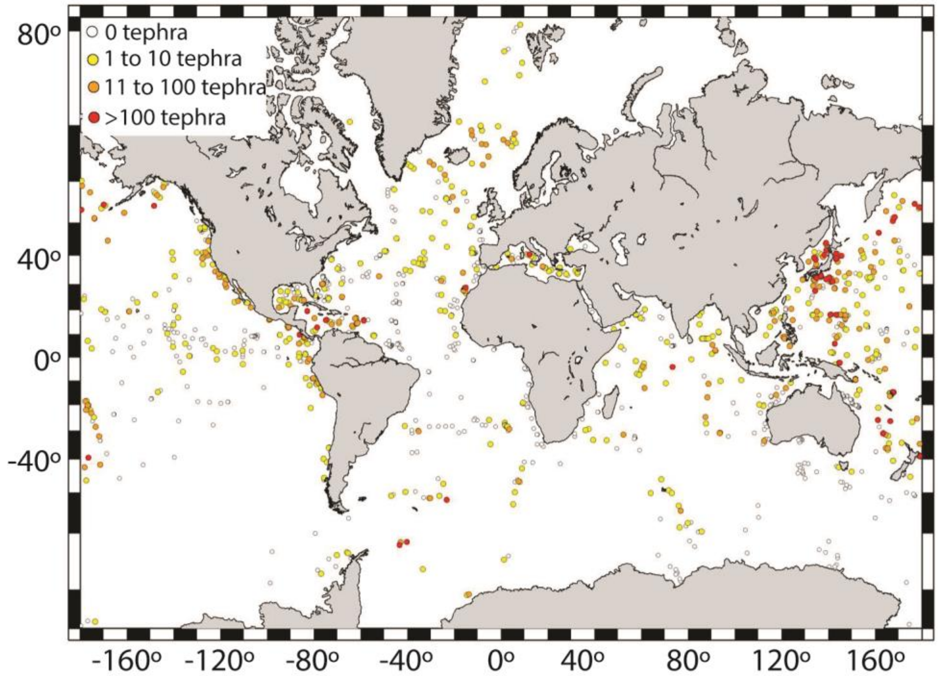


**Figure 2.** (Reproduced from reference [6]). Distribution of ocean sediment cores from DSDP, ODP, and IODP cruises as reflected in the VOLCORE database, coloured to indicate the number of tephra layers found at each site. Coastal areas where cores record many ash deposits (e.g., Japan, the Caribbean) reflect highly active volcanic systems in these areas. More remote cores with many tephra layers may indicate locations close to volcanic islands or simply very long cores. The VOLCORE database can be found at https://doi.org/10.1594/PANGAEA.934363 (accessed on 18 March 2023).

Whilst marine cores can preserve ash fall deposits better than subaerial deposits, they are not comprehensive in their spatial coverage. The expense and difficulty of recovering cores means that the distribution of core sites might be limited to low numbers or even a single core in one location—especially when deep drilling (>100 metres) is the main objective (e.g., IODP). This limited spatial core distribution may under-record eruptions for any particular volcano if the prevailing wind direction or ocean currents have changed significantly over time. Furthermore, the offshore distance of many core sites from nearby volcanic sources means that preservation of macroscopic tephra deposits tends to be limited to large-magnitude explosive eruptions. Such records do not, therefore, generally contain information on more frequent, lower magnitude events that may typify a volcano's activity.

The length of cores and the local sedimentation rate dictates the timescale of eruptive records retrieved via coring. As most cores are shallow, our knowledge of eruption histories becomes increasingly under-sampled beyond the Holocene and latest Pleistocene period; for example, 41% of all eruptions in the LaMEVE database of large-magnitude explosive eruptions [7] are Holocene in age, and this record is also strongly biased towards the largest-magnitude events. Deposits from smaller eruptions, which would generally be both thinner and finer at any individual site, may be winnowed away by currents, bioturbated, or just be preserved as diffuse cryptotephras, and therefore be more difficult to identify [8].

The reconstruction of volcanic records is not usually the primary drilling target or the reason for selecting core locations, so the spatial distribution of marine cores does not match up with the global distribution of volcanoes and is not optimal for providing comprehensive eruption records. Some volcanic regions such as Japan have many marine cores around the coast, but others have few, such as Indonesia, the Pacific islands, or S. America [6] (Figure 2). Some regions are therefore understudied from both the marine and subaerial record perspectives. For instance, the Kuril islands as well as Indonesia, the Philippines, and Papua New Guinea have far fewer eruptions in the LaMeve database than Japan [7], but this representation is not proportional to historical levels of volcanism in these regions [9]. There is also the possibility of over-recording events, through the false identification of re-worked volcanic material in secondary volcaniclastic deposits. In this instance, methods to distinguish reworked from primary tephra through structural and component features, as well as via image analyses of roughness, sorting, and elongation may be employed [3].

Readers interested in developing research projects using ocean sediment cores should consult the VOLCORE database in conjunction with the Index of Marine and Lacustrine Geological Samples for a comprehensive interactive map of ocean sediment cores from all research cruises found at www.ncei.noaa.gov/maps/sample_index/ (accessed on 18 March 2023).

## 2. Marine Sediment Cores as Archives of Volcanic Activity

### *2.1. Volcanogenic Deposits in Marine Sediment Cores*

There are several types of volcanogenic deposits found in marine sediments [3,10,11] and these are exemplified in Figure 3. They are:

- Visible ash (tephra) deposits. These are primary deposits representing fallout from an ash cloud and can yield grain-size data (informing on eruption magnitude and direction [12], geochemistry [13], and potentially eruption dates through direct dating [14,15].
- Non-visible (crypto) tephra deposits. These are also primary fallout deposits, but where the concentration of shards is too low to make the layer visible to the naked eye. Such deposits can be found many 100′s of km away from their source. The finding such layers can be helped by techniques such as magnetic susceptibility and high-resolution XRF core scanning [16,17], but the most rigorous methodology requires contiguous sampling of the core and processing of the samples to extract any shards [18].
- Pyroclastic density current deposits and their offshore equivalents, representing a transition to turbidity currents [10,11,14,19].
- Reworked volcaniclastic deposits (turbidites, flood deposits, landslides [3,9,11]).

### *2.2. Determining the Source Volcano for Volcanogenic Deposits in Marine Sediment Cores*

The contribution of marine sediment cores to volcanic hazard assessments depends critically on the correct attribution of each deposit to its source volcano. This is a particular challenge for regions with several related eruptive centres [20]. This is done primarily through geochemical characterization of the juvenile glass component of the deposit that is taken to represent the composition of the erupted magma. Major elements are analysed using WDS EPMA. In many cases it is desirable to also measure trace elements using either LA-ICP-MS or SIMS [18]. The resulting values are then compared to data from proximal deposits on the slopes of a range of possible source volcanoes and their known eruptions (Figure 4). Where a match is made, any date assigned to the distal tephra (perhaps from a marine core age model) can be imported into the proximal stratigraphic record and inform on the eruptive frequency of that volcano. Where the geochemical comparison is ambiguous, multivariant data analyses such as principle component analyses may be deployed [18]. It is often possible to define the source volcano, but not the precise eruption. In these cases, the tephra may represent a previously unknown eruption, thereby enhancing the known record of volcanic activity for that volcano.

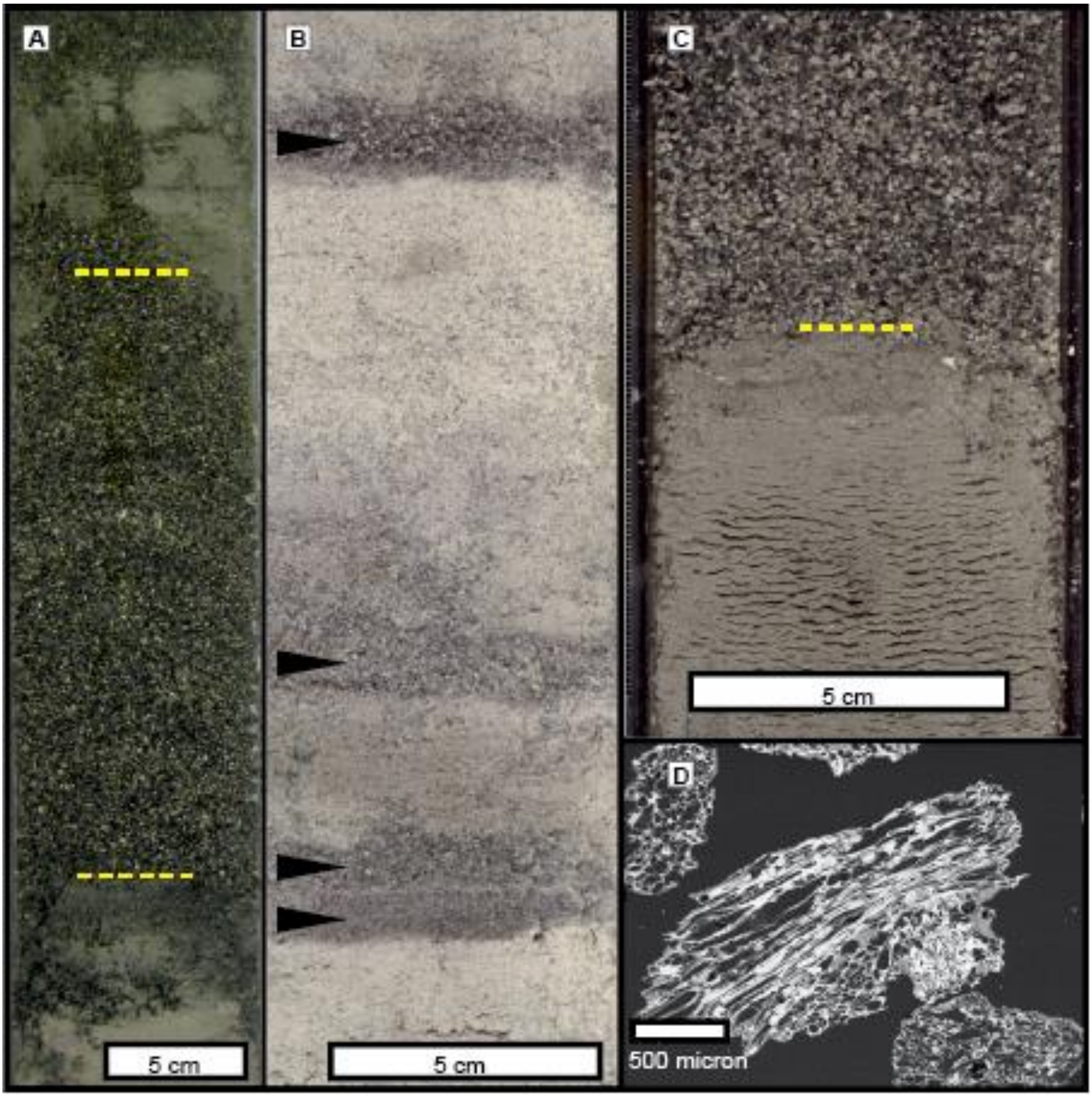


**Figure 3.** Examples of cored marine volcaniclastic deposits offshore Montserrat, Lesser Antilles. (**A**): An andesitic volcaniclastic turbidite (core JR123-21), bounded by hemipelagic mud, with the main sandy deposit bounded by the yellow lines. At the deposit scale, the features of such deposits can share many similarities with tephra fall deposits. (**B**): Thin volcaniclastic deposits—interpreted as ash fall deposits—further offshore Montserrat (IODP U1396A-3H-2) within bioclastic sediment, with each discrete bed marked by triangles. (**C**): The base of a thicker pumiceous coarse sand, interpreted as a fall deposit (IODP U1396A-3H-2); (**D**): an SEM image of pumice clasts from the deposit shown in (**C**); where primary deposition does not form macroscopic layers, the identification of individual juvenile glass clasts (generally on a much finer shard scale) dispersed within background sediment can form the only evidence of an eruptive event. Images from web.iodp.tamu.edu (IODP images, accessed on 18 March 2023) and courtesy of the British Ocean Sediment Core Research Facility (**A**).

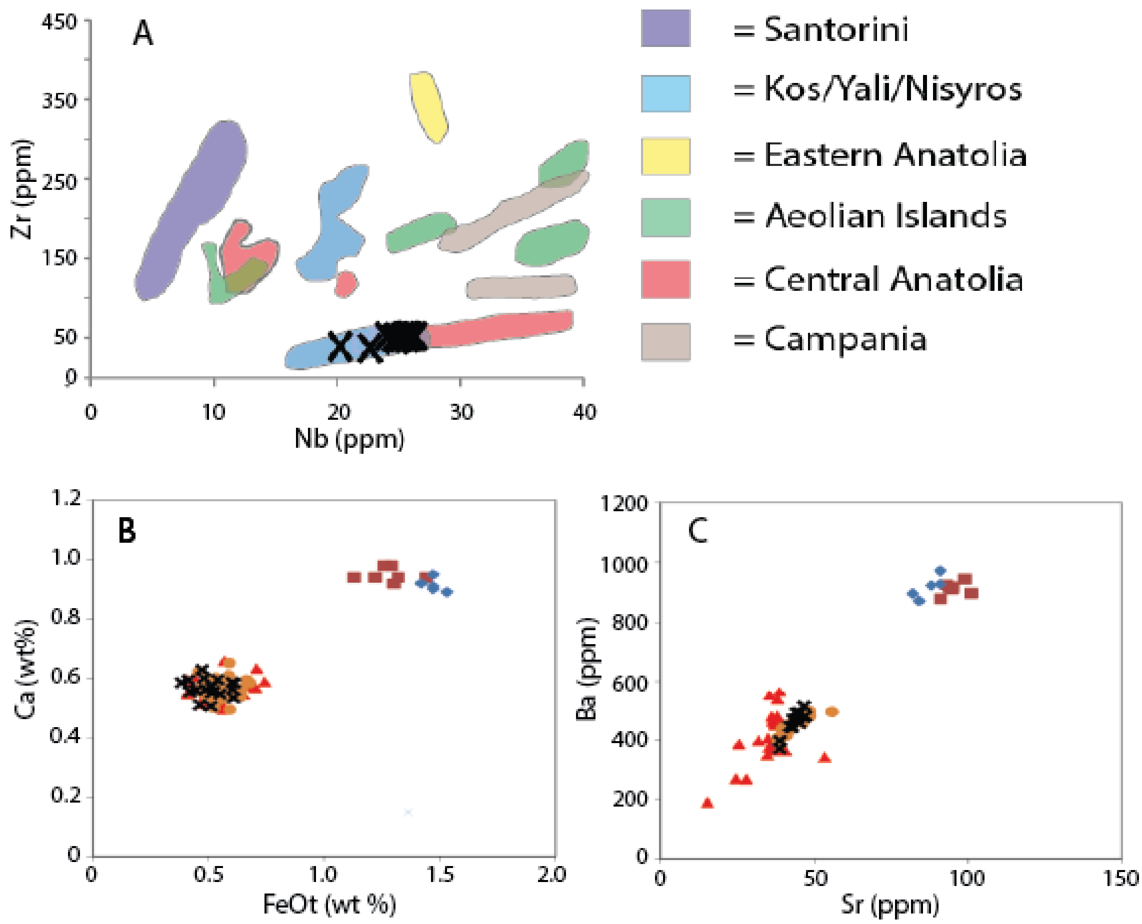


**Figure 4.** Geochemical comparison (juvenile glass) of an example marine tephra deposit (black crosses) with a known age found in an Eastern Mediterranean marine sediment core (ODP 967) to undated proximal deposits from various candidate volcanoes or volcanic regions in the Eastern Mediterranean. (**A**); adapted from [21], shows that the analyses most closely match proximal deposits on the islands of Kos, Yali and Nisyros. ((**B**,**C**); adapted from reference [22]) show that the marine tephra (black crosses) closely matches the major element (calcium and iron) composition (**B**) of two of the undated proximal deposits of the Kos/Yali/Nisyros volcanic system (red triangles and orange circles), but just one of these deposits (orange circles) when trace elements (Ba and Sr) are considered (**C**). The marine tephra deposit is therefore correlated to, and gives a date for, the proximal deposit represented by the orange circles.

### *2.3. Age Determination of Volcanic Events in Marine Sediment Cores*

Establishing the patterns and frequencies of eruptions through time is key to providing the geological context for volcanic hazard assessments. One of the main benefits of including marine sediment cores in a volcanological study is that eruptions evidenced within them are often easily and cheaply dated, with a range of methods that can be applied both directly to volcanic deposits and to the bounding marine sediment. Often, age models for cores already exist because of previous paleoceanographic or biostratigraphic work. When correlated with proximal stratigraphies, marine ash deposits can constrain the timing of events that do not otherwise have precise stratigraphic contexts, including effusive episodes, minor explosive eruptions, and major destructive episodes or periods of quiescence [3,5,13]). The techniques most routinely used to create ocean sediment core age models (and therefore to date the volcanogenic deposits within them) are summarised briefly in Table 1 to assist readers planning to utilise marine cores in research projects.

**Table 1.** Methods of age determination in marine sediment cores. Chronological information from all these techniques can be integrated through a Bayesian age modelling approach [23]. This incorporates both dating and sedimentological information (such as turbidite deposits or erosional surfaces), allowing interpolated dates to be justifiably defined for any depth (such as the depth of a volcanogenic deposit) in the core sequence.

| Dating Technique | Notes | References |
| --- | --- | --- |
| Radiocarbon | Radiocarbon on foraminifera can date the sediment immediately above or below a volcanic deposit. The use of the technique is limited to sediments younger than about 50,000 years old. Bayesian age modelling of the core allows justifiable interpolation between dated samples. | [23–25] |
| Biostratigraphy | Prominent changes in marine fauna within an ocean basin often have existing dates (from other methods). These can be used to provide constraints on the ages of volcanogenic deposits. | [25,26] |
| Palaeomagnetism | A routine method of the IODP. This is low-cost and can provide initial chronostratigraphic information from which to formulate a sampling strategy for other forms of dating. Palaeomagnetic events are relatively rare and cannot therefore be used in isolation to determine a precise date for a volcanogenic deposit. | [27] |
| OSL and ESR | Volcanogenic deposits can be dated directly by OSL (Optically Stimulated Luminescence) using the glass shards or the quartz or feldspar crystals associated with the deposit. Indirect dating of the surrounding sediment is also possible and has a much more established methodology. | [14,15,27,28] |
| Tephrochronology | Correlation of ash layers to proximal deposits with known dates through their geochemistry is described briefly in Section 2.2. The reliability of this approach depends ultimately on the integrity of the proximal stratigraphy. | [18,29] |
| Tuning | Alignment of a palaeoenvironmental proxy record (such as $\delta^{18}O$) from the sediment core to either a Milankovitch cycle (e.g., the precession cycle) or a dated proxy record from another location such as a speleothem can provide a low-cost way of producing an age model for the core and the tephra layers within it. | [25,27,30] |
| Direct radiometric dating | U series (usually U-Th) dating on marine carbonate sediment. Directly dating volcanic material using K-Ar or Ar:Ar techniques in marine cores is also possible when the amount of material preserved in the cores is large enough, the grain size is large enough, and the composition is appropriate (usually from K-bearing phenocrysts such as sanidine). | [27,31] |

### *2.4. Examples of the Contributions of Marine Sediment Cores to Volcanic Hazard Assessments*

Ash layers preserved in marine cores have informed volcanic hazard assessments by providing evidence for the erupted volume of magma in past eruptions [32,33]; this is done by calculating the Dry Rock Equivalent (DRE) volume from an isopach map. The timing (and therefore frequency) of past eruptions can also be derived where the marine core has an age model [5,13,34] and tephrostratigraphies also track the changing composition of erupted products over time [35]. Such information is needed to produce justifiable Bayesian hazard event trees [36,37], which attempt to quantify the contemporary volcanic hazard. Here, we briefly summarise three example volcanic locations at the local, national, and international scales that demonstrate how marine ash deposits can contribute to volcanic hazard assessments.

#### 2.4.1. Santorini, Greece

Santorini is considered by some to be one of the world's most dangerous volcanoes [38]. The eruption style from this island caldera has been diverse, ranging from minor lava extrusion and phreatomagmatic activity to Plinian explosive events—with the last eruption (minor effusive activity) occurring in 1950 [39,40]). There is also a known tsunami risk from both the Santorini volcano itself, and from the neighbouring submarine volcano

Kolumbo [41]. Marine sediment cores have been critical in deciphering the long-term behaviour of Santorini [5,13]. Even though Santorini has one of the best preserved and exposed proximal stratigraphies in the world, dating those proximal deposits is challenging.

Recently, however, ash layers with known dates (from various methods—Table 1) have been found in several distal marine cores [13,42]. These layers not only inform on eruption magnitudes [42] but importing their dates into geochemically correlated deposits within the proximal stratigraphy allows constraints to be placed on the entire eruptive history of the volcano [13]. As the marine cores that contain the ash layers also preserve a sea level record [30], an hypothesis that sea-level changes could affect the frequency of eruptive activity could be investigated [5], with implications for existing hazard assessments [38]. Most minor eruptions in the past have occurred at low sea levels. Now that the sea level is high, it is proposed that the likelihood of minor explosive and lava eruptions is diminished, but that larger explosive eruptions remain possible as their occurrence is more independent of the sea level's influence [5].

#### 2.4.2. Vesuvius, Phleagran Fields and Ischia Island, Italy

The volcanically famous region of Campania in Italy is home to three million people and hosts a wide range of volcanic hazards. The island of Ischia alone is home to 65,000 people. Recent studies [33,43] have demonstrated how supplementing work on proximal eruptive deposits with information from marine tephra layers can improve modelled reconstructions of the largest magnitude event from Ischia in the last 3 kyrs—the Cretaio eruption. Marine sediments provide the only constraint on tephra thickness beyond the shores of the island (although seismic profiles can identify deposits over 10 m or so in thickness [44]. The resulting reconstruction improves assessments of future eruption hazard parameters such as plume height and the total volume of eruptive material (the magnitude of eruption).

Similarly, in the neighbouring Bays of Salerno and Naples tephra layers in nine marine gravity cores allowed new dates to be applied to previously unknown medieval eruptions postdating the 79 A.D. eruption of Vesuvius [12]. Sacchi et al. [45] also detailed marine tephra deposits from the Holocene that constrain the eruption magnitude and frequency in the area, as well as the distribution of eruptive products associated with the most recent activity of Vesuvius. This information could ground-truth eruption scenario models [46] and has already contributed to the updating of hazard assessments [47–49].

#### 2.4.3. Central America and Mexico

The volcanoes of Central America have erupted with VEI > 2 over 200 times in recorded history. Some have large populations within their immediate vicinity, such as the San Salvador volcano, which has half a million inhabitants within 10 km of its summit. While some of these volcanoes (e.g., Arenal) have established eruption histories to effectively inform their risk assessment, others (e.g., Ceboruco or Tacana) lack these—resulting in high volcanic risk ratings (ranking volcanoes based on their risk to society) [50]. Studies of ash deposits in marine sediment cores can help to address these gaps.

Several existing studies of marine cores have informed on the eruption frequency, magnitude, and long-term magma flux of specific volcanoes and of the Central American volcanic arc as a whole. Kutterolf et al. [51] derived erupted magma volumes and rates back to 200 ka, while Schindlbeck et al. [52] defined the ages (and therefore constraints on eruption frequency) of 49 major eruptions of Costa Rican and Nicaraguan volcanoes using tephra deposits in marine sediment cores.

Many Central American Volcanoes are under-monitored, meaning that robust hazard (and therefore risk) assessments must rely instead on historical and geological records of eruptions [50]. Ceboruco, Mexico [36] is such an example. A probabilistic volcanic hazard assessment has been built upon the geological record of small, medium, and large (Plinian) eruptions for the volcano [53,54], including information from ash deposits in marine sediment cores.

## 3. New Opportunities to Use Marine Sediment Cores to Improve Volcanic Hazard Assessments; an Example from Sumatra, Indonesia

There are several areas of the world where historical under-sampling of proximal deposits and under-reporting in historical records has resulted in long-term hazard assessments (Figure 1) being poorly informed. Brown et al. [7] and Rougier [55] proposed that, while most regions of the world become more under-represented further back in time (in the LaMEVE database [7] of explosive eruptions), several regions are chronically under-represented throughout their histories; these are: Melanesia, Indonesia, Kamchatka, Mainland Asia, The Kuril Islands, and Alaska. All of these regions could thus benefit from research into their marine core records (Figure 2). We draw particular attention to the island of Sumatra, part of the Western Sunda Arc (Indonesia), as an example of a location where the analysis of tephra in marine sediment cores could contribute significantly to long-term hazard assessments.

The western Sunda Arc is one of the most volcanically active regions in the world and has hosted both the largest known eruption of the last two million years (the Younger Toba Tuff) and the famous 1883 eruption of Krakatoa that caused regional devastation through concomitant tsunamis. Detailed knowledge of the long-term behaviour of its volcanoes is, however, largely limited to historical accounts from the last few hundred years [29]. High erosion rates may have removed much of the terrestrial volcanic record, and the landscape itself is often densely vegetated and difficult for researchers to access. Marine sediment cores are, therefore, the only viable long records of volcanic activity available. The VOLCORE database [6] itemises 1260 tephra layers in the wider Indian Ocean region (defined to include the Sunda Arc), demonstrating the huge potential contribution of marine cores to our understanding of the Western Sunda Arc.

The island of Sumatra itself (Figure 5) is home to over four million people, and the nearby Indonesian capital Jakarta to around 8.5 million. The Strait of Malacca is located downwind of Sumatra and is one of the busiest shipping lanes and airspaces in the world—a major eruption in this area could therefore initiate a cascade of systems and supply chain failures across the globe [56]. A modelled eruption of Mt Merapi, Java created an estimated USD 2.51 trillion of global GDP output loss [57].

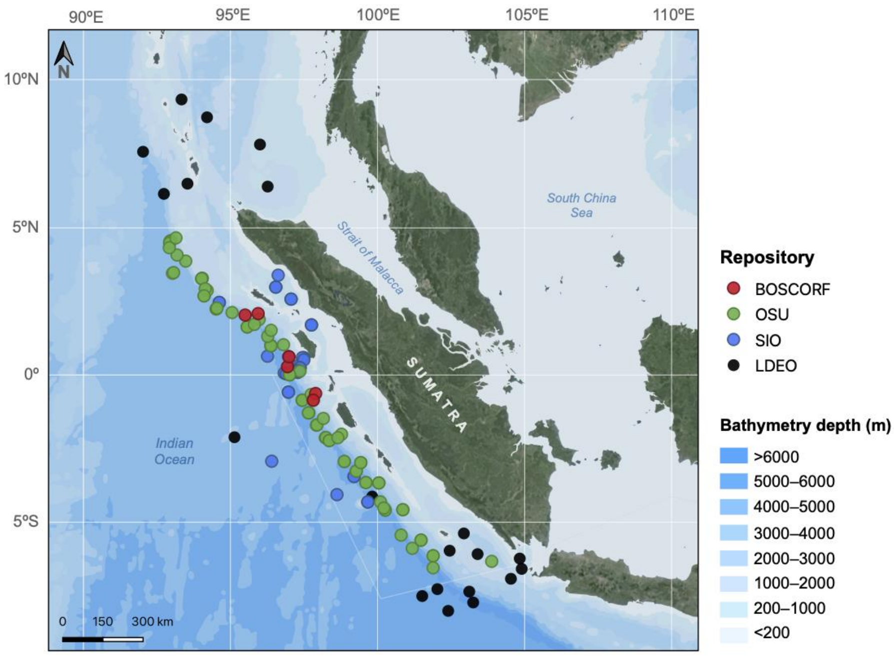


**Figure 5.** Map of existing marine sediment cores off the island of Sumatra (Western Sunda Volcanic Arc) from www.ncei.noaa.gov/maps/sample_index/ (accessed on 18 March 2023). Core repositories listed are: Oregon State University (OSU), the Scripts Institution of Oceanography (SIO), BOSCORF (British Ocean Sediment CORe Facility), and the Lamont–Doherty Core Repository (LDEO).

The only local marine core study of volcanic deposits to date sampled visible tephra layers in 17 marine cores off the western coast of Sumatra and revealed evidence of five previously unknown major explosive eruptions within the last 35 kyrs [29]. No cryptotephra work has yet been undertaken—this would significantly augment the eruptive record. While the region does not host many long IODP, DSDP, or ODP cores, a multitude of shorter cores gathered from smaller cruises (Figure 5) are already available. An existing regional tephrostratigraphy comprising 20 dated deposits [58] could provide an initial chronological framework for the generation of more detailed eruption histories of individual volcanoes.

## 4. Marine Tephra to Inform and Mitigate Global Volcanic Hazards

A key challenge for volcanology is to identify volcanoes capable of large-magnitude eruptions, with a potential for a global impact on the climate and civilization [59]. If such volcanoes can be identified, increased monitoring efforts and preparedness may help to mitigate a significant amount of risk to these regions and forewarn of global cascading hazards [56]. Currently, the global frequency of such very large eruptions is estimated by measuring sulphate peaks in dated ice core records from both the northern and southern hemispheres. Approximate recurrence estimates for eruptions equivalent to Magnitude 7 are 625 years [60] over a 60,000-year timeframe, and are even shorter (444 years) since the last glacial maximum [61]. However, geological records that statistically adjust for completeness suggest a much longer recurrence timescale for Magnitude 7 eruptions of 1200 years [55], highlighting that many large eruptions are missing from these longer-timescale records.

An additional problem is that only a handful of the eruptions identified in ice cores can be attributed to particular volcanoes. Many, such as a Magnitude 6 eruption in 1809 (the 3rd largest eruption since 1500 [62]) remain unassigned. However, new advances in sulfur isotope analysis can provide information on the latitude of the source [63]. The combination of ice core records with analyses of dated tephras in regional marine sediment cores and new approaches to modelling [64,65] could be a powerful way of linking global impacts to specific volcanic sources. Tephra found in marine sediment cores provide the means to both enhance the completeness of the global large magnitude eruption record and to assist in source attribution for these events. This approach has worked in the subaerial realm to identify the 1257 Samalas eruption of Rinjani volcano [66] and the Changbaishan eruption in 946 [67], and marine sediment cores have been successfully used to attribute Icelandic volcanoes to sulphate peaks in Greenland ice cores [68].

## 5. Summary

Volcanic deposits in marine sediment cores can contribute valuable information to volcanic hazard assessments [69]. They can provide dates for past eruptions, constrain frequencies of eruptions, show the geochemical evolution of a system through time, and allow the behaviour of a volcano to be related chronologically to environmental changes such as sea-level changes. Perhaps most importantly, they are the only way to directly sample much of the material erupted by island and coastal volcanoes. Several databases (VOLCORE [6], LaMeve [7], and the NOAA's index of Marine and Lacustrine Geological Samples) can facilitate volcanological researchers in the identification of existing sediment cores that may inform their research and hazard assessments. We outlined three locations that have already benefited from such work, and a fourth (the Western Sunda Arc) which shows that marine cores are currently underused for volcanological applications in some locations. Finally, we propose that ash deposits in marine sediment cores could contribute to our understanding of the locations and frequency of globally significant eruptions (VEI > 7) through the integration of marine ash records with sulphate concentrations in ice cores.

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