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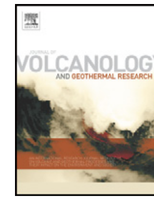

Hydroacoustic, infrasonic and seismic monitoring of the submarine eruptive activity and sub-aerial plume generation at South Sarigan, May 2010

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A B S T R A C T

Explosive submarine volcanic processes are poorly understood, due to the difficulties associated with both direct observation and continuous monitoring. In this study hydroacoustic, infrasound, and seismic signals recorded during the May 2010 submarine eruption of South Sarigan seamount, Marianas Arc, are used to construct a detailed event chronology. The signals were recorded on stations of the International Monitoring System, which is a component of the verification measures for the Comprehensive Nuclear-Test-Ban Treaty. Numerical hydroacoustic and infrasound propagation modelling confirms that viable propagation paths from the source to receivers exist, and provide traveltimes allowing signals recorded on the different technologies to be associated. The eruption occurred in three stages, separated by three-hour periods of quiescence. 1) A 46 h period during which broadband impulsive hydroacoustic signals were generated in clusters lasting between 2 and 13 min. 95% of the 7602 identified events could be classified into 4 groups based on their waveform similarity. The time interval between clusters decreased steadily from 80 to 25 min during this period. 2) A five-hour period of 10 Hz hydroacoustic tremor, interspersed with large-amplitude, broadband signals. Associated infrasound signals were also recorded at this time. 3) An hour-long period of transient broadband events culminated in two large-amplitude hydroacoustic events and one broadband infrasound signal. A speculative interpretation, consistent with the data, suggests that during phase (1) transitions between endogenous dome growth and phreatomagmatic explosions occurred with the magma ascent rate accelerating throughout the period; during phase (2) continuous venting of fragmented magma occurred, and was powerful enough to breach the sea surface. During the climactic phase (3) discrete powerful explosions occurred, and sufficient seawater was vaporised to produce the contemporaneous 12 km altitude steam plume.

1. Introduction

Approximately a quarter of Earth's explosive volcanism occurs beneath the sea surface (White et al., 2003a). However, due to the difficulties of working in the submarine environment there are few direct observations of explosive underwater eruptive activity (e.g., Chadwick et al., 2008; Resing et al., 2011). Therefore, the eruption processes and hazards posed by submarine explosive volcanism are less well understood than at similar sub-aerial volcanoes (White et al., 2003b).

Although direct observation of explosive activity at submarine volcanoes using Remotely Operated Vehicles (ROVs) has become feasible, these field campaigns are expensive and only observe volcanic activity at times of ROV dives. For example, Chadwick et al. (2008) describe extraordinary video footage of explosive eruptions at NW Rota-1 volcano, Marianas Arc, but the ROV only observed the vent for 13.5 h during a five day period. To aid an understanding of the eruption chronology, Chadwick et al. (2008) also deployed a hydrophone at a distance of 60 m from the vent to provide continuous recordings of the eruptive activity.

Acoustic measurements of underwater eruptive activity do not always require hydrophones close to the source. Due to efficient acoustic propagation within the SOFAR (Sound Fixing and Ranging) waveguide and the low acoustic attenuation in the ocean, low-frequency (<1000 Hz) sound generated by submarine volcanic activity can be detected at ranges of thousands of kilometres (e.g., Richards, 1963; Johnson and Norris, 1972; Northrop, 1974). Such recordings have allowed eruption chronologies to be generated (e.g., Dietz and Sheehy, 1954) and have constrained explosive durations, amplitudes and generation mechanisms (e.g., Dziak and Fox, 2002; Chadwick et

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al., 2008). A recent study of Monowai volcano, Kermadec Arc, combined bathymetric surveys taken 17 days apart with hydroacoustic data at a range of 1835 km (Watts et al., 2012), allowing the rate of edifice growth at an explosive submarine eruption to be estimated.

The construction of the International Monitoring System (IMS) as part of the verification measures for the Comprehensive Nuclear-Test-Ban Treaty (CTBT) has provided an opportunity to extend global studies of acoustic and seismic signals generated by volcanoes. The IMS contains networks of seismic, hydroacoustic and infrasound sensors (alongside radionuclide measurement facilities) for the primary purpose of detecting signals from nuclear test explosions (e.g., Dahlman et al., 2009). Low-frequency acoustic signals propagating in the atmosphere, recorded across the IMS infrasound network at thousands of kilometres from sub-aerial volcanoes, have provided useful information about relative eruption size and eruption chronologies (e.g., Fee et al., 2010; Dabrowa et al., 2011; Matoza et al., 2011). At present, the IMS hydroacoustic data has not been extensively used to identify submarine volcanic events (e.g., Lawrence, 2004). In this paper we begin to address this paucity of literature by describing signals recorded at IMS sensors from the 27 to 29 May 2010 eruption at South Sarigan seamount (16.66 N, 145.78 E), located on the Marianas Arc.

The South Sarigan seamount is part of a volcanic centre comprised of multiple cone edifices, and until the 2010 eruption was considered hydrothermally inactive (Baker et al., 2008). The depth of the South Sarigan summit has not been extensively studied, but is reported to have been between ~200 and 350 m below the sea surface in the years prior to the eruption (Bloomer et al., 1989; McGimsey et al., 2010). On 27 May 2010 discoloured water was observed alongside possible light-coloured debris 8 to 11 km south of Sarigan island, indicating that an eruption at South Sarigan had begun (McGimsey et al., 2010). Seismic sensors within 50 km of South Sarigan recorded pulses of tremor-like signal that merged into continuous tremor by early 29 May 2010. At ~12:00 UTC 29 May 2010 strong local seismic activity occurred simultaneously with the generation of a sub-aerial plume that was estimated to reach an altitude of ~12 km by the Washington Volcanic Ash Advisory Center. Because the plume diminished rapidly on satellite imagery, it has been suggested that the plume composition was dominated by water-vapour (McGimsey et al., 2010).

In the context of the IMS, the South Sarigan eruption is of particular note because it was the first event to generate signals that were detected and associated across the three waveform sensor networks: seismic, hydroacoustic and infrasound (Fig. 1). Integrating the analysis of data across the three technologies helps in constraining both the eruption chronology and the interpretation of the volcanic source processes.

In a volcanological context, the South Sarigan sub-aerial plume is of great interest; observations of sub-aerial products produced by submarine explosive eruptions in ocean water at depths greater than 100 m are rare. Mastin and Witter (2000) list examples at only two volcanoes: Kick 'em Jenny, West Indies and Ritter Island, Papua New

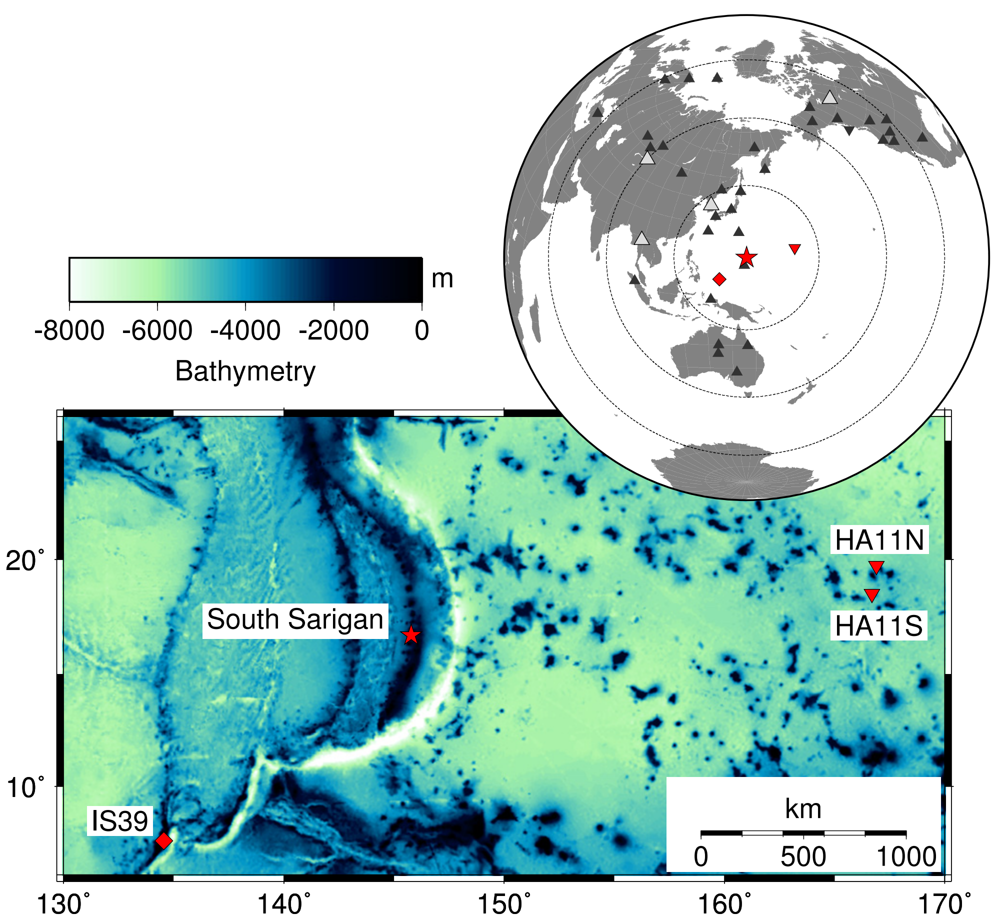

Fig. 1. The location of South Sarigan volcano (star), on the Marianas volcanic arc, and the IMS stations that recorded signals from the May 2010 eruption. Seismic stations are shown as triangles, hydroacoustic stations as inverted triangles, and the IS39 infrasound array as a diamond. The main bathymetric map shows the locations of the two HA11 hydroacoustic triad arrays (north and south) and the IS39 infrasound station with respect to the source. The bathymetry is taken from the ETOPO-2 model (Smith and Sandwell, 1997). The inset shows all the stations that had arrivals associated with the South Sarigan source in the Reviewed Event Bulletin (REB). The large grey triangles indicate seismic stations that recorded arrivals for over 50% of the 47 REB events; each of these is a seismic array (MKAR, Kazakhstan; CMAR, Thailand; KSRS, Rep. of Korea; YKA, Canada).