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Perspectives Article

The contributions of marine sediment cores to volcanic hazard assessments: present examples and future perspectives.

Chris Satow [1*], Sebastian Watt [2], Mike Cassidy[2], David Pyle[3] and Yuqiao Natalie Deng[4]

[1] Department of Geography, Royal Holloway, University of London; christopher.satow@rhul.ac.uk
[2] School of Geography, Earth and Environmental Sciences, University of Birmingham, UK
[3] Department of Earth Sciences, University of Oxford, UK
[4] Department of Geography, University College London, UK

Abstract: Rigorous assessment of volcanic hazards relies on setting contemporary monitoring observations within an accurate, longer-term geological context. Revealing that geological context requires 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 a location where marine sediment cores are yet to contribute to hazard assessment and 4. proposing that marine sediment cores can contribute to our understanding of very large eruptions which 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

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1. Marine Sediment Cores and Volcanic Hazard Assessment

1.1. Volcanic Hazard Assessment

Assessment of volcanic hazard requires the integration of data from active monitoring systems such as gas emissions, geodetic height and seismic data (short term hazard assessment), with an understanding of the long-term behaviour of a volcanic system (Fig. 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 (Pyle and Barclay, 2020[1]). 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 years or more) (e.g. Coussens et al., 2016). The volcanogenic deposits and their host sediment can be analysed in the laboratory to inform on the magma chemistry, eruption size (Cashman and Rust, 2020) and date (Table 1), and therefore provide insights of a volcanoes range of eruption styles, magnitudes and 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 caldera or sector collapse (e.g. Cassidy et al. 2014, Coussens et al., 2016) or external environmental changes such as sea-level change (e.g. Kutterolf et al., 2019, Satow et al. 2021).

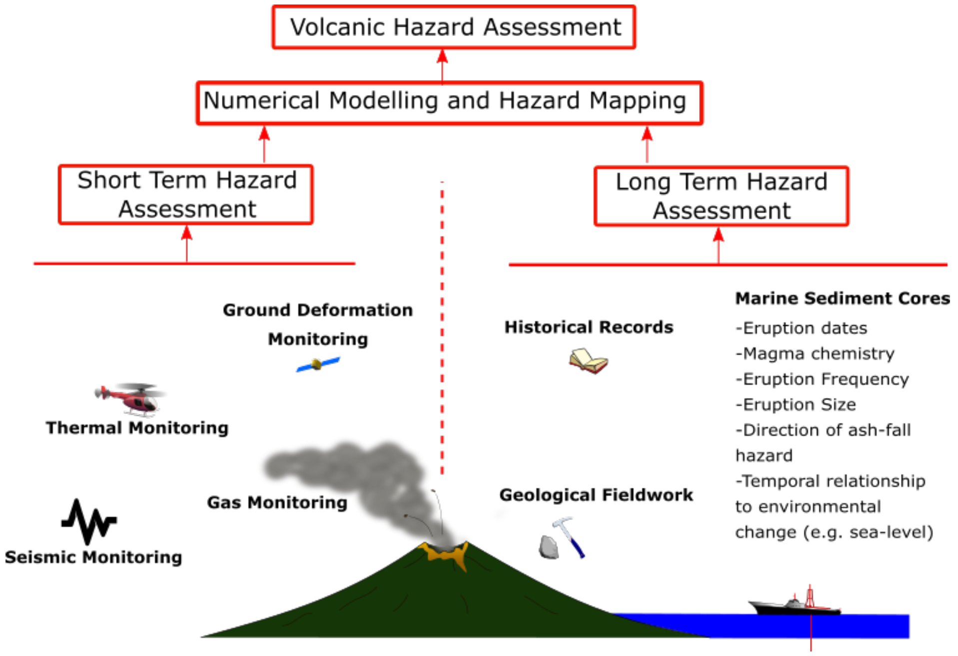

Figure 1.1 Schematic representation of the sources of information contributing to a volcanic hazard assessment for an island or coastal volcano, with the details of the types of information which can be provided by marine sediment cores.

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 100s to 100,000s 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 Mahony et al. (2020). 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: Deep Sea Drilling Project, Ocean Drilling Program and International Ocean Discovery Program. There have been many more, 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 which are too shallow for large vessels and deep drilling techniques. If added to fig. 1.2, these cores would improve the sampling density closer to the volcanic coasts and islands, although their temporal extent is generally much shorter than that covered by the coring projects in Fig. 1.2, and they are unlikely to capture evidence of eruptive events prior to the Quaternary.

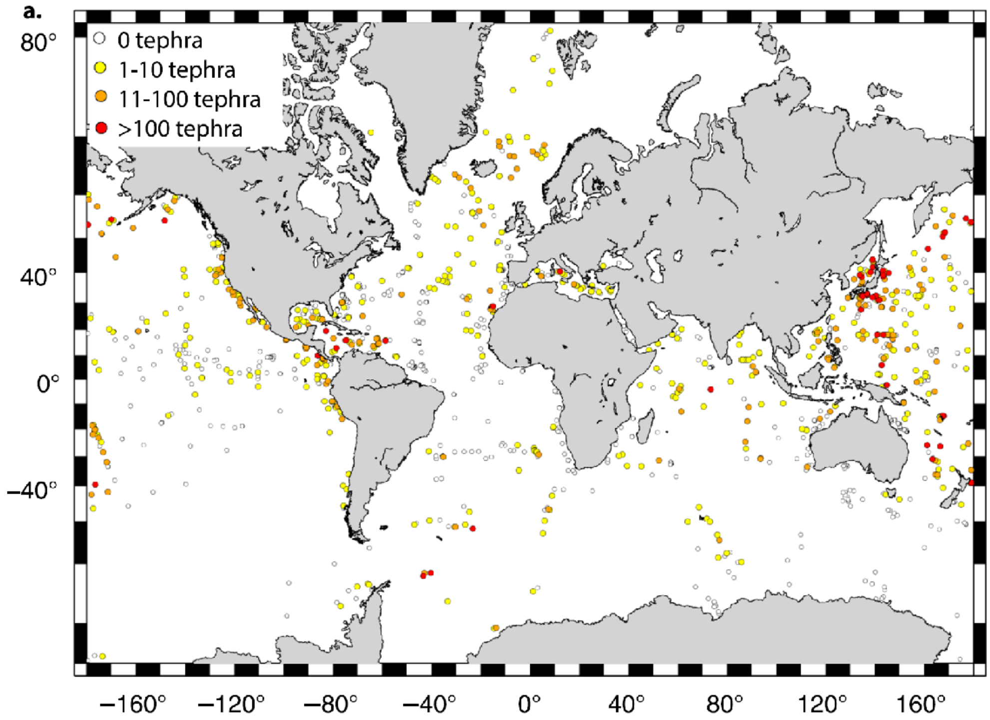

Figure 1.2 (reproduced from Mahony et al. 2020). Distribution of ocean sediment cores from DSDP, ODP and IODP cruises as reflected in the VOLCORE database, coloured to indicate the number of tephra layers found at each site. Coastal areas where cores record many ash deposits (e.g Japan, Caribbean) reflect highly active volcanic systems in these areas. More remote cores with many tephra layers indicate locations close to volcanic islands or simply very long cores. The VOLCORE database (Mahony et al. 2020) can be found at https://doi.org/10.1594/PANGAEA.934363

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 through 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 events of lower magnitude or intensity, that may typify a volcano's activity.

The length of cores and the local sedimentation rate dictates the timescale of eruptive record retrieved via coring. Because 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 (Brown et al. 2014) 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 more difficult to identify (Lowe et al., 2011).

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 (Mahony et al. 2020) (Figure 1.2). Some regions are therefore understudied from both marine and subaerial record perspectives. For instance, the Kuril islands as well as Indonesia, Philippines and Papua New Guinea have far fewer eruptions in the LaMeve database than Japan (Brown et al 2015), but this representation is not proportional to historical levels of volcanism in these regions (cf. Watt et al., 2014). There is also the possibility of over-recording events, though 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 analysis of roughness, sorting and elongation may be employed (Cassidy et al. 2014).

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 (https://www.ncei.noaa.gov/maps/sample_index/).

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 (Schindlbeck et al. 2013, Cassidy et al., 2014, Freundt et al. 2021), and these are exemplified in figure 2.1. 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 e.g. Insinga et al. 2008), geochemistry (Wulf et al. 2019) and potentially eruption dates through direct dating (Bosken and Schmidt, 2019, Yoon et al. 2022)

- Non-visible (crypto) tephra deposits. These are also primary fallout deposits, but where the concentrations 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. Finding such layers can be helped by techniques such as magnetic susceptibility and high-resolution XRF core scanning (Balascio et al. 2015, Kylander et al. 2011), but the most rigorous methodology requires continuous sampling of the core and processing of the samples to extract any shards (see Wallace et al. 2022).

- Pyroclastic density current deposits and their offshore equivalents, representing a transition to turbidity currents (e.g. Trofimovs et al., 2006; Schindlbeck et al. 2013, Cassidy et al. 2014, Freundt et al. 2021)

- Reworked volcaniclastic deposits (turbidites, flood deposits, landslides. e.g. Watt et al. 2021, Cassidy et al. 2014, Freundt et al. 2021)

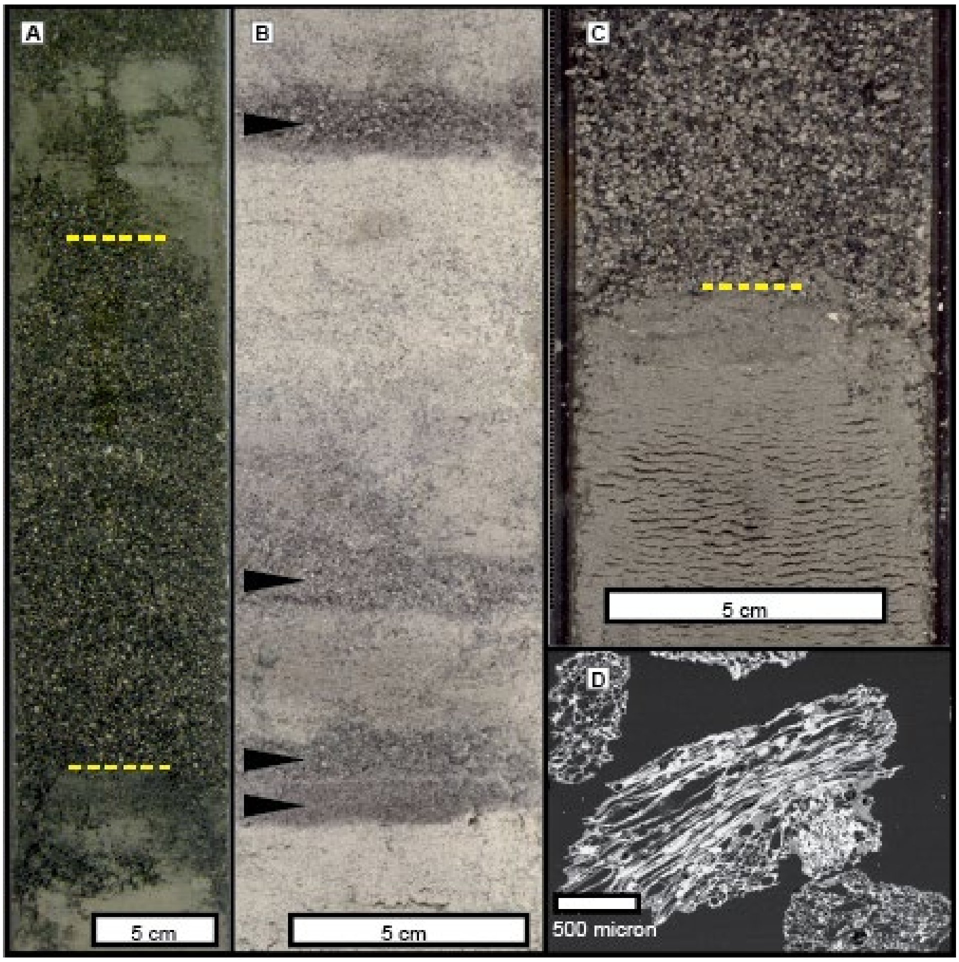

Figure 2.1 Examples of cored marine volcaniclastic deposits offshore Montserrat, Lesser Antilles. A: An andesitic volcaniclastic turbidite (core JR123-21), bounded by hemipelagic mud, with the main sandy deposit bounded by the yellow lines. At the deposit scale, the features of such deposit can share 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 doesn't 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 https://web.iodp.tamu.edu (IODP images) and courtesy of British Ocean Sediment Core Research Facility (A).

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 (Villemant et al. 2022). This is done primarily through geochemical characterization of the juvenile glass component of the deposits which 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 (Wallace et al. 2022). 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 (fig. 2.2). 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 the eruptive frequency for that volcano. Where the geochemical comparison is ambiguous, multivariant data analyses such as principle components analysis may be deployed (Wallace et al. 2022). 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 also enhancing the known record of volcanic activity for that volcano.

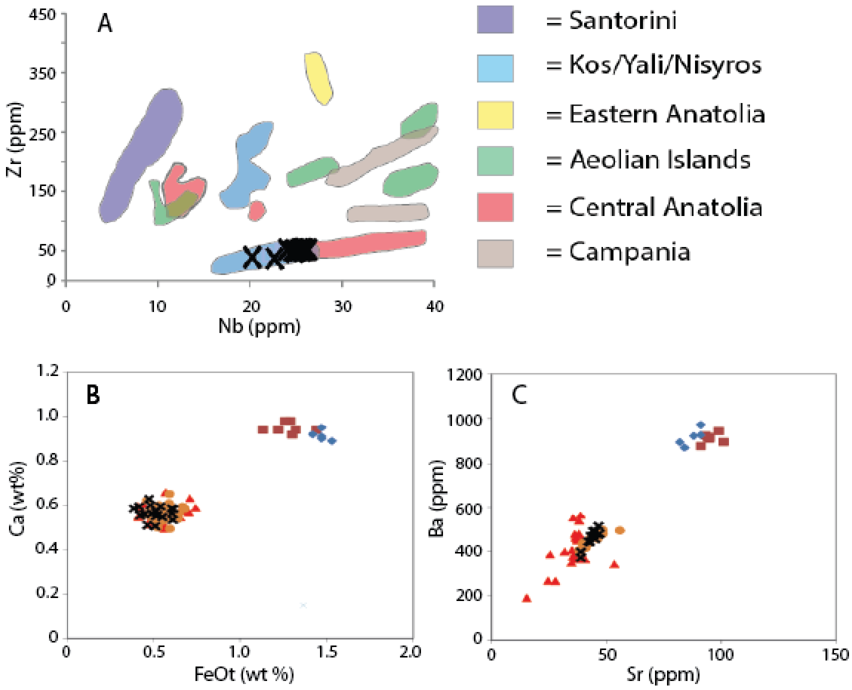

Figure 2.2. Geochemical comparison (juvenile glass) of an example marine tephra deposit (black crosses) with a known age found in an Eastern Mediterranean marine sediment core (ODP 967) to undated proximal deposits from various candidate volcanoes or volcanic regions in the Eastern Mediterranean. A. (adapted from Satow et al. 2012) shows that the analyses most closely match proximal deposits on the islands of Kos, Yali and Nisyros. B and C (adapted from Satow et al. 2015) show that the marine tephra (black crosses) matches closely 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 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 exist already 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 (e.g. Cassidy et al. 2014, Wulf et al. 2019, Satow et al. 2021). 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.

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.	Hajdas et al. (2021), Wall-Palmer et al. (2014) Zhang et al. (in prep),
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.	Wall-Palmer et al. (2014), Matsu'ura et al. (2018)
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.	Li et al. (2021), Zhang et al. (in prep)
OSL and ESR	Volcanogenic deposits can be dated directly by OSL (Optically Stimulated Luminescence) using the glass shards, or quartz or feldspar crystals associated with the deposit. Indirect dating of the surrounding sediment is also possible and has a much more established methodology.	Li et al. (2021), Yoon et al. 2022, Kim et al. 2019, Zhang et al. (in prep), Bosken and Schmidt, 2020
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.	(Wallace et al. 2022) (Salisbury et al. 2012)
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.	Li et al. (2021), Grant et al. (2012) Wall-Palmer et al. (2014)
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).	Li et al. (2021), Ton-That et al. (2001)

Table 1. Methods of age determination in marine sediment cores. Chronological information from all the techniques can be integrated through a Bayesian age modelling approach (Zhang et al. in prep). 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.

2.3 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 (e.g. Schindlbeck et al. 2018, Primerano et al., 2021). 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 (e.g. Pillans et al. 1993, Wulf et al. 2019, Satow et al. 2021) and tephrostratigraphies also track the changing composition of erupted products over time (e.g. Shane et al. 2006). Such information is needed to produce justifiable Bayesian hazard event trees (e.g. Constantinescu et al. 2022, Martí et al. 2008) which attempt to quantify the contemporary volcanic hazard. Here we briefly summarise three example volcanic locations at the local, national and international scales which demonstrate how marine ash deposits can contribute to volcanic hazard assessments.

2.3.1 Santorini, Greece

Santorini is considered by some to be one of the world's most dangerous volcanoes (Vougioukalakis et al. 2016). 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 (Parks et al. 2015, Pyle 2017). There is also a known tsunami risk from both the Santorini volcano itself, and from the neighbouring submarine volcano Kolumbo (Dominey-Howes, 2002). Marine sediment cores have been critical in deciphering the long-term behaviour of Santorini (Wulf et al. 2019, Satow et al. 2019, 2021). 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 (Wulf et al. 2019, Kutterolf et al. 2021). These layers not only inform on eruption magnitudes (Kutterolf et al. 2021) 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 (Wulf et al. 2019). As the marine cores which contain the ash layers also preserve a sea level record (Grant et al. 2017), an hypothesis that sea level change could affect the frequency of eruptive activity could be investigated (Satow et al. 2021) with implications for the existing hazard assessment (section 3, Vougiokalakis et al. 2016). 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 independent of the sea level influence (Satow et al. 2021).

2.3.2 Vesuvius, Phleagran Fields and Ischia Island, Italy.

The volcanically famous region of Campania in Italy is home to 3 million people and hosts a wide range of volcanic hazards. The island of Ischia alone is home to 65,000 people [Selva, 2019]. Primerano et al. (2021) demonstrated how supplementing studies of proximal eruptive deposits with 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 could identify deposits over 10m or so in thickness eg. Calanchi et al. 1994). The resulting reconstruction improves assessments of future eruption hazard parameters such as plume height and the total volume of eruptive material (magnitude of eruption).

Similarly in the neighbouring Bays of Salerno and Naples, Insinga et al. (2008) showed that tephra layers in 9 marine gravity cores allowed new dates to be applied to previously unknown medieval eruptions postdating the 79A.D. eruption of Vesuvius. Similarly Sacchi et al. (2020) detailed marine tephra deposits from the Holocene which 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 (e.g. Macedonio et al. 2008) and has already contributed to updating of the hazard assessment (Rolandi, 2010, Troise et al. 2022, Italian Department of Civil Protection, 2019).

2.3.3 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 10km of its summit. While some of these volcanoes (e.g. Arenal) have established eruption histories to effectively inform the risk assessment, others (e.g. Ceboruco or Tacana) lack these, resulting in high volcanic risk ratings (ranking volcanoes based on their risk to society) (Guimaraes et al. 2021). 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 for specific volcanoes and also for the Central American volcanic arc as a whole. Kutterolf et al. (2008) derive erupted magma volumes and rates back to 200ka, while Schindlbeck et al. (2016) define ages (and therefore constraints on eruption frequency) for 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) assessment must rely instead on historical and geological records of eruptions (Guimaraes et al. 2021). Ceboruco, Mexico (Constantinescu et al. 2022) is such an example. A probabilistic volcanic hazard assessment was built upon the geological record of small, medium and large (Plinian) eruptions for the volcano (Serion and Siebe, 2008, Sieron et al. 2019), including information from ash deposits in marine sediment cores.

3. New opportunities to use marine sediment cores to improve volcanic hazard assessments; an example of 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 the Long-Term Hazard Assessment (fig. 1) being poorly informed. Brown et al. (2014) and Rougier (2018) proposed that, while most regions of the world become more underrepresented further back in time (in the LaMEVE database- Brown et al. 2014- of explosive eruptions), several regions are chronically underrepresented throughout their histories. These are: Melanesia, Indonesia, Kamchatka and Mainland Asia, The Kuril Islands and Alaska. All of these could thus benefit from research into their marine core records (fig. 1.2). We draw particular attention to the island of Sumatra, part of the Western Sunda Arc (Indonesia) as an example of a location where analysis of tephra in marine sediment cores could contribute significantly to long-term hazard assessment.

The western Sunda Arc is one of the most volcanically active regions in the world and hosted both the largest known eruption of the last 2 million years (the Younger Toba Tuff) and the famous 1883 eruption of Krakatoa which 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 (Salisbury et al. 2012). 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 (Mahoney et al. 2020) 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.

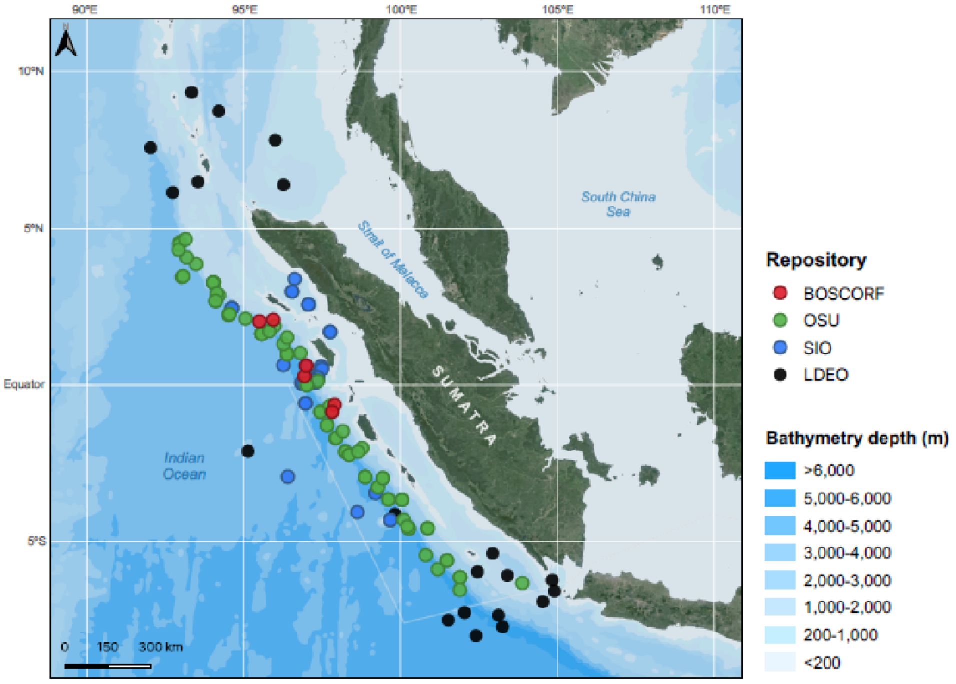

Figure: 3.1- map of existing marine sediment cores offshore the island of Sumatra (Western Sunda Volcanic Arc) from https://www.ncei.noaa.gov/maps/sample_index/ Core repositories listed are: Oregon State University (OSU), Scripts Institution of Oceanography (SIO), BOSCORF (British Ocean Sediment CORe Facility) and Lamont-Doherty Core Repository (LDEO).

The island of Sumatra itself (fig. 3.1) is home to over 4 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. An major eruption in this area could therefore initiate a cascade of systems and supply chain failures across the globe (Mani et al. 2021). A modelled eruption of Mt Merapi, Java created an estimated US$2.51 trillion of global GDP output loss (Mahalingham et al. 2018).

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 5 previously unknown major explosive eruptions within the last 35 kyrs [Salisbury et al. 2012]. No cryptotephra work has yet been undertaken and 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 (fig. 3.1) are already available. An existing regional tephrostratigraphy comprising 20 dated deposits (Bouvet de Maisonneauve and Bergal-Kuvikas, 2019) 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 potential for global impacts on the climate and civilization (Cassidy and Mani, 2022). 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 (Mani et al., 2021). Currently, the global frequency of such very large eruptions is estimated by measuring sulfate peaks in dated ice core records from both northern and southern hemispheres. Approximate recurrence estimates for eruptions equivalent to magnitude 7 are 625 years (Lin et al 2021) over a 60,000 year timeframe and even shorter (444 years) since the last glacial maximum (Sigl et al. 2022). However, geological records that statistically adjust for completeness, suggest a much longer recurrence timescale for magnitude 7 eruptions of 1200 years (Rougier et al., 2018), 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 (Timmerick et al., 2021) - remain unassigned. However new advances in sulfur isotope analysis can provide information on the latitude of the source (Burke et al 2019). The combination of ice core records with analysis of dated tephras in regional marine sediment cores, and new approaches to modelling (Aubry et al. 2022; Marshall et al, 2022) 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 assist in source attribution for those events. This approach has worked in the subaerial realm, to identify the 1257 Samalas eruption of Rinjani volcano (Lavinge et al., 2013) and the Changbaishan eruption in 946 (Oppenheimer et al., 2017), and marine sediment cores have been successfully used to attribute Icelandic volcanoes to sulfate peaks in Greenland ice cores (Abbott and Davies, 2012).

5. Summary

Volcanic deposits in marine sediment cores can contribute valuable information to volcanic hazard assessments. 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 change. Perhaps most importantly, they are the only way to directly sample much of the material erupted by island and coastal volcanoes. Several databases (VOLCORE- Mahony et al. 2020, LaMeve- Brown et al. 2014, and the NOAA's index to Marine and Lacustrine Geological Samples) can facilitate volcanological researchers in the identification of existing sediment cores which may inform their research and hazard assessments. We outlined three locations which 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 integration of marine ash records with sulfate concentrations in ice cores.

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References (currently in Harvard format, will be correctly formatted for Geosciences at the editing stage)

1. Abbott and Davies (2012) Volcanism and the Greenland ice-cores: the tephra record. Earth Science Reviews 115, 173-191 https://doi.org/10.1016/j.earscirev.2012.09.001
2. Aubry, T.J., Farquharson, J.I., Rowell, C.R. et al. (2022) Impact of climate change on volcanic processes: current understanding and future challenges. Bull Volcanol 84, 58. https://doi.org/10.1007/s00445-022-01562-8
3. N. Calanchi, G. Gasparotto, C. Romagnoli. Glass chemistry in volcaniclastic sediments of ODP Leg 107, Site 650, sedimentary sequence: provenance and chronological implications. J. Volcanol. Geoth. Res., 60 (1994), pp. 59-85
4. Cassidy, M., Watt, S. F. L., Palmer, M. R., Trofimovs, J., Symons, W., Maclachlan, S. E., & Stinton, A. J. (2014). Construction of volcanic records from marine sediment cores: a review and case study (Montserrat, West Indies). Earth Science Reviews, 138, 137-155. https://doi.org/10.1016/j.earscirev.2014.08.008
5. Cassidy and Mani (2022)Huge volcanic eruptions: time to prepare. Nature 608, 469-471 (2022)doi: https://doi.org/10.1038/d41586-022-02177-x
6. Cashman and Rust (2020) Far-travelled ash in past and future eruptions: combining tephrochronology with volcanic studies. Volume35, Issue1-2. Special Issue: Tephrochronology as a global geoscientific research tool
7. Coussens et al. (2016) The relationship between eruptive activity, flank collapse, and sea level at volcanic islands: A long-term (>1 Ma) record offshore Montserrat, Lesser Antilles. Geochemistry, Geophysics, Geosystems. 17, doi:10.1002/2015GC006053.
8. Constantinescu et al. (2022) Probabilistic volcanic hazard assessment at an active but under-monitored volcano: Ceboruco, Mexico. Journal of Applied Volcanology (2022) 11:11 https://doi.org/10.1186/s13617-022-00119-w
9. Balascio, N. et al. (2015). Investigating the Use of Scanning X-Ray Fluorescence to Locate Cryptotephra in Minerogenic Lacustrine Sediment: Experimental Results. In: Croudace, I., Rothwell, R. (eds) Micro-XRF Studies of Sediment Cores. Developments in Paleoenvironmental Research, vol 17. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9849-
10. Brown et al. (2014) Characterisation of the Quaternary eruption record: analysis of the Large Magnitude Explosive Volcanic Eruptions (LaMEVE) database. Journal of Applied Volcanology. 2:3
11. Burke et al. (2019) Stratospheric eruptions from tropical and extra-tropical volcanoes constrained using high-resolution sulphur isotopes in ice cores. EPSL 521, pp113-119. https://doi.org/10.1016/j.epsl.2019.06.006
12. Bosken and Schmidt (2020) Direct and indirect luminescence dating of tephra: a review. JQS. 35 (1-2) DOI: 10.1002/jqs.3160
13. Bouvet de Maisonneauve and Bergal-Kuvikas (2019) Timing, magnitude and geochemistry of major Southeast Asian Volcanic eruptions: identifying tephrochronologic markers. JQS 1-16 DOI: 10.1002/jqs.3181
14. Dominey-Howes, D. (2002) Documentary and Geological Records of Tsunamis in the Aegean Sea Region of Greece and their Potential Value to Risk Assessment and Disaster Management. Natural Hazards 25 pp195-224
15. Freundt, A., Schidelbeck-Belo, J.C., Kutterholf, S., Hopkins, J.L. (2021) Tephra layers in the marine environment: a review of properties and emplacement processes. From: Di Capua, A., De Rosa, R., Kereszturi, G., Le Pera, E., Rosi, M. and Watt, S. F. L. (eds) Volcanic Processes in the Sedimentary Record: When Volcanoes Meet the Environment. Geological Society, London, Special Publications, 520, https://doi.org/10.1144/SP520-2021-50
16. Grant et al. (2017) Sea-Level variability over 5 glacial cycles. Nat. Commun. 5 5076 DOI: 10.1038/ncomms6076 (2014).
17. Guimarães LF, Nieto-Torres A, Bonadonna C and Frischknecht C (2021) A New Inclusive Volcanic Risk Ranking, Part 2: Application to Latin America. Front. Earth Sci. 9:757742. doi: 10.3389/feart.2021.757742
18. Hajdas, I., Ascough, P., Garnett, M.H. et al. Radiocarbon dating. Nat Rev Methods Primers 1, 62 (2021). https://doi.org/10.1038/s43586-021-00058-7
19. Insinga et al. (2008) The proximal marine record of Somma-Vesuvius volcanic activity in the Naples and Salerno bays, Eastern Tyrrhenian Sea, during the last 3 kyrs. JVGR 117 170-186. http://dx.doi.org/10.1016/j.jvolgeores.2007.07.011
20. Kim, J.C., Chang, T.S., Yi, S., 2019. OSL chronology of the Huksan mud Belt, southeastern Yellow sea, and its paleoenvironmental implications. Quat. Int. 503, 170–177.
21. Italian Department of Civil Protection (2019) Update of the National Emergency Plan for Vesuvius. https://www.protezionecivile.gov.it/en/approfondimento/update-national-emergency-plan-vesuvius
22. Kutterolf et al. (2008) Pacific offshore record of plinian arc volcanism in Central America: 2. Tephra volumes and erupted masses. Geochemistry, Geophysics, Geosystems. 9, doi:10.1029/2007GC001791
23. Kutterolf, S. et al. (2019) Milankovitch frequencies in tephra records at volcanic arcs: The relation of kyr-scale cyclic variations in volcanism to global climate changes. Quaternary Science Reviews 204, 1-16
24. Kylander ME, Lind EM, Wastegård S, Löwemark L. Recommendations for using XRF core scanning as a tool in tephrochronology. The Holocene. 2012;22(3):371-375. doi:10.1177/0959683611423688
25. Lavigne et al. (2013) Source of the great A.D. 1257 mystery eruption unveiled, Samalas volcano, Rinjani Volcanic Complex, Indonesia. PNAS 110 (42) 16742-16747 https://doi.org/10.1073/pnas.1307520110
26. Li et al. (2021) A review of current and emerging approaches for Quaternary marine sediment dating. Science of the Total Environment 780 https://doi.org/10.1016/j.scitotenv.2021.146522
27. Lin et al. (2021) Magnitude, frequency and climate forcing of global volcanism during the last glacial period as seen in Greenland and Antarctic ice cores (60–9 ka) Clim. Past, 18, 485–506 https://doi.org/10.5194/cp-18-485-2022

28. Loughlin, S.C., Sparks, R.S.J., Sparks, S., Brown, S.K., Jenkins, S.F. and Vye-Brown, C. eds., 2015. Global volcanic hazards and risk. Cambridge University Press
29. Lowe, D. (2011) Tephrochronology and its application: a review. Quaternary Geochronology 6. p107-153
30. Mahalingam, A. et al. Impacts of Severe Natural Catastrophes on Financial Markets. https://www.jbs.cam.ac.uk/faculty-research/centres/risk/publications/natural-catastrophe-and-climate/impacts-of-severe-naturalcatastrophes-on-financial-markets/ (2018).
31. Mahoney et al. (2020) VOLCORE, a global database of visible tephra layers sampled by ocean drilling. Nature Scientific Data https://doi.org/10.1038/s41597-020-00673-1
32. Mani et al. (2021) Global catastrophic risk from lower magnitude volcanic eruptions. Nature Communications https://doi.org/10.1038/s41597-020-00673-1
33. Marshall, L.R., Maters, E.C., Schmidt, A. et al. (2022) Volcanic effects on climate: recent advances and future avenues. Bull Volcanol 84, 54. https://doi.org/10.1007/s00445-022-01559-3
34. Martí J, Aspinall WP, Sobradelo R, Felpeto A, Geyer A, Ortiz R, Baxter P, Cole P, Pacheco J, Blanco MJ, Lopez C (2008) A long-term volcanic hazard event tree for Teide-Pico Viejo stratovolcanoes (Tenerife, Canary Islands). J Volcanol Geotherm Res 178(3):543–552
35. Macedonio, G. et al. (2008) Ash fallout scenarios at Vesuvius: Numerical simulations and implications for hazard assessment Journal of Volcanology and Geothermal Research 178 (2008) 366–377
36. Matsu'ura et al. (2018) Using Late and Middle Pleistocene tephrostratigraphy and cryptotephrostratigraphy to refine age models of Holes ODP1150A and ODP1151C, NW Pacific Ocean: A cross-check between tephrostratigraphy and biostratigraphy. Quaternary Geochronology 47 29-53. https://doi.org/10.1016/j.quageo.2018.03.012
37. Oppenheimer et al. (2017). Multi-proxy dating the 'Millennium Eruption' of Changbaishan to late 946 CE. Quaternary Science Reviews, v. 158, p.164-171. doi:10.1016/j.quascirev.2016.12.024.
38. Parks, M.M. et al (2012). Evolution of Santorini volcano dominated by episodic and rapid fluxes of melt from depth. Nature Geosci. 5, 749-754 (2012).
39. Pillans et al. (1993). Revision of the marine chronology in the Wanganui Basin, New Zealand, based on the isothermal plateau fission-track dating of tephra horizons. Sedimentary Geology, 82, 299-310.
40. Primerano et al. (2021) Reconstructing fallout features and dispersal of Cretaio Tephra (Ischia Island, Italy) through field data analysis and numerical modelling: Implications for hazard assessment. JVGR 415. https://doi.org/10.1016/j.jvolgeores.2021.107248
41. Pyle, DM (2016), Field observations of tephra fallout, in Volcanic Ash: Hazard Observation, eds. S Mackie, K Cashman, H Ricketts, A Rust, M Watson, Elsevier, pp 25-38. ISBN 9780081004050
42. Pyle, DM (2017) What can we learn from records of past eruptions to better prepare for the future? In: Fearnley, C.J., Bird, D.K., Haynes, K., McGuire, W.J., Jolly, G. (eds), 'Observing the Volcano World', Advances in Volcanology, Springer, Cham. pp 445-462. https://doi.org/10.1007/11157_2017_5
43. Pyle, DM and Barclay J (2020) Historical records of volcanic eruptions deserve more attention. Nature Reviews Earth & Environment. https://doi.org/10.1038/s43017-020-0044-z
44. Rolandi, G. (2010) Volcanic hazard at Vesuvius: An analysis for the revision of the current emergency plan. Journal of Volcanology and Geothermal Research 189 (2010) 347–362
45. Rougier et al. (2018) Regional and global under-recording of large explosive eruptions in the last 1000 years. Journal of Applied Volcanology 7:1 DOI 10.1186/s13617-017-0070-9
46. Sacchi et al. (2020) The Holocene marine record of unrest, volcanism, and hydrothermal activity of Campi Flegrei and Somma Vesuvius. In: B. De Vivo, H.E. Belkin and G. Rolandi 810 (Eds.) Vesuvius, Campi Flegrei, and Campanian Volcanism, Elsevier Inc., Amsterdam, l435-469
47. Salisbury et al. (2012) Deep-sea ash layers reveal evidence for large, late Pleistocene and Holocene explosive activity from Sumatra, Indonesia. Journal of Volcanology and Geothermal Research 231-232. pp61-71.
48. Satow et al. (2019) Detection and Characterisation of Eemian Marine Tephra Layers within the Sapropel S5 Sediments of the Aegean and Levantine Seas. Quaternary, 3(1), 6; https://doi.org/10.3390/quat3010006
49. Satow, C., Gudmundsson, A., Gertisser, R., Ramsey, C.B., Bazargan, M., Pyle, D.M., Wulf, S., Miles, A.J. and Hardiman, M., 2021. Eruptive activity of the Santorini Volcano controlled by sea-level rise and fall. Nature Geoscience, pp.1-7.
50. Schindlbeck, J.C., Kutterolf, S., Freundt, A., Scudder, R.P., Pickering, K.T., Murray, R.W., 2013. Emplacement processes of submarine volcaniclastic deposits (IODP Site C0011, Nankai Trough). Mar. Geol. 343, 115–124.
51. Schindlbeck et al. (2016) Late Cenozoic tephrostratigraphy offshore the southern Central American Volcanic Arc. 1. Tephra ages and provenance. Geochem. Geophys. Geosyst., 17, doi:10.1002/ 2016GC006503.
52. Schindlbeck, J.C., Kutterolf, S., Straub, S.M., Andrews, G. D.M., Wang, K-L, and Vautravers, M.J. (2018) One Million Years tephra record at IODP Sites U1436 and U1437: Insights into explosive volcanism from the Japan and Izu arcs. Island Arc. 27 https://doi.org/10.1111/iar.12244

53. Selva et al. (2019) Multiple natural hazards at volcanic islands: a review for the Ischia volcano (Italy). J Appl. Volcanol. 8, 5 (2019). https://doi.org/10.1186/s13617-019-0086-4
54. Sieron, K and Siebe, C. (2008) Revised stratigraphy and eruption rates of Ceboruco stratovolcano and surrounding monogenetic vents (Nayarit, Mexico) from historical documents and new radiocarbon dates Journal of Volcanology and Geothermal Research 176 (2008) 241–26
55. Sieron, K., Ferres, D., Siebe, C. et al. Ceboruco hazard map: part I - definition of hazard scenarios based on the eruptive history. J Appl. Volcanol. 8, 9 (2019). https://doi.org/10.1186/s13617-019-0088-2
56. Sigl et al. (2022) Timing and climate forcing of volcanic eruptions for the past 2,500 years Nature 523 543-459 www.nature.com/doifinder/10.1038/nature14565
57. Shane, P.A.R., Sikes, E.L., and Guilderson, T.P., (2006). Tephra beds in deep-sea cores off northern New Zealand: implications for the history of Taupo volcanic zone, Mayor Island and White Island volcanoes. Journal of Volcanology and Geothermal Research 154, 276e290.
58. Timmerick et al. (2021) The unidentified eruption of 1809, a climatic cold case. Clim. Past, 17, 1455–1482, https://doi.org/10.5194/cp-17-1455-2021
59. Ton-That, T., Singer, B., Paterne, M., 2001. 40Ar/39Ar dating of latest Pleistocene (41ka) marine tephra in the Mediterranean Sea: implications for global climate records. Earth and Planetary Science Letters 184, 645e658.
60. Trofimovs, J. et al. (2006) Submarine pyroclastic deposits formed at the Soufrière Hills volcano, Montserrat (1995–2003): What happens when pyroclastic flows enter the ocean. Geology 34, 7 https://doi.org/10.1130/G22424.1
61. Troise, C. et al. (2022) Mitigating the highest volcanic risk in the World: a multidisciplinary strategy for the Neapolitan area. EGU22, Abstracts for the 24th EGU General Assembly, Vienna, Austria and Online. https://doi.org/10.5194/egusphere-egu22-12949
62. Villemant B, Le Friant A, Caron B, Del Manzo G, Lafuerza S, Emmanuel L, Ishizuka O, Guyard H, Labourdette N, Michel A and Hidalgo S (2022) A 1.5 Ma Marine Record of Volcanic Activity and Associated Landslides Offshore Martinique (Lesser Antilles): Sites U1397 and U1399 of IODP 340 Expedition. Front. Earth Sci. 10:767485. doi: 10.3389/feart.2022.767485
63. Vougiokalakis et al. (2016) Volcanic Hazard Assessment at Santorini Volcano: a review and a synthesis in the light of the 2011-2012 Santorini unrest. Bulletin of the Geological Society of Greece 50 274-283 http://dx.doi.org/10.12681/bgsg.11728
64. Watt, S.F.L., Karstens, J., Berndt, C. (2021). Volcanic-Island Lateral Collapses and Their Submarine Deposits. In: Roverato, M., Dufresne, A., Procter, J. (eds) Volcanic Debris Avalanches. Advances in Volcanology. Springer, Cham. https://doi.org/10.1007/978-3-030-57411-6_10
65. Wallace et al. (2022) Community established best practice recommendations for tephra studies—from collection through analysis Nature Scientific Data. https://doi.org/10.1038/s41597-022-01515-y
66. Wulf, S. et al. (2019) Advancing Santorini's tephrostratigraphy: new glass geochemical data and improved marine-terrestrial tephra correlations for the past ~360 kyrs. Earth Sci. Rev. https://doi.org/10.1016/j.earscirev.2019.102964 (2020).
67. Wall-Palmer et al. (2014) Late Pleistocene stratigraphy of IODP Site U1396 and compiled chronology offshore of south and south west Montserrat, Lesser Antilles. Geochemistry, Geophysics, Geosystems. https://doi.org/10.1002/2014GC005402
68. Yoon et al. (2022) Multi dating approach of long marine core sediments from the south-eastern continental shelf of Korea: Comparison of SAR OSL, TT-OSL and pIRIR dates. Quaternary Geochronology 73 https://doi.org/10.1016/j.quageo.2022.101338
    Zhang et al. (in prep).