

Research Paper**CTD DATA PROFILING TO ASSESS THE NATURAL HAZARD OF ACTIVE SUBMARINE VENT FIELDS: THE CASE OF SANTORINI ISLAND**

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Abstract

Almost three quarters of known volcanic activity on Earth occurs in underwater locations. The presence of active hydrothermal vent fields in such environments is a potential natural hazard for the environment, the society, and the economy. Despite its importance for risk assessment and risk mitigation, monitoring of the activity is impeded by the remoteness and the extreme conditions of underwater volcanoes. The large difference of population present on Santorini between the winter and summer seasons, all within a partially enclosed system, make the Santorini-Kolumbo volcanic field, an ideal place for detailed exploration. In 2017, GEOMAR in collaboration with the National and Kapodistrian University of Athens (mission: POS-510 ANYDROS), used an Autonomous Underwater Vehicle (AUV) to map the NE-trending Santorini-Kolumbo line, where it also collected CTD data. Here we present the preliminary results from the 15-hour survey held on the 25th March 2017, during the POS-510 expedition targeting the vent field which is located in the North Basin of Santorini Caldera. Detailed CTD 3D profiles have been reconstructed from the raw data of Santorini's vent field. An anomaly emerges at the depth of 350 m in the Conductivity and Salinity depth profiles, as the CTD sensor is placed directly above the vent sources.

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Anomalies were evident in the 3D maps reconstructed, showing for the first time a rather weak, but underlying hydrothermal vent activity at various locations. As the present results are the first ones produced from this expedition, further investigation is required incorporating the full dataset. Based on those results, the impact of developing appropriate mechanisms and policies to avoid the associated natural hazard is expected to be immense.

Keywords: Santorini, CTD, AUV, hydrothermal vent field

Περίληψη

Σχεδόν τα τρία τέταρτα της γνωστής ηφαιστειακής δραστηριότητας στη Γη συμβαίνουν υποθαλάσσια. Η παρουσία ενεργών υδροθερμικών πεδίων σε τέτοια περιβάλλοντα είναι ένας εν δυνάμει φυσικός κίνδυνος για το περιβάλλον, την κοινωνία και την οικονομία. Παρά την αναγκαιότητα για εκτίμηση και μείωση του κινδύνου, η σωστή παρακολούθηση της δραστηριότητας παρεμποδίζεται από τις ακραίες συνθήκες που επικρατούν στα υποθαλάσσια ηφαίστεια. Η μεγάλη διακύμανση του πληθυσμού που υπάρχει στη Σαντορίνη μεταξύ των εποχών χειμώνα και καλοκαιριού, όλα μέσα σε ένα μερικώς κλειστό σύστημα, κάνουν το ηφαιστειακό πεδίο Σαντορίνης-Κολούμπο ένα ιδανικό μέρος για λεπτομερή εξερεύνηση. Το 2017, το GEOMAR, σε συνεργασία με το Εθνικό και Καποδιστριακό Πανεπιστήμιο Αθηνών (Αποστολή: POS-510 ANYDROS), χρησιμοποίησε Αυτόνομο Υποβρύχιο Οχημα (Autonomous Underwater Vehicle - AUV) για να χαρτογραφήσει τη γραμμή με διεύθυνση ΒΑ Σαντορίνης-Κολομούμπο, όπου συγκέντρωσε μεταξύ άλλων και δεδομένα CTD. Εδώ παρουσιάζουμε τα αρχικά αποτελέσματα της 15ωρης έρευνας που πραγματοποιήθηκε στις 25 Μαρτίου 2017, κατά τη διάρκεια της αποστολής POS-510, η οποία εστίασε στο υδροθερμικό πεδίο που βρίσκεται στη βόρεια λεκάνη της καλδέρας της Σαντορίνης. Λεπτομερή 3D προφίλ CTD έχουν ανακατασκευαστεί από τα πρωτογενή δεδομένα του υδροθερμικού πεδίου της Σαντορίνης. Μια ανωμαλία εμφανίζεται σε βάθος 350 μέτρων στα κατακόρυφα προφίλ της αγωγιμότητας και αλατότητας, καθώς ο αισθητήρας CTD τοποθετείται ακριβώς πάνω από τις πηγές. Ανωμαλίες είναι εμφανείς στους 3D χάρτες που δημιουργήθηκαν, παρουσιάζοντας για πρώτη φορά μια αδύναμη, αλλά υποκείμενη υδροθερμική δραστηριότητα σε διάφορες τοποθεσίες. Δεδομένου ότι τα αποτελέσματα που προκύπτουν είναι τα πρώτα που παράγονται από αυτή την αποστολή, απαιτείται περαιτέρω διερεύνηση στο σύνολο των δεδομένων. Με βάση τα αποτελέσματα αυτά, ο αντίκτυπος της ανάπτυξης κατάλληλων μηχανισμών και πολιτικών για την αποφυγή του σχετικού φυσικού κινδύνου αναμένεται να είναι τεράστιος.

1. INTRODUCTION

Active hydrothermal vent fields are potential natural hazards for the environment, the society, and the economy. Despite its importance for risk assessment and risk mitigation, monitoring of the activity is impeded by the remoteness and the extreme conditions of underwater volcanoes (Cantner et al., 2014; Fuller et al., 2018). Kolumbo underwater volcano, located 7 km NE of Santorini island, features an active hydrothermal vent field (Carey et al., 2011; 2013), which has shown near-explosive dynamics in the recent years (Nomikou, P., et al., 2013; Bakalis et al., 2017). CTD (conductivity, temperature, depth) time series from an earlier expedition in 2010–2011 (Christopoulou et al., 2015), which investigated mainly the northern part of the vent field, have been used to develop an advanced mathematical model based on the Generalized Moments Method (Hansen, 1982) to describe the underlying mechanisms governing the hydrothermal vent activity (Bakalis et al., 2017). The model was further tested successfully in the inactive caldera near Nisyros Island (Dodecanese, Greece) (Bakalis et al., 2018). Santorini consists of three older islands (Thera, Thirasia and Aspronisi), which are arranged in a dissected ring around a flooded caldera, and the post-caldera islands Palea Kameni and Nea Kameni. Subaerial volcanism on Thera began at about 650 ka (Druitt et al., 1999). After the Minoan eruption of 3.6 ka, volcanic activity was concentrated mainly in the intercaldera area building up Palea Kameni and Nea Kameni. The caldera is subdivided into three flat-floored basins (Nomikou et al., 2014) and is connected to the sea via three breaches: one in the NW, and two in the SW. To date, ROV explorations of the caldera floor have failed to find any high-temperature hydrothermal vents (Sigurdsson et al. 2006; Nomikou et al. 2013). However, a low-temperature hydrothermal vent field (18–20 °C) in the NE part of the northern basin extends over 200–300 m², with several hundred bacterial mounds up to 2 m high and several meters in diameter. Slightly north of this hydrothermal field, unusual CO₂-rich fluid pools were discovered at the base of the caldera wall and at shallower depths of 200–250 m, with temperatures about 5°C above that of the bottom waters (Camilli et al., 2015).

The submerged volcanic activity of Santorini and the large difference of population present on the island between the winter and summer seasons, all within a partially enclosed system, make Santorini and its nearby active hydrothermal vent field of Kolumbo, an ideal place for detailed investigation for the potential impact of natural hazards. The main objective of this work is to study high-frequency recorded CTD data in the water column over the hydrothermal vents in Santorini caldera. The data were used to create depth profiles of the oceanographic properties, such as conductivity, temperature and salinity and map their anomalies over active vents. The comprehensive structure includes a scheme for studying CTD time series by developing appropriate stochastic and non-stochastic mathematical models to understand the underlying mechanisms responsible for the activity, as well as lay the foundations for machine-learning methods to assess the risk of associated natural hazards.

2. METHODS

In March 2017, GEOMAR, in collaboration with the National and Kapodistrian University of Athens, investigated the evolution of the NE-trending Santorini–Kolumbo line (Figure 1). The POS-510 ANYDROS mission lasted 25 days (March 6–March 27), 19 of which were onboard operations (Hannington et al., 2017). We used the Autonomous Underwater Vehicle (AUV) *Abyss*, which can be operated in water depths up to 6000 m (Figure 2). The system comprises the AUV itself, a control and workshop container, and a mobile Launch and Recovery System (LARS) with a deployment frame that was installed at the afterdeck of R/V *POSEIDON*. The AUV *Abyss* can be launched and recovered at weather conditions with a swell up to 2.5 m and wind speeds up to 6 BFT. The AUV missions were planned based on ships bathymetry. The CTD Sensor of the AUV *Abyss* was Seabird SBE49 FastCAT; S/N 4948793-0168. Its exported data contains latitude, longitude, mission time, depth, conductivity, temperature, salinity, sound speed, recorded at a sampling rate of 4 Hz (Hannington et al., 2017).

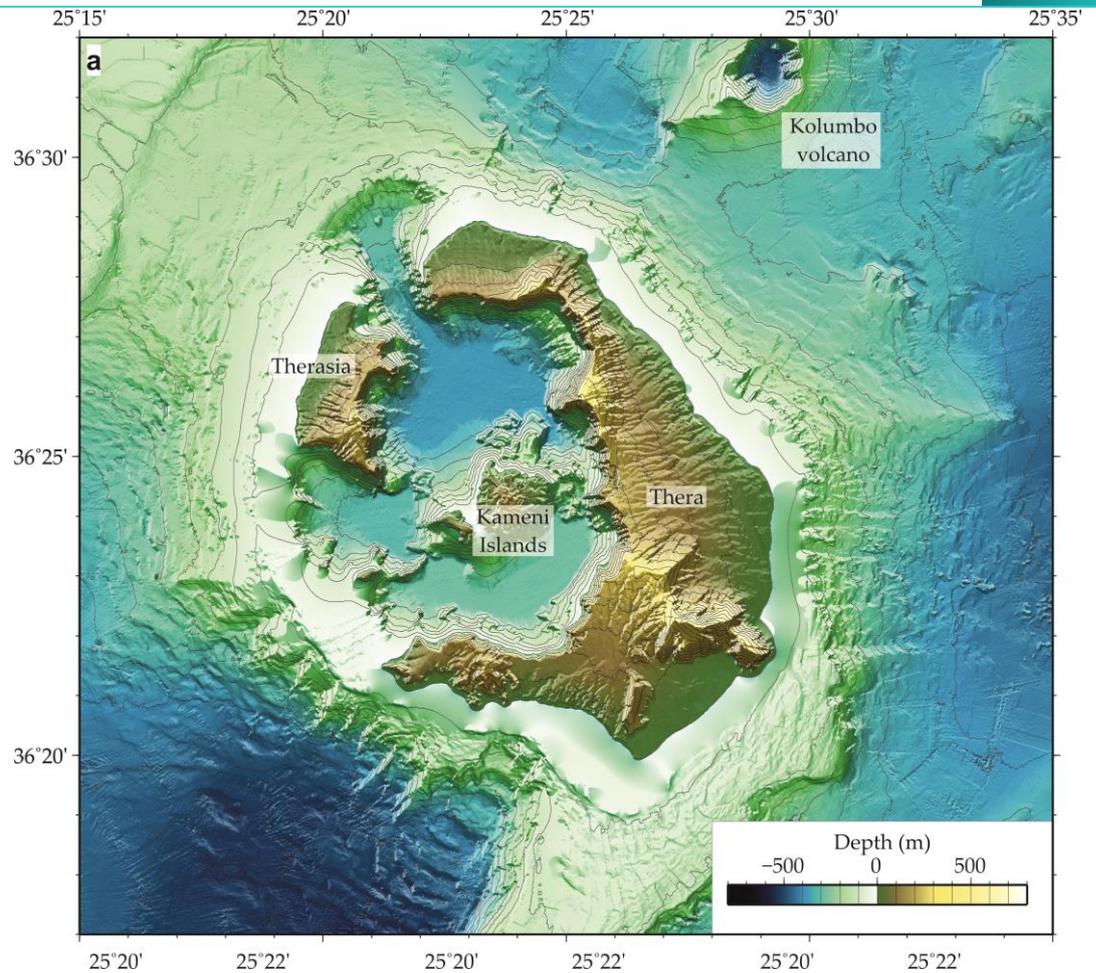


Fig. 1: High-resolution synthetic topographic map of Santorini volcano (Nomikou et al., 2016).

2.1. The POS-510 ANYDROS mission

Using an integrated approach of high-resolution bathymetry, AUV-based bathymetry and sidescan, heat flow and gravity coring, the POS-510 ANYDROS Mission documented the emergence of a high heat flow rift basin in the continental margin arc of the southern Aegean Sea (Hannington et al., 2017). The focus of the mission was on the Anydros Rift system and the Santorini-Kolumbo volcanic line, one of the few places in today's oceans where submarine rifting of a continental margin arc can be studied in its earliest stages. Using integrated geophysical and geological approaches the mission aimed to answer key questions related to the thermal and structural evolution of arc rifts.



Fig. 2: AUV-Abyss (GEOMAR) operations on board R/V POSEIDON (March 2017) (photo credits to Sven Petersen).

The POS-510 ANYDROS mission focused on the thermal evolution of one of the near-arc rift basins, where recent volcanic and hydrothermal activity are a direct consequence of the arc rifting. GEOMAR used heat flow and gravity coring, together with high-resolution imaging of local fault structures, seafloor volcanism, and dikes to address a fundamental question about the evolution of continental margin arcs: at what stage of rifting of the arc crust do magmatic and hydrothermal systems first emerge in the back-arc region and where do the associated ore deposits form?

The AUV *Abyss* operated during the POS-510 cruise collected CTD data from three separate areas of the Northern basin of the Santorini caldera collected at three separate days as shown in Figure 3. On Saturday, March 11, 2017, the north-east part (Area A, dive #259) of the caldera was surveyed; on Saturday, March 25, the survey was conducted at the center (Area B, dive #270); and the south-west part was surveyed the next day, Sunday, March 26 (Area C, dive #271):

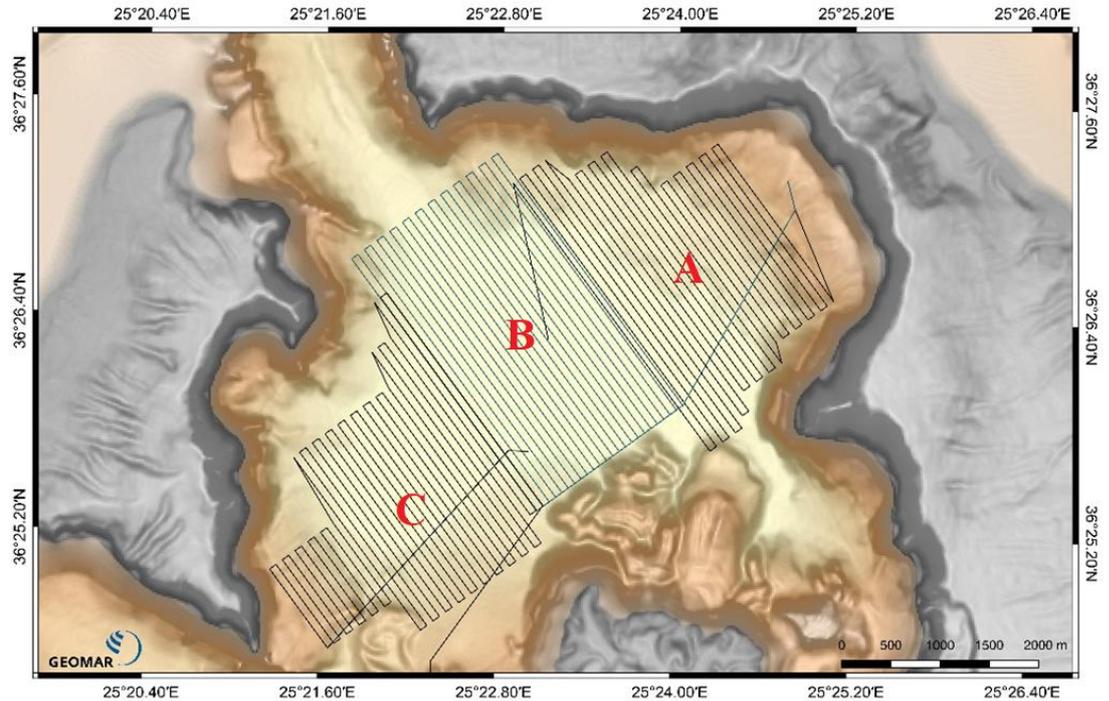


Fig. 3: The area of the North Basin of the Santorini caldera that was surveyed by three separate missions (A, B, and C) using the AUV Abyss during POS-510 (Nomikou et al., 2014; Hannington et al., 2017).

2.2. Data Analysis

The data collected from the Santorini vent fields consist of the Temperature ($^{\circ}\text{C}$), Conductivity (S/m), Salinity (‰) and Sound Velocity (m/s), among other parameters recorded. Detailed CTD 3D profiles have been reconstructed from the raw data (in ASCII format) to study Santorini's vent field to a full extent. Here, we present the results from the 15-hour dive #270 held on the 25th March 2017, during the POS-510 expedition targeting the Santorini vent field located in the North Basin of the Santorini Caldera (Area A). We have also constructed surface plots for the deepest parts of the caldera for all three days of survey, which show the distribution of each parameter in relation to the coordinates of the area.

3. RESULTS

The depth profiles of Temperature (T), Conductivity (C), Salinity (S), and Sound Velocity (V), which were collected on 25th March, are presented in Figure 4. The change in temperature seems to follow a typical open-ocean CTD profile, with higher values near the surface and the thermocline zone, which tend to become smaller as the depth reaches its maximum values near the seafloor and above the vent field. This behavior is evident in the profiles of salinity, conductivity and sound velocity, as well.

However, an anomaly emerges at the depth of 350 m in the conductivity and salinity profiles, while the CTD sensor was placed directly above the vent sources, as can be seen at the profiles recorded between 250 and 350 m in Figure 4. The anomaly is attributed to existing hydrothermal vent activity, which is not so intense as to change the local thermodynamics of the system, thus having no significant impact on the T profiles, but is recorded in the high-sensitivity C and S sensors, indicating that hydrothermal fluids are entering the water column from the crust in a weak, but continuous fashion.

Negative changes can be attributed to a phase separation of the saline hydrothermal fluid, as it enters the water column from below (Bischoff and Rosenbauer, 1987), similarly to what it was observed earlier in the case of the hydrothermal vent field inside the Kolumbo crater (Christopoulou et al., 2015).

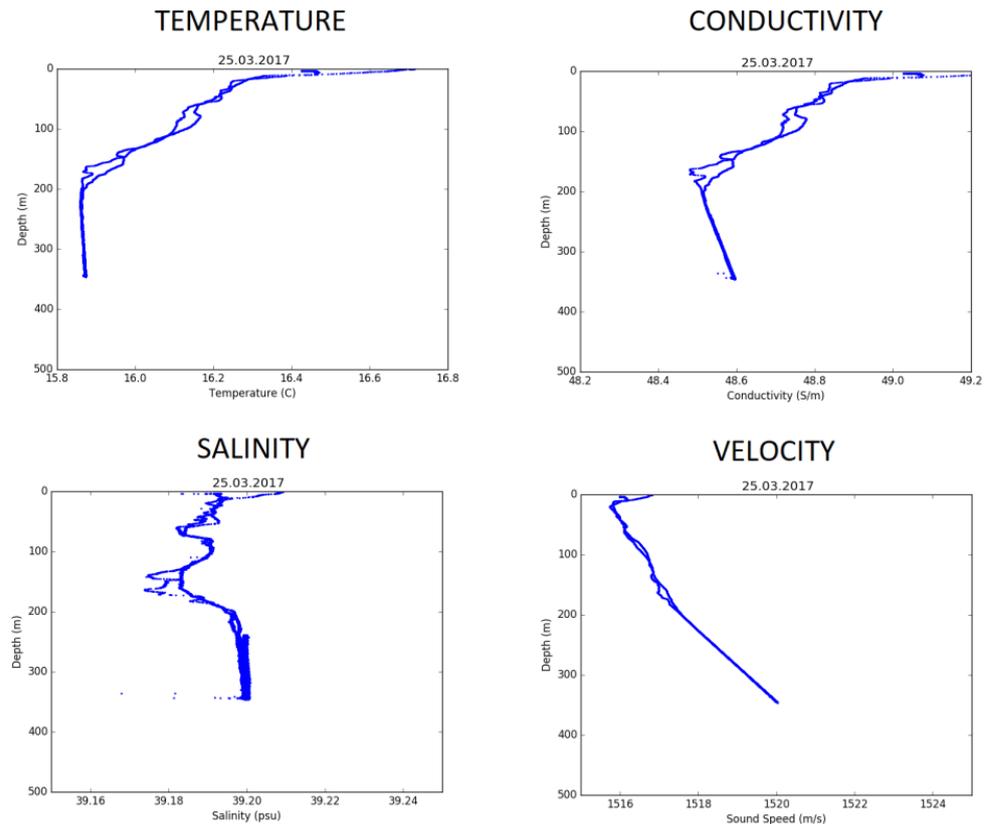


Fig. 4: Temperature, conductivity, salinity and sound velocity profiles for dive # 270 (25-3-2017) survey in the North Basin of Santorini. Anomalies in the profiles are circled with dashed ovals and indicate hydrothermal vent activity. A high-resolution copy of this Figure can be found at the supplementary material.

The profiles of each CTD parameter (conductivity, temperature, salinity, sound speed) at the depth of 350 m, where the anomaly in the profiles was noticed, were grouped and constructed for each separate day and dive. In Figure 5, we show the spatial distribution for the data collected in Area A, in Figure 6, the data collected in Area B, and the plots in Figure 7 represent Area C. It is noticeable that in most cases Temperature, Salinity and Conductivity follow the same distribution. Higher changes of the values presented in these plots are considered indicators of hydrothermal activity. Sound speed only indicates the increase in water density as the depth increases.

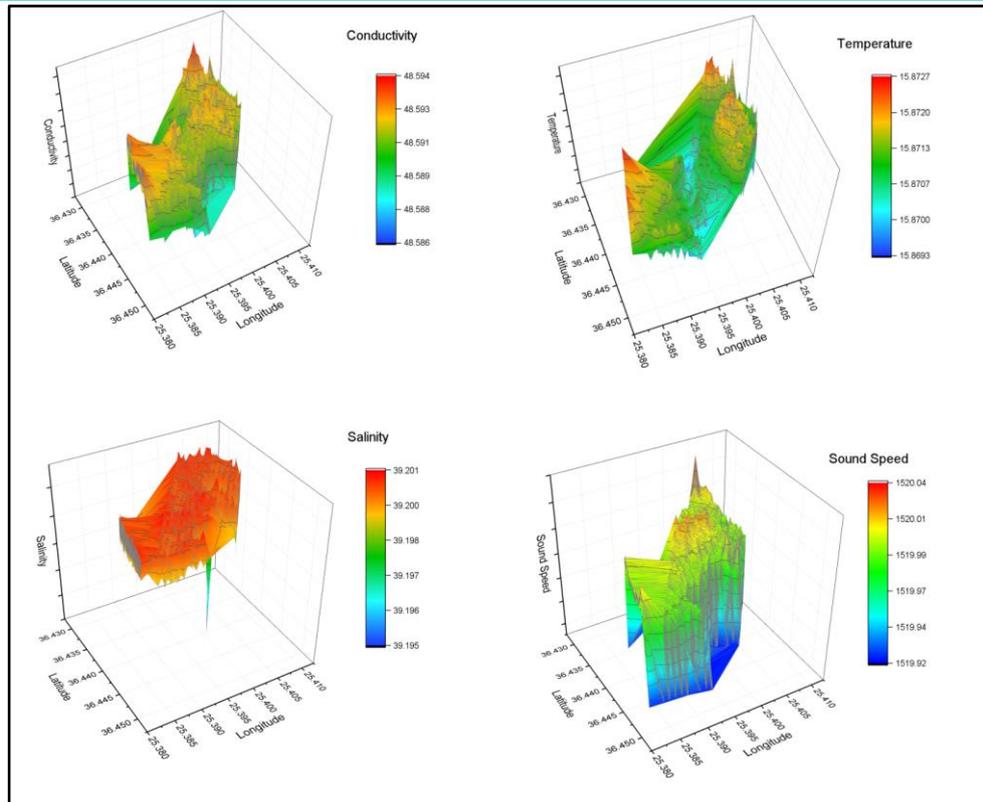


Fig. 5: Reconstructed 3D maps from recorded data of conductivity (S/m), temperature ($^{\circ}\text{C}$), salinity (‰) and sound velocity (m/s), for the North-East area, investigated on the 11th (Area A; dive #259). A high-resolution copy of this Figure can be found at the supplementary material.

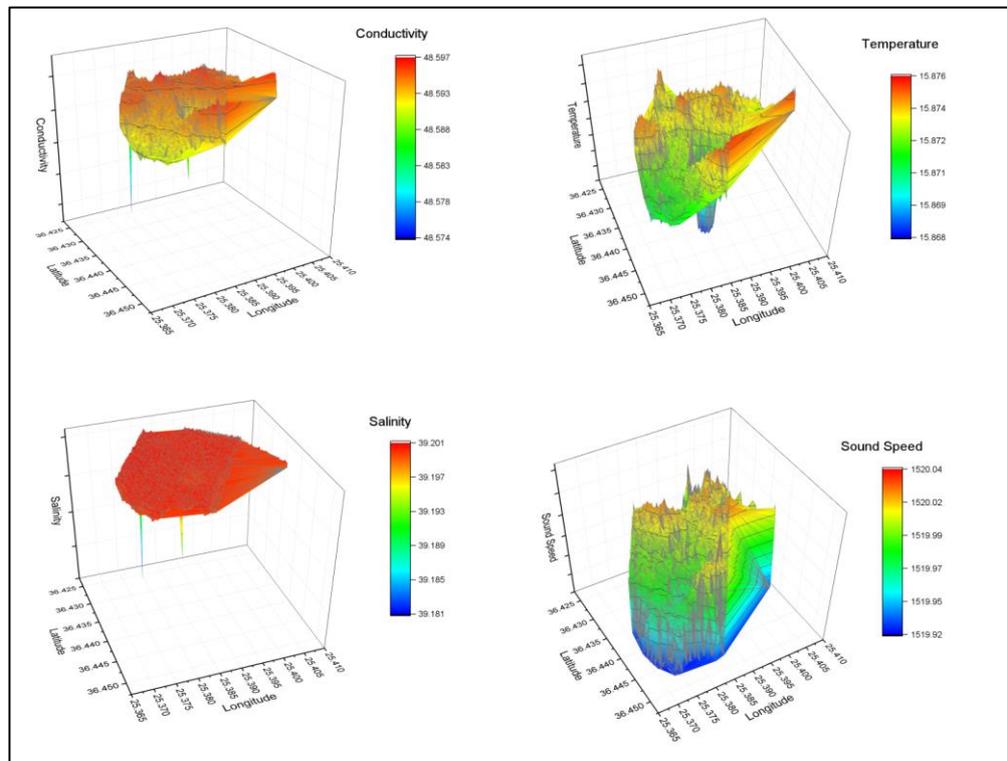


Fig. 6: Reconstructed 3D maps from recorded data of conductivity (S/m),

temperature ($^{\circ}\text{C}$), salinity (‰) and sound velocity (m/s), for the central area, investigated on the 25th (Area B; dive #270). A high-resolution copy of this Figure can be found at the supplementary material.

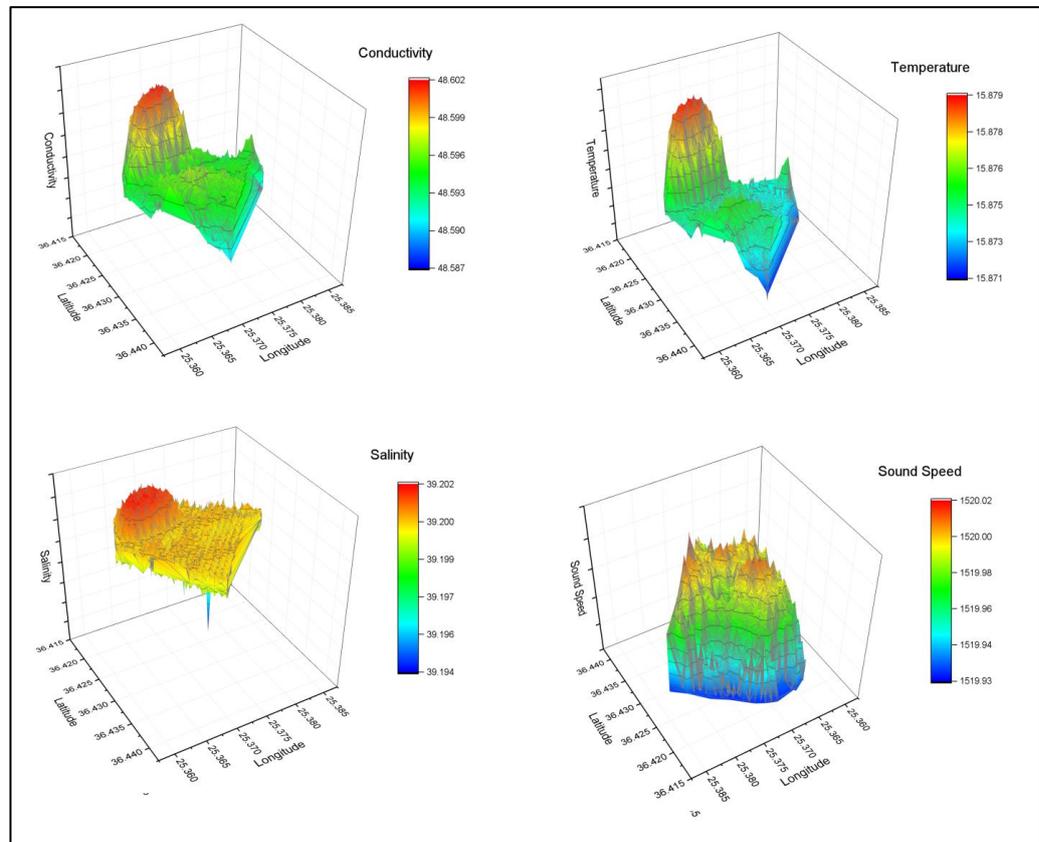


Fig. 7: Reconstructed 3D maps from recorded data of conductivity (S/m), temperature ($^{\circ}\text{C}$), salinity (‰) and sound velocity (m/s), for the south-west area, investigated on the 26th (Area C; dive #271). A high-resolution copy of this Figure can be found at the supplementary material.

4. DISCUSSION

The GEOMAR expedition POS-510 has provided detailed CTD data inside the Santorini caldera and its known vent field. The purpose of this work has been multifaceted. So far, we have surveyed, discovered and documented for the first time and at specific locations inside Santorini's caldera vent field previously unknown, CTD anomalies in depth profiles. Using the continuous operation of the AUV, a 2D map of vent activity has been partially constructed from the measurements at constant depth, while work to that direction is in progress. The observed anomalies are rather weak with respect to other vent fields exhibiting

intense activity, such as the Kolumbo hydrothermal vent field (Christopoulou et al., 2015), however they are both interesting and useful, as they can serve to assess the underlying physicochemical mechanisms that shape them. In recent work from our group, advanced mathematical models developed over the consideration of non-linear phenomena (Bakalis et al., 2017;2018) has proven that such weak sources of hydrothermal activity can reveal the existing dynamics in a submarine volcano's activity in near-real time, where traditional techniques (e.g., visual inspection) fail or come too late. Besides the 2D spatial mapping shown here, the present work has also provided time series data of hydrothermal vent activity sufficient enough to apply non-linear dynamics modelling. The present work has reported on the former, while the latter is work in progress (Dura et al., in prep.). All these steps are crucial towards developing a supervised machine-learning algorithm able to provide a reliable description of the dynamic conditions over the hydrothermal vent field in near-real-time fashion and potentially provide the means to predict near-explosive conditions solely based on monitoring of the CTD anomalies. Based on the expected results, the impact of developing appropriate mechanisms and policies to avoid the associated natural hazard is expected to be immense.

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