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Explorations of Mariana Arc Volcanoes Reveal New Hydrothermal Systems

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Some 20,000 km of volcanic arcs, roughly one-third the length of the global mid-ocean ridge (MOR) system, rim the western Pacific Ocean. Compared to 25 years of hydrothermal investigations along MORs, exploration of similar activity on the estimated ~600 submarine arc volcanoes is only beginning [*Ishibashi and Urabe*, 1995; *De Ronde et al.*, 2003]. To help alleviate this under-sampling, the R/V *T. G. Thompson* in early 2003 (9 February to 5 March) conducted the first complete survey of hydrothermal activity along 1200 km of the Mariana intra-oceanic volcanic arc. This region includes both the Territory of Guam and the Commonwealth of the Northern Mariana Islands.

The expedition mapped over 50 submarine volcanoes with stunning new clarity (Figures 1 and 2) and found active hydrothermal discharge at 12 sites, including the southern back-arc site. This includes eight new sites along the arc (West Rota, Northwest Rota, E. Diamante, Zealandia Bank, Maug Caldera, Ahyi, Daikoku, and Northwest Eifuku) and four sites of previously known hydrothermal activity (Seamount X, Esmeralda, Kasuga 2, and Nikko) (Figures 1 and 2). The mapping also fortuitously provided a "before" image of the submarine flanks of Anatahan Island, which had its first historical eruption on 10 May 2003 (Figures 1 and 3).

The geological and hydrothermal features of volcanic arcs merit exploration because they are distinct from MORs in several important ways: the variety of rock composition in volcanic arcs generates a wider range of hydrothermal fluid chemistry than is found at typical MOR sites; the broad depth range of submarine volcano summits injects hydrothermal effluents throughout the water column, including the euphotic zone; the geologic environments at arc volcanoes are similar to those known to be conducive to large ore deposits; and the wide range of habitat conditions on volcanic arcs may nurture unique and diverse microbial and faunal communities.

The Submarine Ring of Fire program funded by NOAA's Office of Ocean Exploration is designed to address these issues through detailed exploration of the Mariana Volcanic Arc (MVA). This first cruise had three primary goals: to map all of the major submarine volcanoes of the MVA from Guam (~12°N) to its juncture with the Volcano Arc at ~23°N using high-resolution sidescan sonar and multibeam systems (Figure 1); conduct a comprehensive survey of hydrothermal activity on submarine volcanoes using a conductivity-temperature-depth (CTD)/rosette system to map and sample hydrothermal plumes (see Figure 2 for an example); and deploy an array of five autonomous hydrophones in the back-arc basin (Figure 1) to monitor acoustic signals. Additional images, maps, and results from the cruise are available at the Ocean Exploration Web site at: http://www.oceanexplorer.noaa.gov/explorations/03fire/welcome.html.

Geologic Setting of the Mariana Arc

Exploratory mapping and sampling of the Mariana Arc have been ongoing since the 1960s [e.g., *Bloomer et al.*, 1989; *Fryer*, 1995; *Stern et al.*, 2004; *Ishibashi and Urabe*, 1995]. Recent high-resolution mapping using shipboard multibeam and the Hawaii Mapping Research Group's MR1 towed sidescan sonar (also used on the 2003 expedition; see http://www.soest.hawaii.edu/HMRG/MR1/index.html) was conducted mostly south of ~16°N by the R/V *Melville* in 1997 and 2001. Additional multibeam data were collected during a dredging campaign in 2001 (S. Bloomer, pers. comm., 2003), and in 2002 during a multichannel seismic survey of the arc (B. Taylor, pers. comm., 2003). A geophysical survey of the Mariana Trough also covered portions of the active volcanic arc [*Iwamoto et al.*, 2002].

Volcanic activity in the MVA is frequent and widespread. The Smithsonian Global Volcanism Program lists nine sub-aerial and 10 submarine volcanoes with recorded activity along the Mariana Arc (http://www.volcano.si.edu/gvp/world/region.cfm?rnum=0804), but more than half of the volcano summits are at depths >300 m, where hydrothermal or volcanic activity can occur unseen and unexplored. Submarine eruptions along the Mariana Arc have been inferred from observations made by passing ships and overflying airplanes, and by acoustic detection of eruption sounds using hydrophones [*Norris and Johnson*, 1969]. Taken together, the acoustic and observational evidence suggests historical submarine eruptive activity on up to seven submarine volcanoes along the MVA. These include, from north to south, Nikko, Fukujin, Kasuga 1, Makhahnas, Ahyi, Ruby, and Esmeralda Bank (Figure 1).

The 2003 Submarine Ring of Fire Expedition

The expedition mapped more than 18,000 km^2 with MR1 and almost 28,000 km^2 with the EM300 multibeam system (Figure 1). CTD operations were conducted over more than 50 individual volcanoes, including 32 "tow-yos" across volcano summits and calderas (see Figure 2 for example). A total of 70 CTD stations yielded 3055 samples divided between chemical analyses of dissolved and particulate hydrothermal tracers, including ^3He, CH_4, CO_2, H_2S, various metals, and microbiology. The MR1 sidescan surveys began at the northern end of the 2001 R/V *Melville* survey at 16°N and extended to Nikko Volcano at 23°05'N.

Evidence for active hydrothermal venting was found at 12 submarine volcanoes, plus at least two sites on the southern back-arc spreading center (Figure 1). Detailed analyses of collected water samples could increase this total. The frequency of hydrothermally active volcanoes is lowest in the Central Island Province between Guguan and Asuncion Islands, where the density of volcanoes is also lowest [*Bloomer et al.*, 1989]. Results confirm continuing hydrothermal activity at Seamount X [*Masuda et al.*, 1994], Kasuga 2 (but not Kasuga 3) [*McMurtry et al.*, 1993], Esmeralda Bank [*Stüben et al.*, 1992], and Nikko (K. Nakamura, pers. comm., 2003). Of the seven volcanoes with evidence for historical volcanic activity, only three—Nikko, Ahyi, and Esmeralda Bank—appear to be hydrothermally active at present. The volcanoes with active hydrothermal systems appear to be about equally divided between those with and without summit calderas.

In situ studies of the hydrothermal systems are needed to determine the history and geological context of the hydrothermal activity, but some interesting questions easily arise from the initial data set. For example, are the

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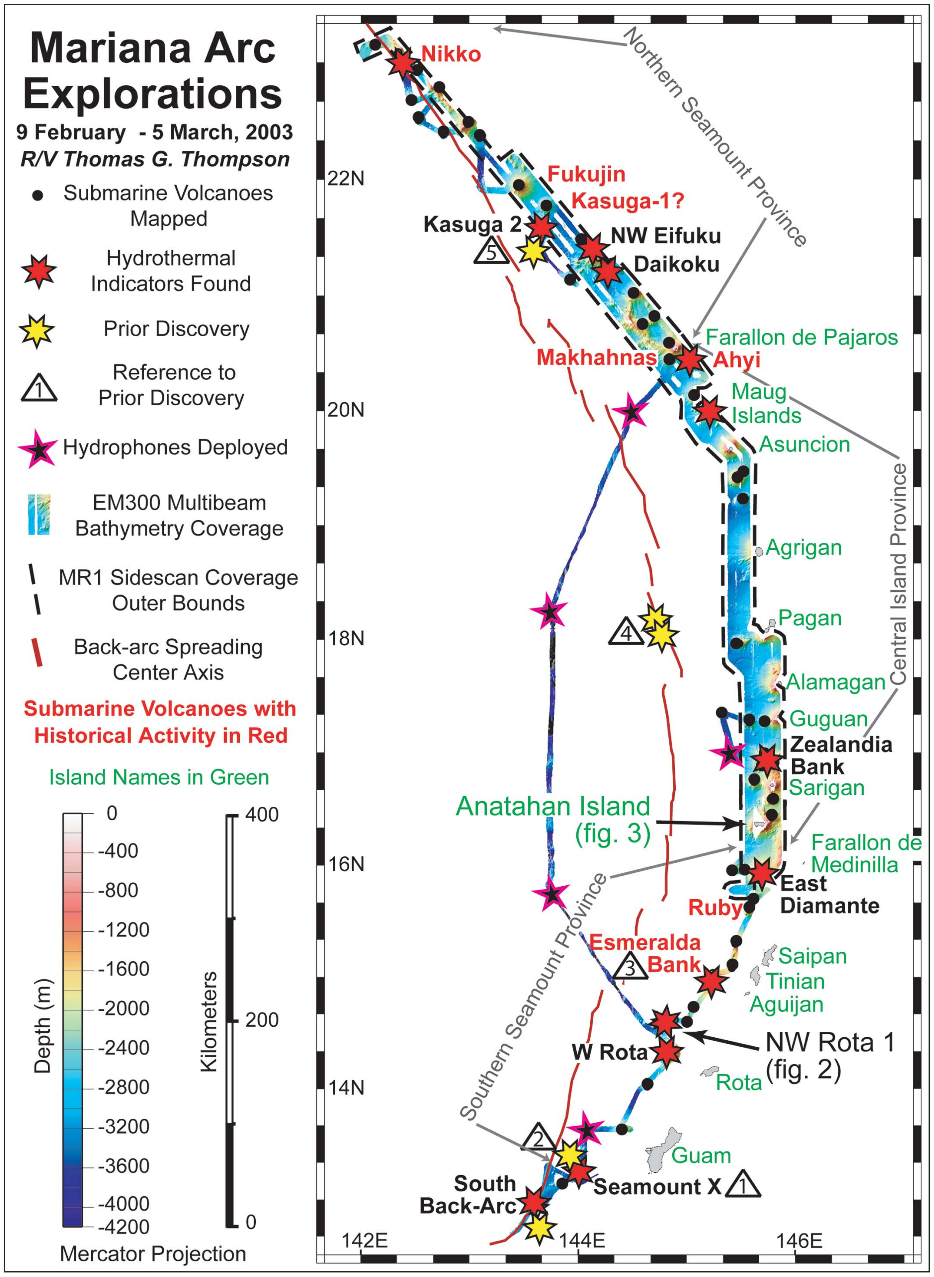

Fig. 1. Mariana Island Arc volcanoes are overlain with the track of T. G. Thompson *cruise 153. Symbols for various features are shown in the legend. References for known hydrothermal sites (numbers in triangles) include: 1 [*Masuda et al., *1994]; 2 and 4 [*Ishibashi and Urabe, *1995]; 3 [*Stüben et al., *1992]; and 5 [*McMurtry et al., *1993]. Hydrothermal vents on Nikko and two other volcanoes in the southern back-arc area are known from Shinkai 6500 dives (K. Nakamura and J. I. Ishibashi, pers. comm., 2003).*

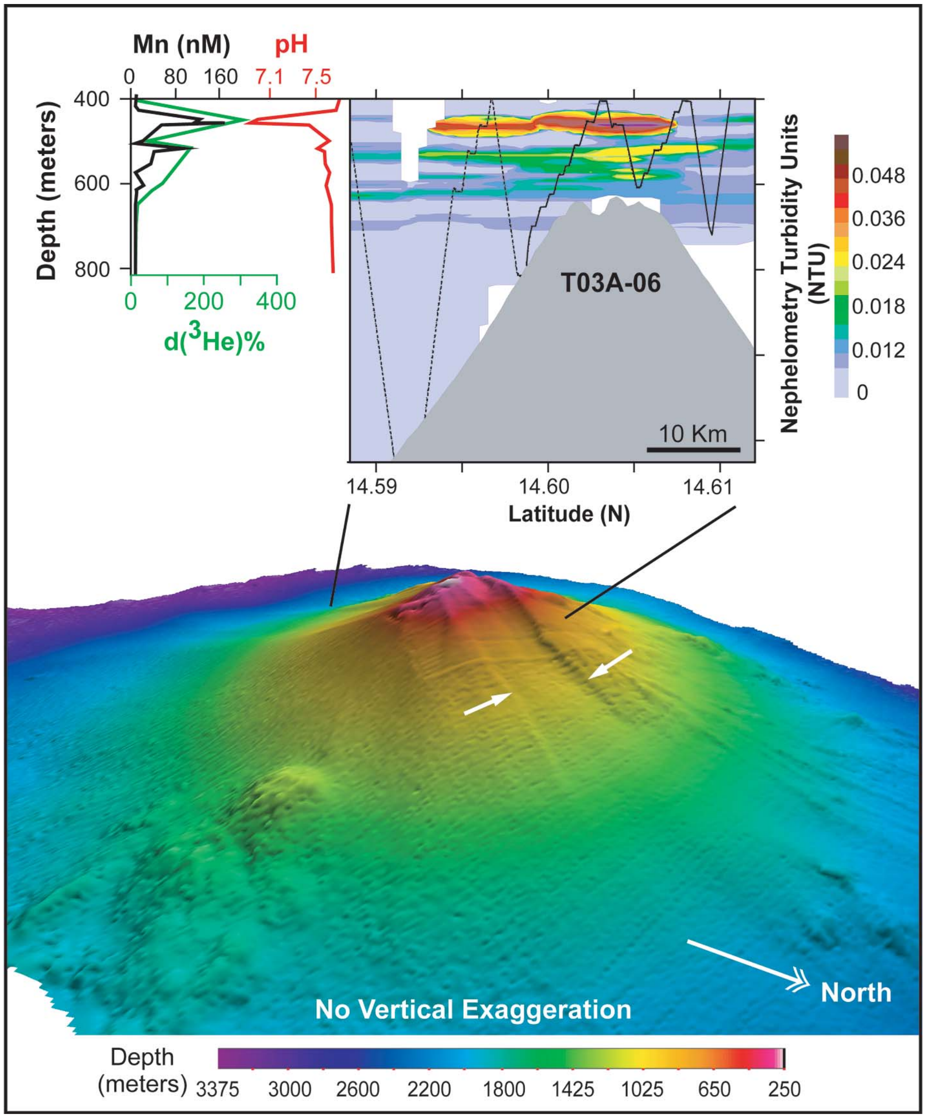

Fig. 2. This EM300 multibeam three-dimensional image of northwestern Rota #1 volcano was taken looking southwest (location on Figure 1). Black lines are approximate end points of CTD tow-yo. Light backscattering data from tow-yo is shown above. Dissolved Mn, pH, and ^{3}He anomalies in plume are shown at left. Small white arrows show location of structural lineaments running through volcano. Diameter of volcano (at base of steepest slope) is ~10 km.

hydrothermal systems associated with summit calderas longer-lived than those on volcanoes without calderas? How do the variations in hydrothermal chemistry relate to geologic parameters; depth, for example?

On 10 May 2003, Anatahan Island began its first known historical eruption (http://www.volcano.si.edu/gvp/world/region08/ivm_arc/anatahan/var.htm). A survey around the flank of the island (Figures 1 and 3), made 3 months before the eruption, shows features indicative of geologically young submarine activity. Ridges extending southeast into deeper water from the southeastern flank of Anatahan could be submarine rift zones; the present eruption of Anatahan is on the eastern side of the island. The well-defined reflective (darker) zones overlying the ridges are probably lava flows erupted during a submarine flank eruption.

Another intriguing discovery is the presence of a robust hydrothermal signal within the caldera of Maug Islands. The three Maug Islands are the remnants of an explosive caldera-forming eruption that occurred sometime in the Quaternary http://www.volcano.si.edu/gvp/world/region08/ivm_arc/maug/var.htm#bgvn_1706).

The hydrothermal activity in the caldera suggests that a shallow magma chamber capable of generating eruptions may underlie it. The Anatahan eruption and the presence of the hydrothermal system at Maug, both formerly considered "dormant" volcanoes, underscores the need for more information about the character of shallow submarine arc volcanoes.

A second expedition to the MVA is scheduled for this year. There is an intent to use a remotely operated vehicle to conduct detailed mapping and sampling of fluids, biota, and mineral deposits at selected submarine volcanoes.

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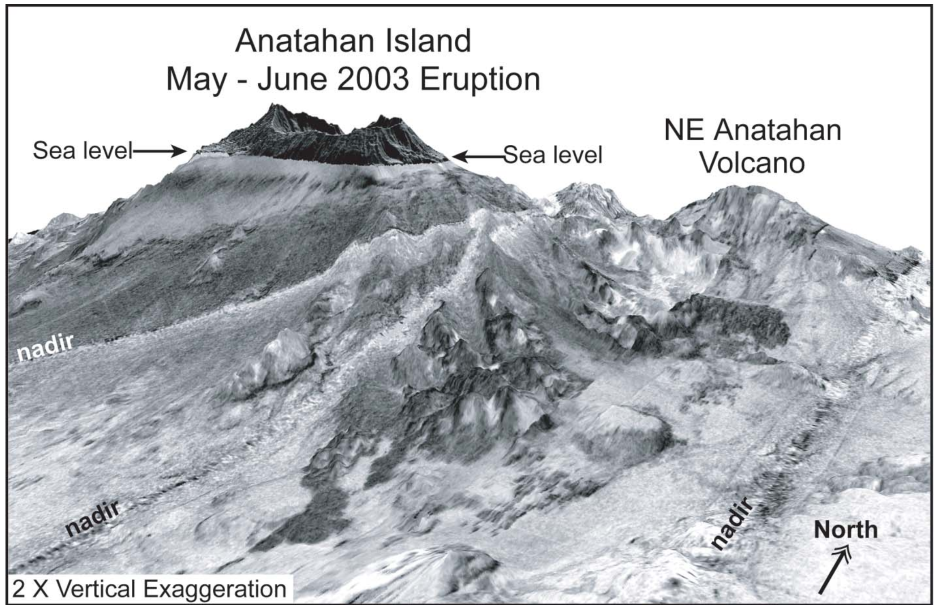

Fig. 3. MR1 sidescan sonar backscatter imagery (16-m grid) draped over EM300 and SB2000 multibeam bathymetry (35-m grid) is shown in the vicinity of Anatahan Island (location on Figure 1). The view is looking north-northwest toward southern flank of the Anatahan Island. Darker shades represent higher backscatter values. Tracks (linear bands marked as "nadir") spaced at approximately 9-km spacing in foreground. Anatahan Island is 9 km in length. The SB2000 data was collected by R. Dziak. The digital elevation model of Anatahan Island was created by Steve Schilling (U.S. Geological Survey) and geo-referenced with control points provided by Frank Trusdell (U.S. Geological Survey).

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FORUM

Cosmic Rays, Carbon Dioxide, and Climate

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Several recent papers have applied correlation analysis to climate-related time series in the hope of finding evidence for causal relationships. For a critical discussion of correlations between solar variability, cosmic rays, and cloud cover, see *Laut* [2003].

A prominent new example is a paper by *Shaviv and Veizer* [2003], which claims that fluctuations in cosmic ray flux reaching the Earth can explain 66% of the temperature variance over the past 520 m.y., and that the sensitivity of climate to a doubling of CO_2 is less than previously estimated.

Shaviv and Veizer's paper was accompanied by a press release titled "Global Warming not a Man-made Phenomenon," in which Shaviv is quoted as stating, "The operative significance of our research is that a significant reduction of the release of greenhouse gases will not significantly lower the global temperature, since only about a third of the warming over the past century should be attributed to man."

Here we present a critical appraisal of the methods and conclusions of *Shaviv and Veizer* [2003].

Reconstructing Cosmic Ray Fluxes

The starting point of *Shaviv and Veizer* [2003] is a reconstruction of cosmic ray fluxes over the past 1000 m.y. based on 50 iron meteorites and a simple model estimating cosmic ray flux (CRF) induced by the Earth's passage through galactic spiral arms [*Shaviv*, 2002, 2003]. About 20 of the meteorites, making four clusters, date from the past 520 m.y., the time span analyzed in *Shaviv and Veizer* [2003]. The meteorites are dated by analyzing isotopic changes in their matter due to cosmic ray exposure (CRE dating [*Eugster*, 2003]). An apparent age clustering of these meteorites is then interpreted not as a collision-related clustering in their real ages, but as an indication of fluctuations in cosmic ray flux.

One difficulty with this interpretation is that variations in CRF intensity would equally affect all types of meteorites. Instead, the ages of different types of iron meteorites cluster at different times [*Wieler*, 2002]. Hence, most specialists on meteorite CRE ages interpret the clusters as the result of collision processes of parent bodies, as they do for stony meteorites (ages $\leq$ 130 m.y.), to which more than one dating method can be applied.

Another problem of the CRF reconstruction is the presumption of "periodicity" of the clusters. The time spans between the clusters' gaps, which correspond to high CRF in their theory, are roughly 90, 90, 140, 130, 190, 140 m.y. (Figure 4 of *Shaviv* [2003]). The claim that these data support a periodicity of 143 ± 10 m.y. does not seem obvious. The passage through the four galactic arms should be a regular process; the high variability of the age gaps is not addressed.

The CRF model is based on the assumption that cosmic ray density should be concentrated in the galactic spiral arms, with a time lag of peak CRF of about 15 m.y. behind the spiral arm passage. CRF is computed by a simple diffusion model with several free parameters. These parameters are constrained by "observational constraints," including the meteorite data. These constraints are very weak; the crucial cosmic ray diffusion coefficient can only be constrained to within two orders of magnitude.

Moreover, even the "best fit" CRF model does not fit the meteorite data well. For the time span analyzed in *Shaviv and Veizer* [2003], the