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REVIEW ARTICLE

Bringing the Submarine Mariana Arc and Backarc Basin to Life for Undergraduates and the Public

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ABSTRACT

This paper aims to better teach about submarine arc and backarc basin volcanic and hydrothermal activity using the ~1400 km long Mariana convergent margin as an example. Four US National Oceanographic and Atmospheric Administration (NOAA) expeditions (2004–2016) equipped with a remotely operated vehicle (ROV) have discovered and explored many of submarine volcanoes and associated hydrothermal fields and generated many short (~1 min long) videos about them. Some of these videos would be very useful for teaching about these processes if they were organized and context provided, which is done here. Eighteen short videos about nine sites generated by NOAA are presented and discussed here. These are organized into three categories: volcanic eruptions, magmatic degassing, and hydrothermal activity. Volcanic eruption videos include two about glassy pillow lavas erupted in 2013–2015 and a rare example of a submarine eruption. Four videos about magmatic degassing include an example of sulfur produced by disproportionation of magmatic sulfur dioxide associated with a submarine eruption, two rare examples of molten sulfur lakes, and liquid carbon dioxide venting. Four videos about hydrothermal activity are provided. Suggestions for how this material might be used in the classroom are also given.

1 | Introduction

This paper provides a guided video tour of submarine volcanism, degassing and hydrothermal activity of the submarine Mariana arc and backarc basin (BAB) system. The intended audience is instructors of geology classes and their students as well as authors of introductory geology and oceanography texts. As a classroom instructor myself, I know how volcanic eruptions and related phenomena interest students and how useful short videos can be for engaging students to want to learn more about them. There are many excellent videos about subaerial erupting volcanoes (e.g., Iceland, Hawai'i, Etna, Mt. St. Helens). The same cannot be said of submarine arc volcanoes, which are much less familiar to most instructors and students.

There are two arc systems in the Western Pacific where modern technology has provided glimpses of submarine arc volcanism and hydrothermal activity, one in the north and one in the south. The southern one is the ~2600 km long Tonga-Kermadec arc and associated BAB (Lau Basin) and rift (Havre Trough), which lies north of New Zealand. The northern one is the ~2800 km long Izu-Bonin-Mariana (IBM) arc between Honshu, Japan, and Guam, USA. Since the beginning of the 21st century, the US National Oceanographic and Atmospheric Administration (NOAA) has brought its remarkable expertise and technology to study the submarine Tonga-Kermadec and Mariana systems. Other organizations such as the Japan Agency for Marine Science and Technology (JAMSTEC) and New Zealand's Institute for Geological and Nuclear Sciences (GNS) have undertaken similar studies, as have many academic researchers. The NOAA effort stands out because they made and posted on-line many short videos about what they found. This paper organizes and briefly explains a subset of these for the submarine Mariana arc and BAB.

I have been studying Mariana volcanoes for almost 50 years (you can learn about this work at https://www.youtube.com/watch?v=Xaa7qTZAu1o&list=PLzpHDPjNs-iHMxRazFgzPiKzqiGpBTKvc&index=12) and have written many scientific papers. During this time, I have witnessed a technological revolution in studying the seafloor. When I began studying Mariana volcanoes in the mid-1970s, I could only study subaerial volcanoes; submarine Mariana arc volcanoes were essentially unknown. With the technology of the time, it was very hard, time consuming, and expensive to find and map a submarine volcano. This was because we had poor navigation (so locations were very approximate), only single-channel reflection profiles to see how deep was the seafloor (so we had to make a star pattern to map it once we found one), and could only sample lavas by dredging (so geologic context and fragile samples were lost). This technology revealed few details about what was on the seafloor. In 1976, I arranged a trip to visit and collect volcanic rocks from Mariana volcanic islands and in 1978 I published my first research paper, on the volcanic island of Agrigan (Stern 1978). The locality map I used (Figure 1B) nicely captures what was known about Mariana submarine geology. We only knew the large-scale features—where were the main elements of this convergent plate margin: trench, forearc, frontal arc, magmatic arc, BAB, and remnant arc. We knew there were some submarine arc volcanoes but little else. We were not sure where the BAB spreading axis was.

Technology for studying the seafloor improved greatly through the last decades of the 20th century with the introduction of SONAR multibeam swath-mapping and GPS locations. GPS continuously revealed to better than a meter where the ship was on the sea surface (Nguyen 2020). Swath-mapping revealed what seafloor topography (bathymetry) looked like in real time as the ship sailed over a region (Mayer 2006). Suddenly, we could easily find all the submarine volcanoes, and we could be sure we could find them again if we wanted. It is these two technologies that allowed creation of the much more detailed map shown in Figures 1A and 2.

At the same time that we mastered locations at sea and mapping bathymetry, our ability to see and sample what was down there also underwent a technological revolution, first by manned submersibles like ALVIN and later by remotely operated vehicles (ROV; Christ and Wernli Sr 2013). An ROV is unmanned submarine robot (Figure 3A) connected to a surface ship with a fiber optic cable. This allows ROV technicians on the ship to control the ROV at the same time that scientists can observe seafloor features and tell the ROV operators where to go and what samples to collect (Figure 3B); this video feed can also be shared with others on shore and the videos can be edited to make short videos. The combination of GPS, swath-mapping, and ROVs has made it possible to study submarine volcanoes and hydrothermal vents, and share these exciting results with others. Results of this technology make the rest of this paper possible. I am motivated to write

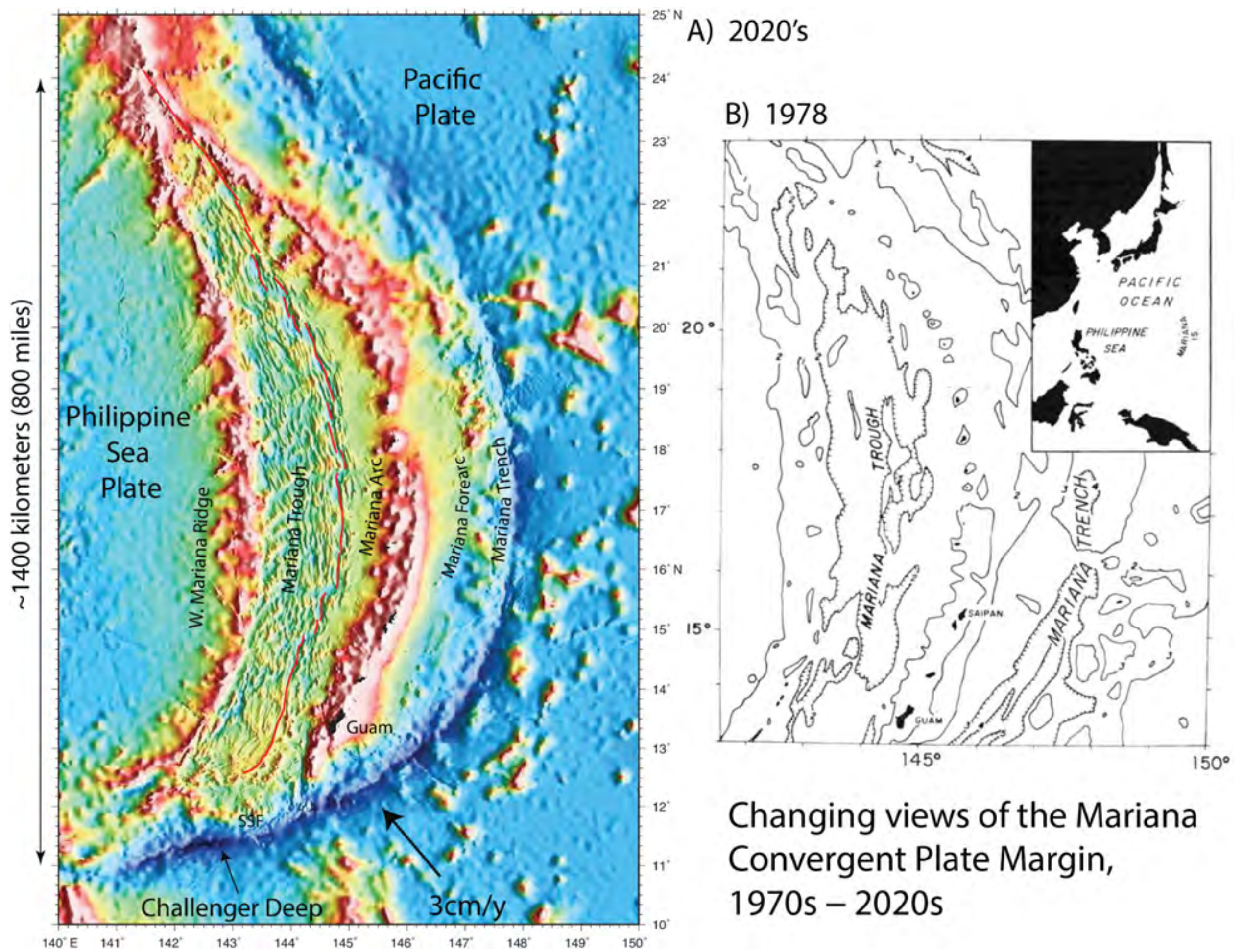

FIGURE 1 | Two views of the Mariana convergent margin. (A) Modern bathymetric map; and (B) about 1978 bathymetric map, from Stern (1978). The difference between the two versions reflects 50 years of amazing technological advances.

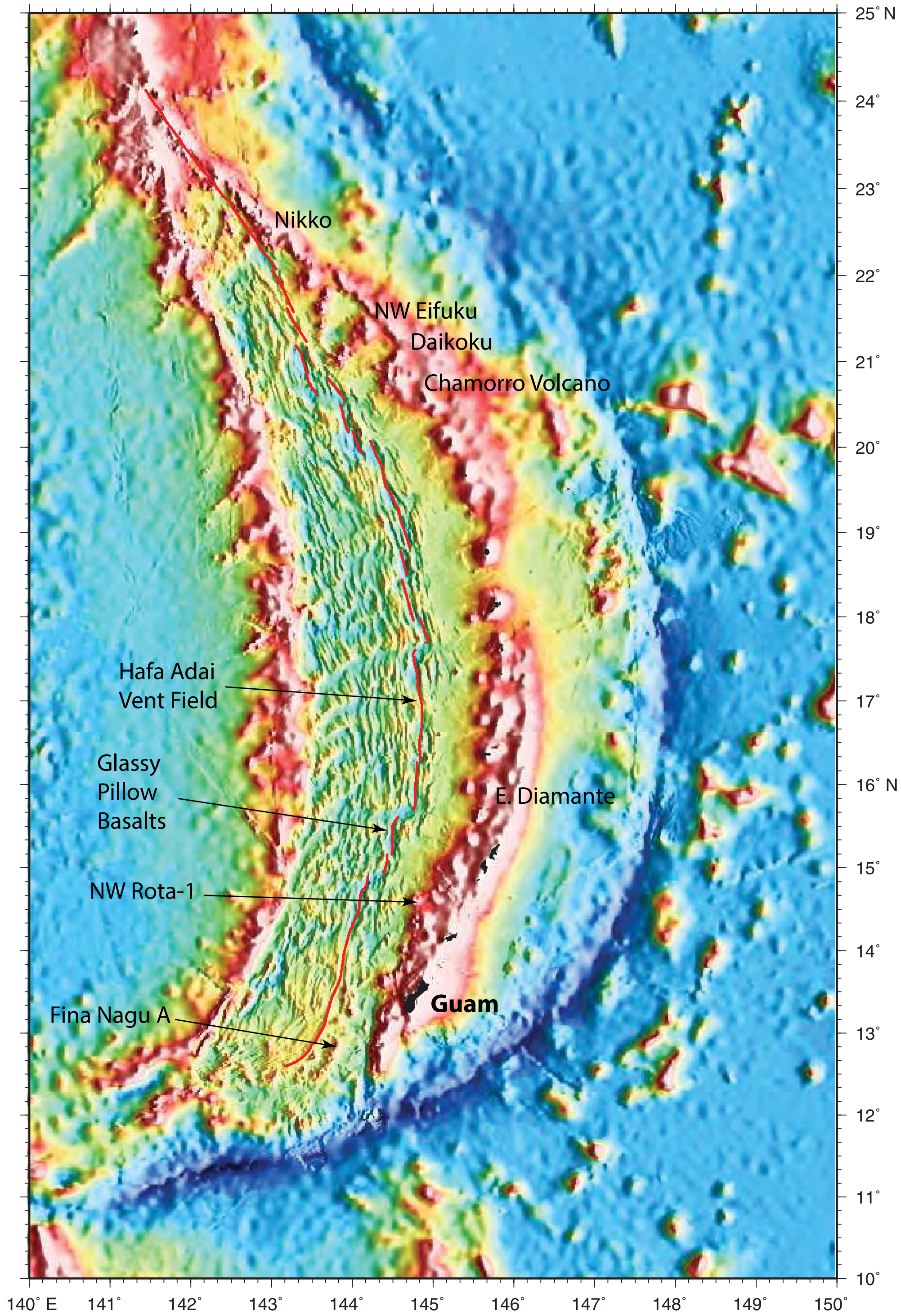

FIGURE 2 | Bathymetric map of Mariana arc system showing locations of nine features discussed in this paper. Red line marks position of backarc basin spreading axis.

this paper because in 2024 I am 73 years old; it is time to share some of what I was fortunate to learn with young people, some of whom might be motivated to learn more.

2 | The Mariana Arc and Backarc Basin

The Mariana arc system is about 1370 km long, about the size of two other famous convergent plate margins: California, USA and Honshu, Japan. The arc system has five key components, from the trench westwards (Figures 1A and 4) these are: (1) the Mariana Trench, where are the Pacific plate begins to subduct beneath the Marianas; (2) the Mariana forearc, which formed during subduction initiation ~52 Ma (Reagan et al. 2023) and hosts multiple serpentinite diapirs (Fryer 2012); (3) the Mariana arc, which includes the arc volcanoes of interest here as well as a structural high in the south, known as the Mariana frontal arc (Stern, Fouch, and

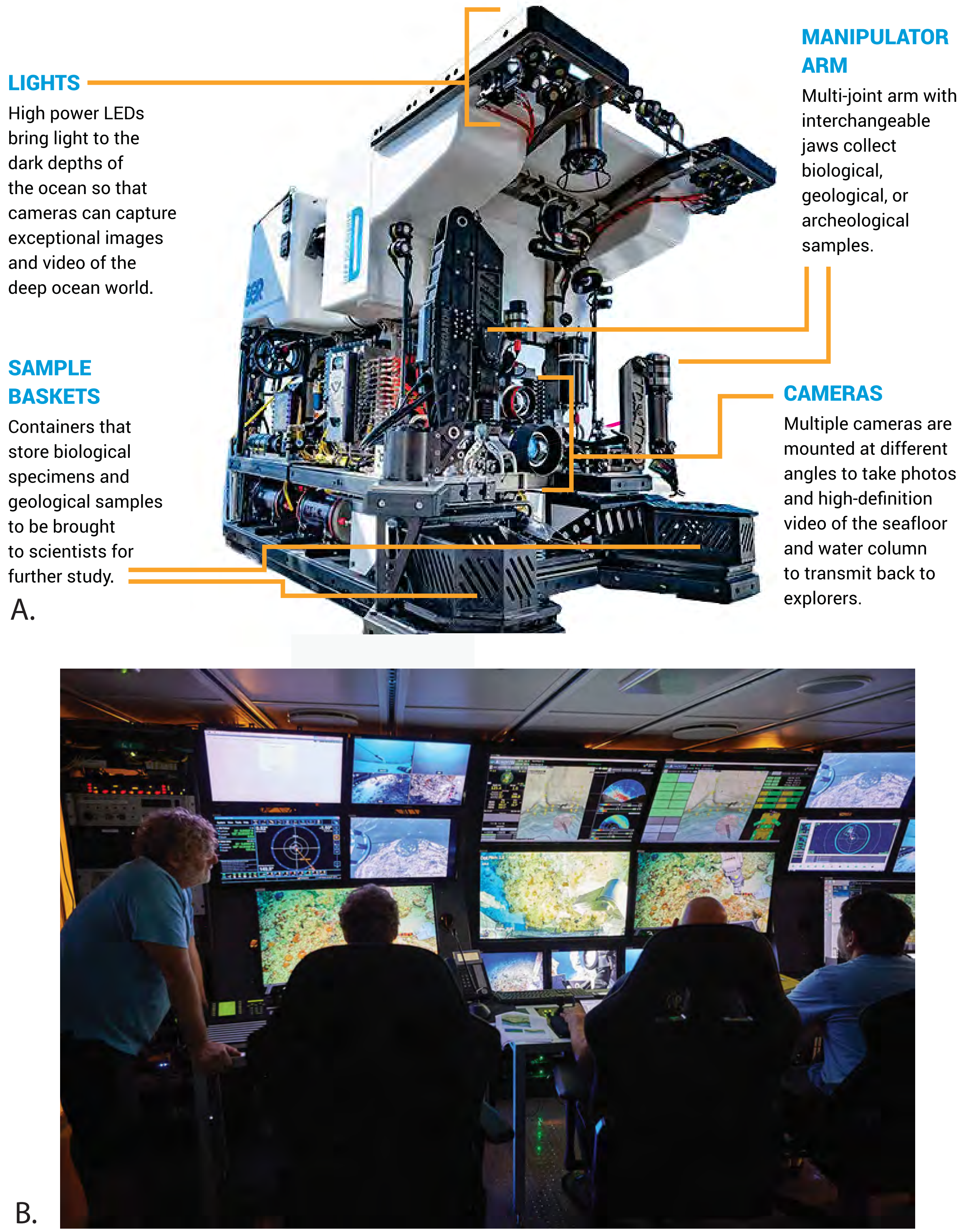

FIGURE 3 | Schematic section through the upper 140 km of the Mariana convergent margen and subduction zone, showing the principal crustal and upper mantle components and their interactions. Note that the location of the "mantle wedge" (unlabeled) is that part of the mantle beneath the overriding plate and between the trench and the most distal part of the arc where subduction-related igneous or fluid activity is found. Modified after Stern (2002). MF, magmatic front.

Klemperer 2003); (4) the Mariana Trough, which is an actively spreading BAB (also of interest); and (5) the West Mariana Ridge, which is an extinct arc that rifted away from the magmatic arc when the BAB began opening sometime in the last 10 million years.

The magmatic arc is subdivided from north to south into three segments on the basis of whether or not arc volcanoes rise above sea level (Figure 1A). All volcanoes in the Northern Seamount Province (NSP; 24°-20°40′ N; Figure 1A) are submarine; many volcanoes in the Central Island Province (CIP;

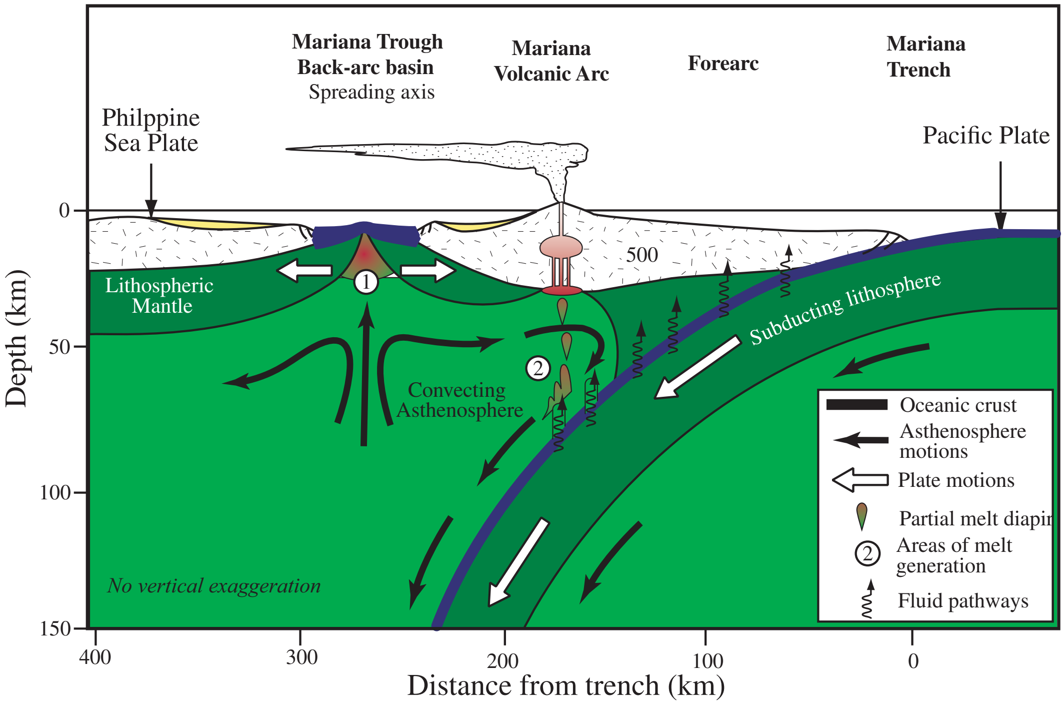

FIGURE 4 | (A) Front of a typical remotely operated vehicle (ROV). Note locations of key features: Lights, cameras (both still and video), manipulator arms, and sample baskets. Modified from NOAA ROV factsheet https://oceanexplorer.noaa.gov/edu/materials/rov-fact-sheet.pdf. (B) A typical ROV control room, from https://schmidtocean.org/cruise-log-post/technology-at-the-seafloor/.

20°40′- 16°20′ N; Figure 1A) rise above sea level; and all volcanoes in the Southern Seamount Province (SSP; south of 16°20′ N; Figure 1A) are submarine (Bloomer, Stern, Fisk et al. 1989). In 2008, Baker et al. (2008) identified 76 volcanic edifices in the Marianas and grouped these into 60 volcanic centers, of which at least 26 (20 submarine) are hydrothermally or volcanically active. The Mariana arc is flanked to the west by the actively spreading Mariana Trough BAB, which also experiences significant volcanism and hydrothermal activity. You can watch a 2.2 min fly-through of the Mariana arc, starting near the southern end of the SSP, moving along the CIP, and finishing at the north end of the NSP. Bathymetry is given in color from blue (deep) to red (shallow); islands are green. https://oceanexplorer.noaa.gov/explorations/06fire/background/marianaarc/media/movies/marianaarc_2006_video.html.

The Mariana Trough is an actively extending BAB behind (W of) the Mariana magmatic arc that stretches 1300 km north–south. Because of its name, it is often confused with the more famous Mariana Trench but its tectonic setting could not be more different: the trench marks a convergent plate boundary whereas the Trough hosts the only seafloor spreading ridge in the NW Pacific Ocean. The Mariana Trough can be subdivided into a northern third that is undergoing rifting and a southern 2/3 with seafloor spreading (Stern, Fouch, and Klemperer 2003). The two video snippets from the Mariana Trough are both from along the BAB spreading axis.

Convergent margins like the Marianas are surficial expressions of subduction zone processes (Figure 4). These are very dynamic systems; static diagrams like Figure 4 are useful for showing relations of deeper processes to surface features shown in Figure 2 to deeper processes but do not show the various parts of the system in motion. In contrast, videos show how the several parts of a subduction zone operate together and are more useful for helping students understand what is going on. Such a video can be seen at https://www.youtube.com/watch?v=6wJBOk9xjto&list=PLzpHDPjNs-iHjUyX7jjV3zfup3gfmc34k.

The magma, magmatic gasses, and metal deposits we discuss below come from mantle melting below the volcano and above the subducted plate (Figure 4). This upper mantle source region is strongly marinated in fluids and melts from the subducted plate (Stern 2002). Scientists think that much of the elements in the lava, gasses, and metal deposits that come out of arc volcanoes are derived from the subducted sediments and oceanic crust.

Below I briefly describe nine examples of Mariana arc and BAB volcanism and hydrothermal activity for which short videos have been made, with locations shown on Figure 2. Presentation is organized by processes, not locality, starting with volcanic eruptions then moving on to magmatic degassing and finishing with hydrothermal activity. The sites can be subdivided into three groups: (1) eruptions (BAB young lava flows; NW Rota-1), (2) arc magmatic degassing (NW Rota-1, Nikko, Daikoku, and NW Eifuku), and (3) hydrothermal activity (BAB new hydrothermal vent, E. Diamante, Chamorro, and Fina Nagu Caldera A), and one example each of BAB volcanism and hydrothermal activity. Locations are shown on Figure 2. The 18 videos about these 9 sites listed below are all about 1 min long. Details about the tools and expeditions that carried out these studies and the agencies that support of this work are provided in Table 1.

TABLE 1 | Expeditions and abbreviations.

Tools:
ROV: Remotely operated vehicle
Agencies:
NOAA: US National Oceanographic and Atmospheric Administration (NOAA)
JAMSTEC: Japan Agency for Marine Science and Technology
GNS: New Zealand Institute for Geological and Nuclear Sciences
Expeditions:
OE16-1: NOAA 2016 Deepwater Exploration of the Marianas, Leg 1 (4/20/2016–5/11/2016)
OE16-3: NOAA 2016 Deepwater Exploration of the Marianas, Leg 3 (6/17/2016–7/10/2016)
SRoF04: 2004 NOAA Submarine Ring of Fire (3/27/2004–4/18/2004)
SRoF06: 2006 NOAA Submarine Ring of Fire (3/18/2006–5/13/2006)
KM23-05: JAMSTEC expedition using R/V KAIMEI and KM-ROV (2/2023–3/2023)

3 | Recent Eruptions and Magmatic Degassing of SO_2 and CO_2

3.1 | Eruptions and Magmatic Degassing

3.1.1 | Young Lava Flows (15.435° N, 144.507° E; ~4000 m)

NOAA Ocean Exploration 2016 Leg 1 Dive 9 explored the Mariana backarc spreading center where there an eruption occurred sometime between 2013 and 2015. Comparison of bathymetry between these years show over 100 m thickness of new lava flows erupted along ~4 km of the spreading (Figure 5; Chadwick Jr et al. 2018). To learn how pillow lavas form, watch this short video: https://www.youtube.com/watch?v=-rFiSSWe2NU. These remarkably fresh basaltic lavas are beautifully glassy and shiny from fresh glass reflecting ROV light. The sheen of fresh pillow basalts disappears quickly, perhaps due to microbial devitrification of glass; in a few years, these pillows will be dull black, like other older mid-ocean ridge basalt pillows.

Glassy Lava (watch or download 50 s. video): https://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/logs/photolog/welcome.html#cbpi=/okeanos/explorations/ex1605/dailyupdates/media/video/0429-glassy-lavas/0429-glassy-lavas.html.

3.1.2 | NW Rota-1 (14°36′ N, 144°46.1′ E ~ 500 m; SRoF04, SRoF06)

NW Rota-1 is located about 100 km north of the island of Guam in the Southern Seamount Province. The volcano is steep-sided (with slope angles of 31° to water depths >1000 m), conical, with a basal diameter of about 16 km at 2700 m and a summit depth of 517 m below sea level (b.s.l.) NW Rota-1 was first visited with an ROV in 2004, at which time it was actively erupting. NOAA teams used ROVs to study it in 2004, 2006, 2009, and 2010, with additional ROV dives by Japanese investigators in 2005 and 2008. The volcano was erupting on every visit during this time period, erupting basalt and basaltic andesite, but the nature and intensity of the activity changed from year to year. An ROV dive in 2014 found that the volcano had stopped erupting. Brimstone Vent, so named because so much sulfur spewed from it, is the name of an active volcanic vent located approximately 45 m SW of the summit. It grew from a depth of 560 m in 2004 to 520 m in 2009 before collapsing to 550 m in 2010 (Schnur et al. 2017). The two short videos listed below are from the lip of the volcano next to Brimstone Pit.

One of the most interesting aspects of NW Rota-1 eruptions is how the yellow elemental sulfur it spewed is produced. Elemental S is not found in the magma but is produced above the eruption vent from disproportionation of magmatic sulfur dioxide (SO_2), a magmatic gas that is the dominant sulfur species in arc magmas. Disproportionation is a chemical redox reaction in which one compound of intermediate oxidation state—in this case, SO_2—converts into two compounds, one of higher and one of lower oxidation states—in this case elemental S and sulfuric acid (H_2SO_4). The presence of water is essential for making sulfuric acid. Sulfur in SO_2 is S^{+4} whereas elemental sulfur is S^0 and in sulfuric acid is S^{+6}. The chemical reaction is:

$$2H_2O + 3SO_2 = S + 2H_2SO_4 \tag{1}$$

The abundant H_2SO_4 produced by this reaction made for a very acidic (low pH) environment around the erupting vent!

Ash and sulfur-laden eruptions (watch or download 1 min video): https://oceanexplorer.noaa.gov/explorations/04fire/logs/april01/media/brimstone01_video.html.

Small sulfur chimney (watch or download 1 min video): https://oceanexplorer.noaa.gov/explorations/04fire/logs/april01/media/brimstone02_video.html.

Eruptive pulses (watch or download 65 s video): https://oceanexplorer.noaa.gov/explorations/06fire/logs/april29/media/movies/nwrota_brimstone13_video.html.

Gas bubbles, probably CO_2 (watch or download 55 s video): https://oceanexplorer.noaa.gov/explorations/06fire/logs/april24/media/nwrota_brimstone3.htmlhttps://oceanexplorer.noaa.gov/explorations/06fire/logs/april24/media/nwrota_brimstone3.html.

3.1.3 | Daikoku (21°19′26″ N, 144°11′38″ E; ~400 m b.s.l.; OE16-3)

Daikoku is a submarine arc stratovolcano in the Northern Seamount Province of the Mariana arc. It rises over 2.5 km from the seafloor, with its summit about 323 m b.s.l. It has erupted andesitic lava (59–63 wt.% SiO_2; Bloomer, Stern, and Smoot 1989). The summit has a ~100 m wide, 50 m deep crater that hosts a

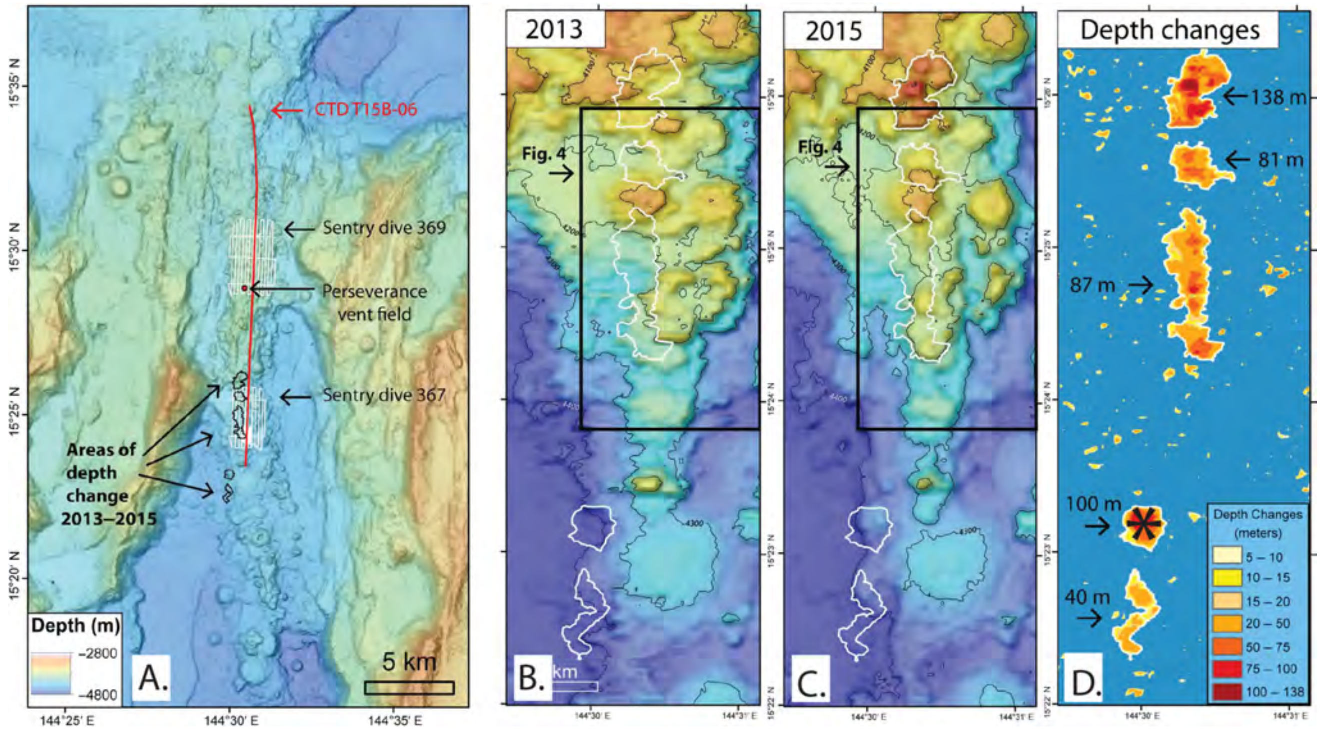

FIGURE 5 | Bathymetric map of the Mariana Trough spreading axis at 15.5°. (A) Areas of depth change between bathymetric surveys in 2013 and 2015 (black outlines; data shown B, C, D). Red dot shows location of Perseverance vent field. (C, D) Depth changes between ship-based multibeam bathymetric surveys in 2013 and 2015. (B) Pre-eruption bathymetry collected in February 2013. (C) Post-eruption bathymetry collected in December 2015. (D) Depth differences between the two surveys showing five areas of significant depth change (outlined in white; color scale at lower right). Numbers indicate maximum depth change within each area. Ignore black boxes. Modified after Chadwick Jr et al. (2018).

lake of molten sulfur; this sulfur must have been produced from disproportionation of magmatic SO_2, similar to the process at NW Rota-1. A temperature of 187°C was measured for the molten sulfur (De Ronde et al. 2015). When a Japanese research team visited it in March 2023 (KM23-05), the summit crater was fuming vigorously making it impossible to see its bottom. Even when the ROV's sonar showed that the ROV was only 2-m away from the caldera wall, the research team could only see white "smoke." To test the hypothesis that the bottom of the caldera hosts a lake of molten sulfur, the ROV approached the bottom near the center of the crater. The bottom was covered in black volcanic fragments—presumably from a recent eruption, which were overlain by fresh-looking bright yellow sulfur spherules arranged in rippled lines and irregular blocks of solid sulfur. Then the team used the scoop sampler on the ROV to punch through the crust and sample the underlying liquid sulfur. Figure 6A–C shows relations between molten sulfur lake and the thin crust that insulates hot molten sulfur from much cooler seawater and how easy it was for an ROV in March 2023 to punch through the crust and sample the underlying liquid sulfur (Sawada et al. 2023). Figure 6D,E shows what the sulfur looks like.

NOAA Ocean Exploration 2016 Leg 1 Dive 9 investigated a possible 2014 eruption and found that the sulfur-rich summit caldera including the sulfur lake was covered with volcanic ash and volcaniclastics. Tube worms and anemones were observed, as well as a high density of flat fish. Plumes of likely carbon dioxide gas and sulfur were observed emanating from various sites near the crater rim and along the lower crater walls. Barnacles, anemones, and tubeworms were also seen around the crater rim.

Underwater volcano (watch or download 55 s video): https://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/dailyupdates/dailyupdates.html#cbpi=june26.html.

Molten sulfur pond (watch or download 1 min video): https://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/logs/photolog/welcome.html#cbpi=/okeanos/explorations/ex1605/background/history/media/video/video1.html.

Lakes of molten sulfur on submarine volcanoes are very unusual and there are two (at Nikko and NW Eifuku) are found in close proximity in the Mariana arc NSP. A brief explanation and several figures provide context, then links are provided to good 1 min seafloor videos are provided.

3.1.4 | Nikko (23°05′ N, 142°19.5′ E, 380 m b.s.l.; SRoF06)

Nikko is an active submarine volcano in the Mariana NSP. It is tectonically interesting because it lies where the Mariana Trough extension axis intersects the arc, which might help explain why it has erupted both basalt and dacite (Bloomer, Stern, Fisk et al. 1989). The summit of Nikko volcano comprises two young cones built on top of an older filled caldera. Sitting atop the western cone is a crater 350-m wide from rim-to-rim, and 150-m wide across its floor at a depth of ~470 m. Molten sulfur has been observed at two sites at Nikko: (1) on the northern floor of the crater (at a depth of 462 m); and (2), outside the crater, ~100 m south of, and 40 m below, the south crater rim. A maximum temperature of 197.8°C for the molten

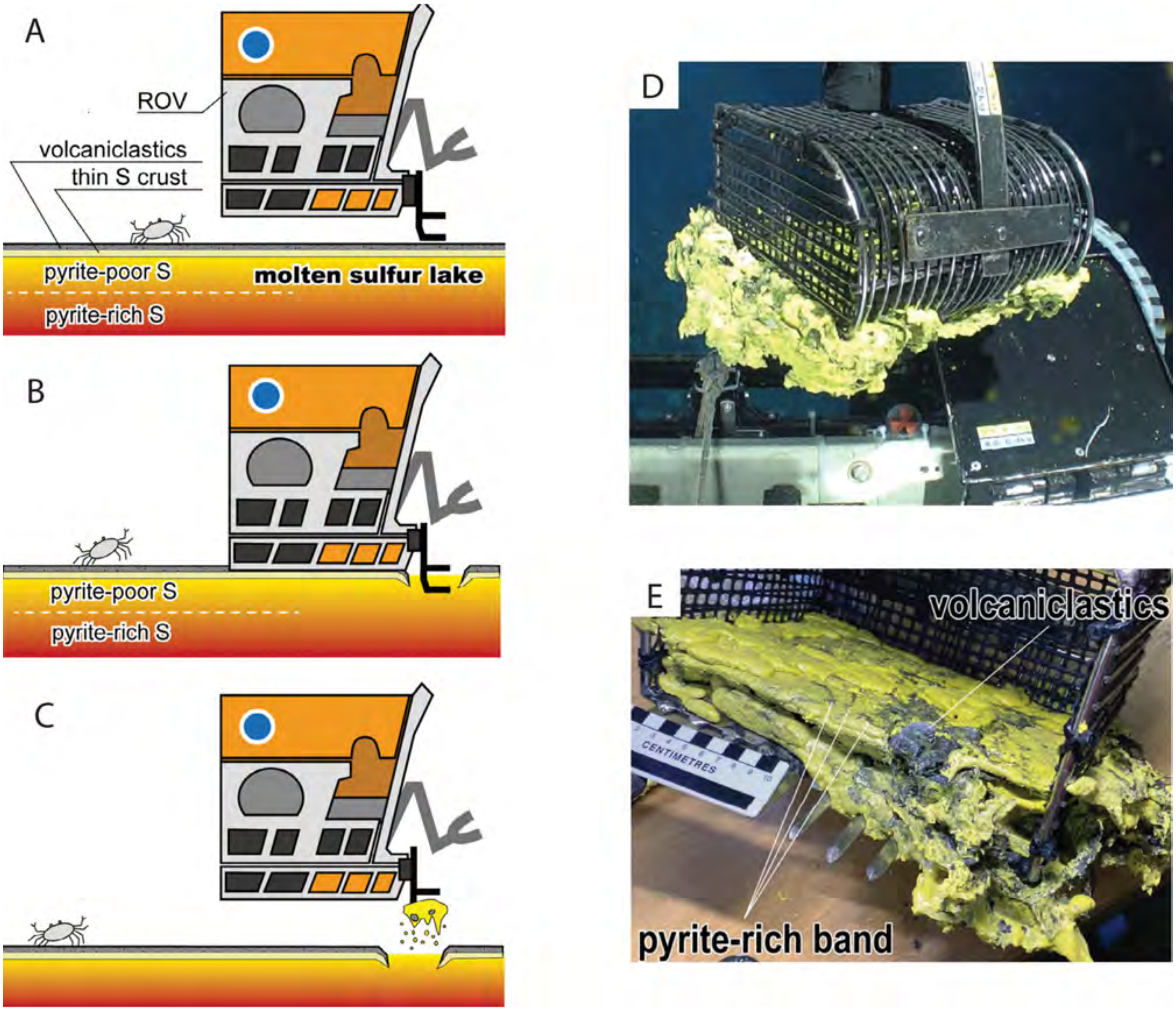

FIGURE 6 | Schematics of molten sulfur sampling in Daikoku sulfur lake carried out using an ROV in March 2023 (Sawada et al. 2023). The ROV scoop sampler after being dunked into the Daikoku sulfur lake. (A) Schematic of ROV scoop sampler resting on sulfur crust; (B) Schematic of ROV scoop sampler breaking through thin sulfur crust; (C) Schematic of ROV rising, bringing scoop sampler encrusted with sulfur with it; (D) Photo of scoop sampler encrusted with sulfur (E) Fresh yellow sulfur cake sampled by the scoop sampler. Modified after Sawada et al. (2023).

sulfur was recorded at the southern sulfur pool (De Ronde et al. 2015). De Ronde et al. (2015) reported that the crater floor surrounding the small molten pool was 'heaving' during SRoF06 observations, suggesting that the solid-looking edges of this pool were a thin crust on a much larger pond of molten sulfur. This was confirmed when the ROV inadvertently broke through this crust, coating its undercarriage with an estimated 27 kg of sulfur (De Ronde et al. 2015).

I wonder if a lava lake lies beneath the sulfur lake? Lava lakes occur in a few subaerial volcanoes, like Erta Ale in Eritrea and sometimes at Kilauea, Hawai'I, but none have been found on the seafloor yet.

SRoF06 bubbling sulfur: https://oceanexplorer.noaa.gov/explorations/06fire/logs/may12/media/movies/nikko4_video.html (1 min).

Closer examination of what appears to be solid ground is really just a thin crust on a lake of molten sulfur! https://oceanexplorer.noaa.gov/explorations/06fire/logs/may12/media/movies/nikko5_video.html (1 min).

SRoF06 Crust on a lake of molten sulfur: https://oceanexplorer.noaa.gov/explorations/06fire/logs/may12/media/movies/nikko6_video.html (1 min).

3.1.5 | NW Eifuku (21.49° N, 144.04°, 1535 m b.s.l., SRoF04)

NW Eifuku is the deepest in a cluster of three volcanoes that includes the larger neighboring volcanoes Daikoku and Eifuku. At a depth of 1604 m, the ROV discovered a remarkable hydrothermal field (later named Champagne) with small white chimneys discharging buoyant milky fluid. Subsequent surveys with the ROV located several additional sites of hydrothermal discharge on NW Eifuku, although the most intense venting was found at the Champagne site 80-m WNW of the volcano summit. Although there were few vent animals right at the Champagne site, an extensive biological community was found within the surrounding few hundred meters, including mussels, shrimps, crabs, and limpets.

Temperatures as high as 103°C were measured in vent fluids (Lupton et al. 2006). In addition to the vent fluid discharge at Champagne vent, droplets with a milky skin rose slowly from the seafloor around the chimneys. The droplets are mainly liquid carbon dioxide (CO_2), with some H_2S (hydrogen sulfide). The droplets were sticky and adhered to the ROV-like clumps of grapes and did not merge into larger droplets. The film coating the droplets was assumed to be CO_2 hydrate (also called clathrate). Liquid CO_2 is more compressible than water and is denser than seawater and sinks at pressures greater than 260 bars, corresponding to 2600-m water depth. Champagne site is 1535 m b.s.l. and so liquid CO_2 is buoyant relative to seawater and rises to the surface, expanding over 50 times in when liquid turns to gas at ~400 m (40 bars).

The flux of liquid CO_2 droplets increased dramatically whenever the seafloor was disturbed by the ROV. This suggests the presence of a layer of liquid CO_2 beneath the surface capped by a layer of CO_2 hydrate. These relations are sketched in Figure 7A.

Seeing how liquid CO_2 behaves and interacts with water is useful because capturing CO_2 from the atmosphere and storing (sequestering) it underground is proposed to help solve the modern climate crisis. We can figure out what will happen when we pump CO_2 into the ground by pondering the phase diagram for CO_2 (Figure 7). A phase diagram is a type of chemical chart that shows pressure–temperature conditions at which thermodynamically distinct phases (such as solid, liquid or gaseous states) occur and coexist at equilibrium. Because rocks are 2.5 times denser than seawater, the P at which injected gas converts to liquid is much shallower underground, ~150 m or so. Probably we will inject CO_2 much deeper into the Earth, 1 or 2-km deep. We cannot inject it much deeper because the phase diagram shows that solid CO_2 (dry ice) becomes the stable phase deeper than a few thousand meters. Dry ice would block flow of CO_2, impeding its storage in the ground.

In 2023, JAMSTEC scientists confirmed that liquid CO2 was issuing from deep-sea hydrothermal vents at NW Eifuku using in situ Raman spectroscopy (Takahashi et al. 2023). This was the first paper to describe natural liquid CO_2 using deep-sea in situ Raman spectroscopy.

Another interesting interaction of carbon dioxide and water is CO_2 clathrate or hydrate. These are composed of molecular water ice cages trapping gasses like methane or carbon dioxide. The chemical reaction for the NW Eifuku clathrate occurrence is:

$$CO_2 + nH_2O = CO_2\left(nH_2O\right) \text{ (clathyate solid)} \quad (2)$$

NW Eifuku white chimneys are CO_2 clathrate, as is the floor of vent area, as shown in Figure 7A.

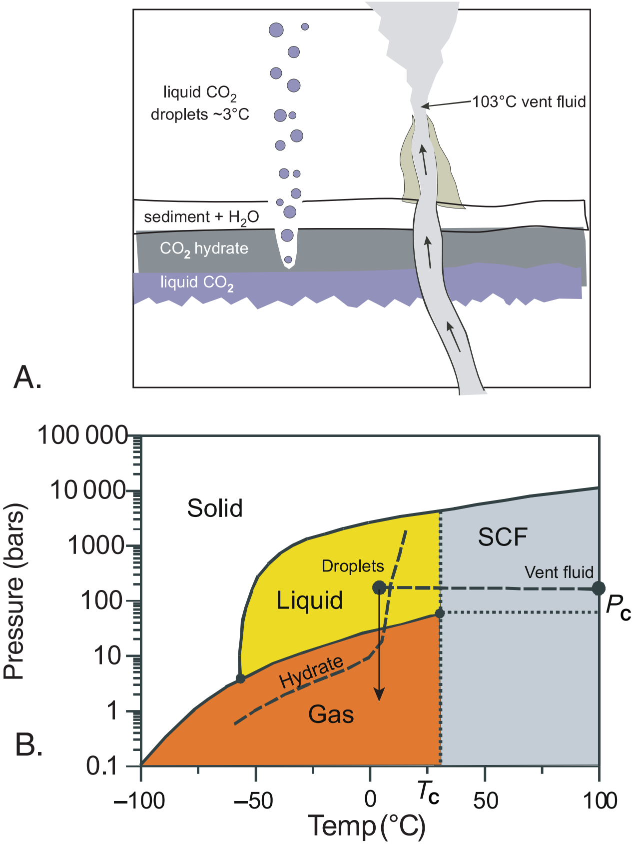

FIGURE 7 | (A) Diagram of near surface conditions at the Champagne vent field. Note that a subsurface lake of liquid CO_2 is covered by a blanket of CO_2 hydrate (De Ronde et al. 2015). (B) Phase diagram for CO_2 showing regions where solid, liquid, gas, and supercritical fluid (SCF) exist. P_C and T_C denote the critical pressure and temperature. The dashed line denotes the boundary of hydrate stability. Pressure and temperature conditions for Champagne site liquid droplets and for the 103°C vent fluid are shown (De Ronde et al. 2015). Arrow shows rise of CO_2 droplets; these become gas ~400 m water depth.

Mariana SRoF 2004 NW Eifuku CO_2 bubbles (1 min): https://www.youtube.com/watch?v=yQvzjRGv9Rk.

Mariana SRoF 2004 NW Eifuku Champagne Vent (1 min): https://www.youtube.com/watch?v=C2qjdxG7JYQ.

Mariana SRoF 2004 NW Eifuku Cliffhouse (1 min): https://www.youtube.com/watch?v=cBacbuJBKKg.

3.2 | Hydrothermal Activity

After an eruption ends, the rocks beneath the volcano remain hot for some time and magma bodies in the crust may continue to degas. The region around the eruption site will be densely fractured, allowing seawater to infiltrate, be heated and react with hot rocks and magmatic gasses (Figure 8). This hot fluid will become acidic due to abundant sulfuric acid from magmatic gasses and rise back toward the seafloor, dissolving and altering surrounding rocks as it rises and becoming greatly enriched in metals like iron, copper, and zinc and also sulfur. When this

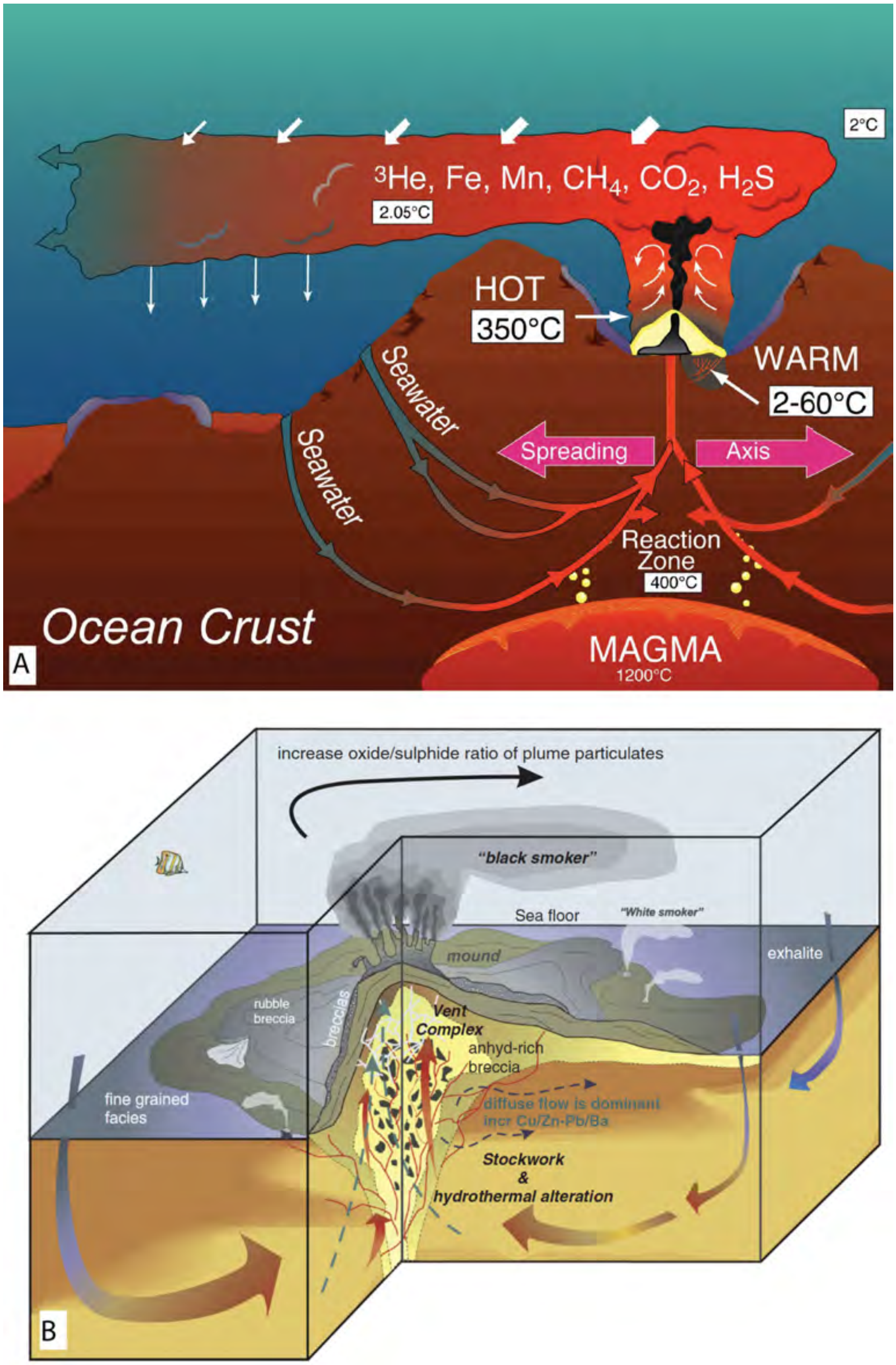

FIGURE 8 | (A) Schematic cross-section of a hydrothermal vent at a spreading ridge (not to scale). Seawater penetrating cracks in the crust is heated by hot rocks several kilometers deep and becomes acidic from magmatic gasses, especially SO_2, which becomes sulfuric acid. Hot, acid fluid is buoyant and rises back to the seafloor, leaching metals from the rocks it passes through; these fluids are discharged back into the ocean at hydrothermal vents. Acidic (low pH) vent fluids mix with slightly basic (pH ~8.1) seawater, precipitating a wide range of minerals including sulfides (pyrite, chalcopyrite, sphalerite) and sulfates (barite, anhydrite). Hot vent fluids are buoyant and rise a few hundred meters into the water column, and are dispersed laterally by local currents. A similar process is responsible for hydrothermal systems on submarine arc volcanoes. Modified after Massoth et al. (2003). (B) Block model schematic diagram of a mound-like volcanogenic massive sulfide (VMS) system illustrating the relationships between the massive sulfide and the underlying stockwork. Red to purple arrows denote fluid circulation pathways. Modified after Tornos et al. (2015).

hot, acid (low pH), metal- and sulfur-rich fluid comes out of the seafloor at hydrothermal vents, it reacts with cold, basic (moderately high pH), oxygenated seawater, the metals and sulfur in the hydrothermal fluid react to make sulfide minerals like pyrite (FeS_2), chalcopyrite ($CuFeS_2$), and sphalerite (ZnS). These precipitate to make sulfide-rich chimneys around the vent and fine particles make the black smoke that issues from some hydrothermal vents (Figure 8). Videos from the next four sites highlight these sulfide chimneys.

Seafloor hydrothermal systems are models for how an important class of mineral deposits formed: volcanogenic massive sulfide (VMS) deposits. VMS deposits are major sources of Zn, Cu, Pb, Ag, and Au. They typically occur as lenses of polymetallic massive sulfide that form at or near the seafloor in submarine volcanic environments. There are over 800 known VMS deposits worldwide that range in age from 3.4 billion years old to actively forming deposits in modern seafloor environments (Galley, Hannington, and Jonasson 2007).

The life around hydrothermal vents is fascinating. Some of the chemicals coming out of the vents are used by microbes (bacteria and Archaea) as a way to make food, similar to how plants use sunlight. These microbes are the base of a food chain that includes shrimp, snails, and other animals, analogous to food chains based on photosynthetic plants (Hessler and Lonsdale 1991). Plants use photosynthesis, vent microbes use chemosynthesis. In the ocean, sunlight does not penetrate below about 300 m so photosynthetic life can only exist in water shallower than this in what is called the euphotic zone. Most life in the ocean deeper than 300 m consists of scavengers that feed on whatever sinks from the euphotic zone; the deep ocean floor is mostly a desert. The exception is around hydrothermal vents, where dense chemosynthetic communities thrive (Davis and Moyer 2008; Kato et al. 2009, 2010). The next three videos show these communities around active vents and the last video shows what happens when vents stop pumping out chemical-rich fluid and the microbial base of the food chain disappears.

3.2.1 | Hafa Adai Vent Field (16.96° N, 144.87° E, ~3300 m b.s.l.; OE16-1)

Baker et al. (2017) report 19 known hydrothermal vent fields along the Mariana Trough spreading axis (Figure 9); this vent site is one of these. The base of these sulfide chimneys is extinct, but the top is growing around several black smoker orifices. Sulfide precipitation creates a range of fantastic structures, from things that look like beehives to skinny spires. A temperature of 339°C was measured in one vent orifice, one of the highest temperatures ever recorded at a Mariana hydrothermal vent.

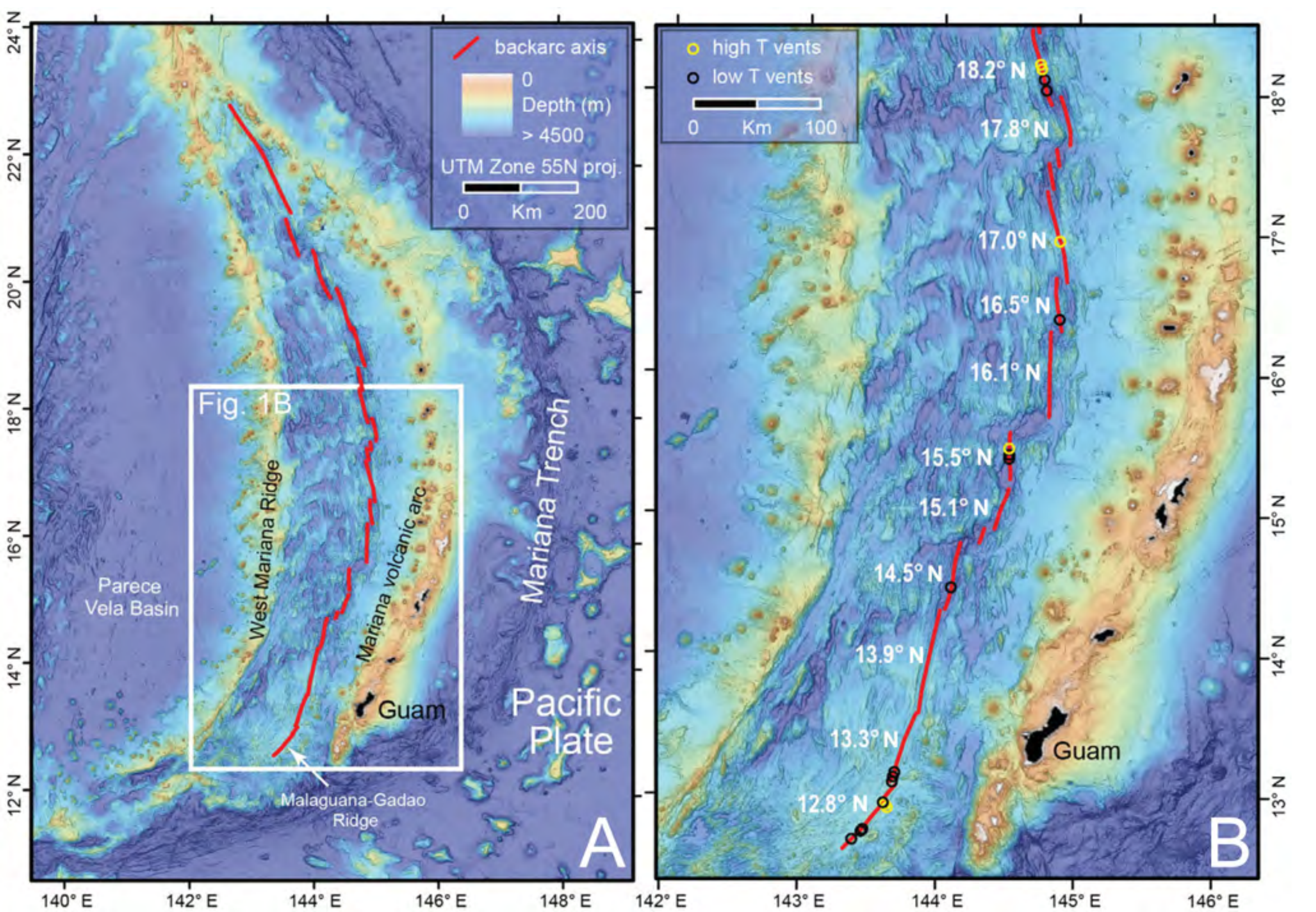

FIGURE 9 | (A) Bathymetry of the Mariana subduction system. Red line marks the Mariana backarc basin spreading axis showing location of B. (B) Spreading axis of Mariana Trough backarc basin showing locations of known hydrothermal vents. Video concerns Hafa Adai hydrothermal vent near 17° N. Note subdivision Modified after Baker et al. (2017).

You might wonder why such hot water does not boil: the answer is because of the tremendous pressure at this depth. This "black smoker" was colonized by numerous species that vary with proximity to the vent, probably because of the toxicity of some vent chemicals. There were a lot of shrimp and tubeworms around the vent sites, then inches to feet away were crabs and limpets. Still farther away, the dominant fauna were anemones. The interested reader can learn more about Mariana Trough hydrothermal vent fauna from Kojima and Watanabe (2015).

Hydrothermal vents (watch or download 50s video): https://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/logs/photolog/welcome.html#cbpi=/okeanos/explorations/ex1605/dailyupdates/media/video/0501-hydrothermal-vents/0501-hydrothermal-vents.html.

3.2.2 | East Diamante (15°56′ N, 145°40′ E, 370 m b.s.l.; SRoF04, SRoF06)

East Diamante is an arc volcano in the Southern Seamount Province that lies about 250 km north of Guam. It has a well-developed (5 × 10 km) caldera (Figure 10) that formed via violent felsic submarine eruptions ~0.5 Ma. Felsic igneous activity continued until at least as recently as approximately 20 000 years ago, with emplacement of resurgent dacite domes in the center of the caldera (Stern et al. 2014). Rocks beneath the caldera remain hot enough to power the only black smoker hydrothermal system known among Mariana arc volcanoes. Based on the mineral assemblage, the maximum fluid temperatures were ~260°C, near the boiling point for the water depths of the mound field (Hein et al. 2014).

This vent field is especially interesting because it is shallow enough that sunlight penetrates to it, providing a unique seafloor environment where chemosynthetic and photosynthetic communities coexist.

Five towers hydrothermal chimney (watch or download 55 s video): https://oceanexplorer.noaa.gov/explorations/06fire/logs/may1/media/movies/diamante2_video.html.

Black forest hydrothermal vents (watch or download 58 s video): https://oceanexplorer.noaa.gov/explorations/04fire/logs/april06/media/black_forest1_video.html.

3.2.3 | Chamorro Volcano (20°49′ N; 144°42.44′ E, ~1000 m; OE16-3)

Chamorro volcano is a submarine arc stratovolcano in the Northern Seamount Province of the Mariana arc. It is sometimes confused with Chamorro Seamount, a serpentine mud volcano in the southern Mariana forearc. Chamorro volcano erupted andesitic-dacitic lava (Bloomer, Stern, and Smoot 1989). NOAA Ocean Exploration 2016 Leg 3 Dive 7 examined the outer southeast slope of its summit crater (Cantwell et al. 2021). The ROV traversed rubbly seafloor composed of volcanic ash, cobbles, and boulders before it discovered hydrothermal activity from a small chimney structure producing 10.5°C fluid. After descending into the crater, the ROV documented additional hydrothermal activity across a previously unknown vent field. The chimney mounds are small (one to two meters high), but the temperature at one was as high as 31°C, much cooler than found in hydrothermal vents found elsewhere, a sign that the rocks beneath

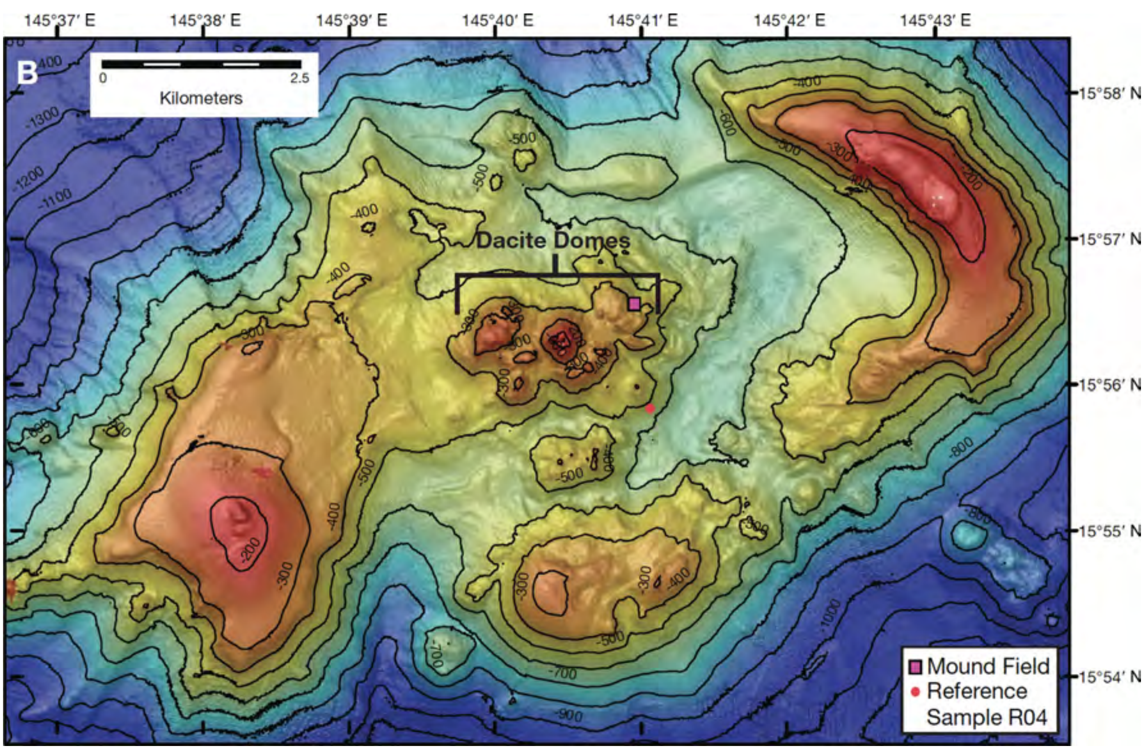

FIGURE 10 | E. Diamante volcano. Shaded bathymetric map shows the location of resurgent dacite domes in the middle of the caldera and associated hydrothermal vents (small pink box). Modified from Hein et al. (2014).

this volcano are cooling off and that the hydrothermal field is slowly dying. There is still enough chemically laden fluid coming of the vents to support a diverse chemosynthetic community. The dominant fauna is stylasterid corals—a type of hydrocoral, and animals known to be commonly associated with hydrothermal vents, like *Alvinoconcha* snails, alvinocaridid shrimp, and vent crabs. Other fauna documented included unusual amphipods, rare blind (polychelid) lobsters, two species of unidentified demosponges, cutthroat eels and rattails, and a variety of fish swimming near the vents.

Chamorro vent discovery (watch or download 1.2 min video): https://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/logs/photolog/welcome.html#cbpi=/okeanos/explorations/ex1605/dailyupdates/media/video/0624-vent/0624-vent.html.

3.2.4 | Fina Nagu Caldera A (12.8615° N, 143.829° E, ~2300 m; OE16-1)

NOAA Ocean Exploration 2016 Leg 1 Dive 7 was conducted on the Fina Nagu volcanic complex SW of Guam. This string of small volcanic edifices and calderas lies marks the southern termination of the Mariana volcanic arc. The Fina Nagu volcanic complex is an unusual alignment of five small, closely spaced submarine calderas, with the youngest (Caldera A) in the NE and the oldest 30 km away in the SW (Brounce et al. 2016). Normally an arc volcano would build up with time as lavas were erupted but the hotspot-like arrangement of aligned small volcanoes is due to a fixed source of arc magma lying beneath strongly extending lithosphere of the southernmost Mariana Trough. More info about the Fina Nagu volcanic complex can be found in the blog "Aging the Craters of the Fina Nagu Complex" https://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/logs/apr28/welcome.html.

3.2.4.1 | Caldera A. The very youthful nature of volcanism at Caldera A is revealed by the very fresh appearance of pillow lavas shown in the first video. You can see many fine details preserved on their surfaces. In this regard, they look a lot like the 2013–2015 pillow lavas shown in Section 3.1.1 but are not glassy, signifying that submarine eruption that formed them was significantly older. We do not know how much older, whether 10 or 1000 years older.

Pillow lava (watch or download 40 s video): https://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/dailyupdates/media/video/0503-pillow/0503-pillow.html.

Extinct hydrothermal chimneys (watch or download 40 s video): https://oceanexplorer.noaa.gov/edu/themes/vents-and-volcanoes/multimedia.html#cbpi=media/video/multimedia-extinctchimney.html.

4 | Suggestions for Use in the Classroom and in Textbooks

The information and videos listed and presented above can be used for teaching purposes in a number of ways, and for different levels of students. The short videos lend themselves to incorporation into PowerPoint presentations on a wide range of topics. Undergraduates in introductory geology or oceanography courses would benefit from the broad overview these provide of convergent margin submarine volcanism and hydrothermal activity. This paper could be assigned to be read by students.

The video links take you to NOAA websites where many other videos from SRoF04, SRoF06, and 2016 Deepwater Exploration of the Marianas are also posted. With time and effort, the interested instructor can find many other short videos and information that can easily be adapted for the classroom.

More advanced students would also benefit if selected videos were incorporated into lectures into specific topics, for example, on magmatic volatiles, mineralization, or submarine arc volcanism. They are also likely to benefit from reading papers in the reference list.

Some non-geoscience students can also benefit from watching some of these videos. For example, biology students would benefit from some of the videos of life around active hydrothermal vents as a way to make concepts about chemosynthetic communities more vivid. Chemistry students would benefit from examples of sulfur chemistry and the behavior of liquid carbon dioxide. Environmental science students and others interested in carbon capture and sequestration would benefit from observing natural examples of liquid CO_2 to better understand its behavior and also the formation of clathrates.

Some of these videos could also be useful in textbooks, especially introductory geology and oceanography textbooks. Readers interested to see more footage like this should look at the seafloor video archive of JAMSTEC, which includes footage of the NW Rota eruptions. https://www.godac.jamstec.go.jp/jedi/e/.

These are just a few examples of how these videos and associated information could be used in the classroom and in textbooks. The author would be very interested to learn from instructors and textbook writers how they are used.

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Ethics Statement

The author has nothing to report.

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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