



Radiation maps of ocean sediment from the Castle Bravo crater

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On March 1, 1954, the United States conducted its largest thermonuclear weapon test in Bikini Atoll in the Marshall Islands; the detonation was code-named “Castle Bravo.” Radioactive deposits in the ocean sediment at the bomb crater are widespread and high levels of contamination remain today. One hundred thirty cores were collected from the top 25 cm of surface sediment at ocean depths approaching 60 m over a ~2-km² area, allowing for a presentation of radiation maps of the Bravo crater site. Radiochemical analyses were performed on the following radionuclides: plutonium-(239,240), plutonium-238, americium-241, bismuth-207, and cesium-137. Large values of plutonium-(239,240), americium-241, and bismuth-207 are found. Comparisons are made to core sample results from other areas in the northern Marshall Islands.

Bravo crater | Bikini Island | cesium-137 | ocean sediment | plutonium

On March 1, 1954, the US military detonated its largest thermonuclear weapon on an island located in the northwestern rim of Bikini Atoll in the Marshall Islands. The weapon, code-named Castle Bravo, released an energy equivalent to 15 million tons of trinitrotoluene (TNT) (15 megatons), a value substantially larger than the US military’s prior estimates, although controversy still remains on this topic (1). [For example, declassified documents show that the routing and placement of observing aircraft were set for a 15-megaton explosion (1, 2).] The Bravo bomb was the first thermonuclear weapon test using solid LiD material as the central design for the fusion process, allowing this device to be aviation deliverable to enemy targets. The test was performed on a strip of land adjacent to Nam Island. The Bravo bomb was the second large-scale thermonuclear weapon test performed, following the first test, code named Ivy Mike, whose yield was 10.4 megatons. Ivy Mike was detonated in the northwest rim of Enewetak Atoll 16 mo earlier, on November 1, 1952.

The Bravo bomb vaporized an artificial island, leaving a ~75-m-deep, 1.5-km-diameter crater located adjacent to a ~0.25-km² patch of land, called Nam Island (Fig. 1). Instantaneously, the Bravo test produced a blast, heat, and prompt radiation, which dissipated rapidly (3). However, residual radiation from radioactive fallout (4) was spread throughout the world and, not surprisingly, a particularly large concentration was deposited locally in the Bravo crater in the northwest corner of the Bikini lagoon and throughout the northern Marshall Islands. Residual radiation from such a massive fallout can last from days to years, decades, centuries, and beyond, depending on the half-life of the radionuclide.

Nuclear weapons testing at the location of the Bravo crater did not end with the Bravo test. Six more nuclear weapons were detonated in close proximity to the Bravo crater. Two tests in particular, named Castle Romeo (detonated 1 mo after Bravo) and Hardtack Poplar (detonated in 1958), had yields of ~10 megatons each, and both were located southwest and approximately 2 km away from the Bravo center. These tests likely knocked the southwestern rim of the initial Bravo crater, making the southern edge of the Bravo crater the deepest side. As a result, today’s radioactive contamination from the Bravo crater

comes from a complicated mix of nuclear weapons tests detonated in the area. The range of yields was from 1 to 15 megatons for the 7 nuclear weapons detonations in the Bravo crater vicinity (Table 1 and Fig. 1). The total yield from nuclear-weapons tests performed in the few-kilometer-diameter Bravo crater region corresponds to one-third of the total yield from the entire US nuclear weapons testing program in the Marshall Islands.

Over the years, sediment samples have been collected in Bikini Atoll to determine the radioactive contamination of the lagoon from the nuclear weapons testing program. In the 1960s and 1970s, a handful of cores was collected in the Bravo crater and the radionuclide presence was measured in these samples (5–7).

A recent study of ocean cores collected at the Bikini and Enewetak test sites provides an up-to-date quantitative result of radiation levels in the crater sediment (8). However, the study was limited to a few cores. No large-scale systematic study has been published on the radioactive contamination to ocean sediment from nuclear weapons testing.

Here, we present measurements of the radioactivity levels of 5 radionuclides from 129 cores collected within the Bravo crater. These results are used to create radiation maps of the Bravo crater, allowing for a more detailed and systematic discussion of radioactive contamination from thermonuclear weapons testing.

Results

On August 1, 2018, we surveyed the depth of the Bravo crater using a JMC V108 video echo sonar installed underneath the

Significance

High-yield thermonuclear explosions cause enormous radioactive contamination to the environment. These “hydrogen bombs,” when tested on small islands in the ocean, vaporize the land and produce radionuclides that settle in the ocean sediment. Even decades later, significant contamination may remain in the sediment surface and deep into the sediment layers. Measuring the radioactive contamination of the crater sediment is a first step in assessing the overall impact of nuclear weapons testing on the ocean ecosystems. We find radiation levels orders of magnitude above background for plutonium-(239,240), americium-241, and bismuth-207 in the top 25 cm of sediment across the entire Bravo bomb crater, the location of the largest aboveground US nuclear weapons test.

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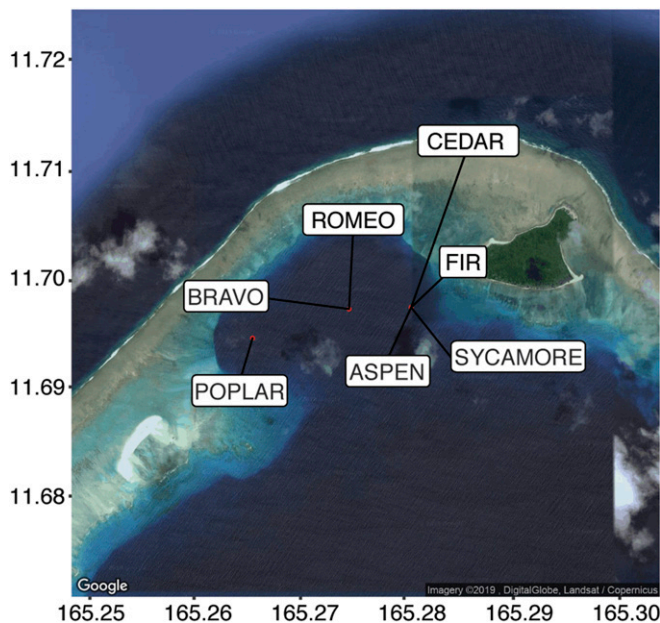


Fig. 1. Approximate location of the 7 tests conducted by the United States inside the Bravo crater. GPS coordinates collected from ref. 16.

hull of a 23-m research vessel, *Indies Surveyor*, owned by the Indies Trader company. Fig. 2 presents the results of an interpolated depth map of the crater by performing a kriging fit to the sonar data using the R programming language (9). The fit used a Gaussian model (10) similar to an analysis done on island gamma radiation measurements (11). A map generated from individual depth measurements, collected by the scuba divers, allowed for an independent assessment of the accuracy of the depth measurements. From this comparison, we estimate an overall uncertainty on our depth map to be ± 1.5 m. The main reason for the depth study was to aid in the dive planning. Sediment collection in the majority of the crater necessitated deep diving to depths greater than 45 m, firmly in the range of advanced technical scuba diving.

A total of 129 cores were collected in the Bravo crater over 2 y, in 2017 and 2018. Measurements were made of the following radionuclides: plutonium-238 (^{238}Pu), plutonium-(239,240) ($^{239,240}\text{Pu}$), americium-241 (^{241}Am), bismuth-207 (^{207}Bi), and cesium-137 (^{137}Cs). Relatively low values were found for 2 radionuclides, namely ^{238}Pu and ^{137}Cs . These radionuclides were chosen for our study as they represent by-products from nuclear weapons testing and were accessible for Gel Laboratories, the company that performed the radiochemical analysis. The average values for ^{238}Pu and ^{137}Cs were found to be 2.3 and 1.6 pCi/g, respectively. The values for $^{239,240}\text{Pu}$, ^{241}Am , and ^{207}Bi were noticeably higher with

Table 1. Nuclear weapons test in the Bravo crater region

Name	Date	Yield, kilotons
Bravo	3/1/54	15,000
Romeo	3/27/54	11,000
Fir	5/12/58	1,360
Sycamore	6/1/58	92
Aspen	6/15/58	319
Cedar	7/3/58	220
Poplar	7/13/58	9,300
Total		37,391

The columns list the test name, the date of the test, and the yield in kilotons. Total yield in the Bravo crater region is also presented.

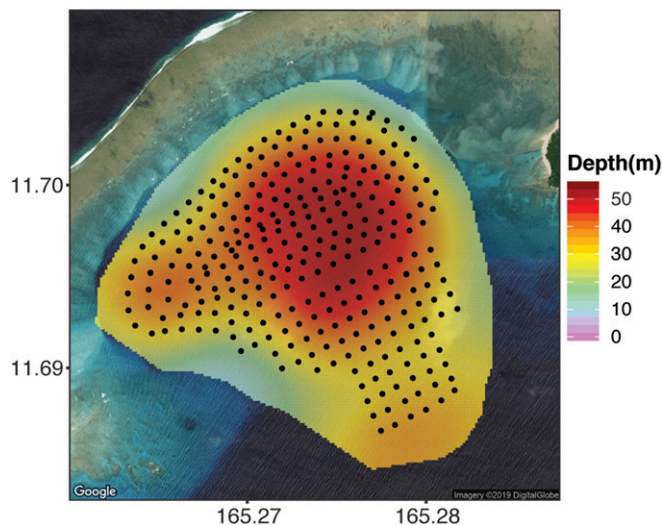


Fig. 2. Interpolated depth map of the Bravo crater based on echo sonar measurements (black dots).

average values of 56, 34, and 10 pCi/g, respectively. The uncertainty in the measurements was less than 1 pCi/g in all cases.

Before the primary radiation mapping project performed in August 2018, we collected 21 cores from 1 location at the Bravo center in May 2017. The main goal of the 2017 coring pilot study was to investigate the reproducibility of the ocean sediment results, when collected from precisely the same location. Table 2 presents the results for the mean and SD from the 5 radionuclides studied for these 21 cores. The analysis of the cores by Gel Laboratories is identical to what was performed on the 2018 cores. In fact, all cores were analyzed in the same batch submission in Fall 2018. In Table 2, we also list the radionuclide half-life, which has an effect on the current levels for a few of the radionuclides, given that the weapons testing occurred 65 y ago.

From August 2 to 9, 2018, 108 sediment cores were collected along 4 diameters across the crater, corresponding to the north-south, east-west, northwest-southeast, and northeast-southwest directions. Fig. 3 presents a map of the designed 100-core plan versus the actual Global Positioning System (GPS)-measured coordinates of the 108 cores that were collected. The origin of the difference between our goals and the true locations come from the limitation in the scuba diver's ability to estimate the distance and direction traveled deep underwater using a compass and a dive propulsion vehicle (DPV).

For the 108 cores collected in 2018, the individual radiation maps for the Bravo crater for ^{238}Pu , $^{239,240}\text{Pu}$, ^{241}Am , ^{207}Bi , and ^{137}Cs are given in Fig. 4. All results come from performing a kriging fit to the raw data. In general, one sees a relatively flat

Table 2. Mean and SD activity levels from radionuclides in 21 sediment cores collected at the same location, near the center of the Bravo crater

Radionuclide	Mean	SD	Half-life, y
Plutonium-239,240	50	6	24,000, 6,560
Americium-241	34	8	432
Plutonium-238	2.3	0.6	88
Bismuth-207	13	7	32
Cesium-137	1.7	0.2	30

Results are given in units of pCi/gm. Half-lives of the radionuclides are also presented.

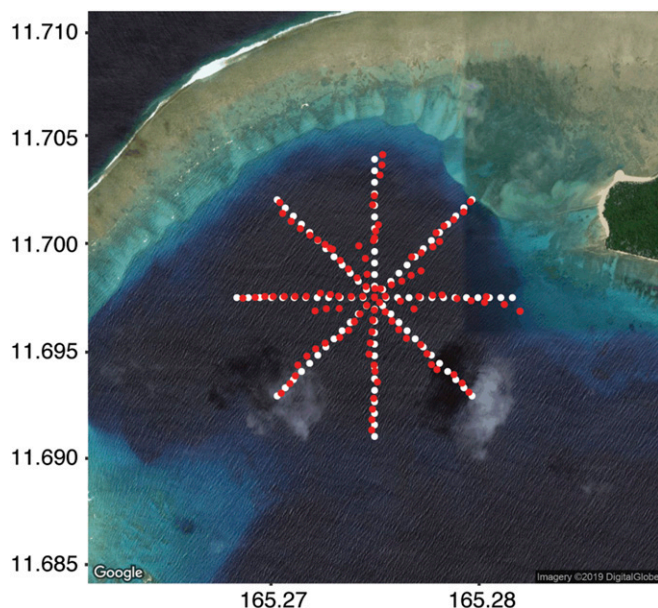


Fig. 3. Desired location (white circles) versus actual location (red circles) of collected sediment cores in the Bravo crater.

distribution with larger values located more centrally in the crater followed by tapering off by the crater edges, with some notable exceptions.

Finally, a comparison is made to cores collected from other islands and atolls in the northern Marshall Islands; we collected cores from additional locations just outside of islands, namely near Bikini and Enyu Islands in Bikini Atoll, Utirik Island in

Utirik Atoll, Rongelap Island in Rongelap Atoll, and several cores from the Lacrosse crater next to Runit Island in Enewetak Atoll. Table 3 presents single-core results for the 5 radionuclides collected from these regions compared with the average results from the Bravo crater. Not surprisingly, contamination levels farther away from the nuclear weapons testing sites have reduced radiation levels.

Discussion

The core samples from the Bravo crater provide radiation data of the lagoon sediment with sufficient statistics to produce interpolated maps. This study allows for the possibility to observe, for example, potential general trends and hot spots in the measured radionuclide distributions. Overall, we find a fairly uniform distribution of $^{239,240}\text{Pu}$ throughout the crater, with an observable tapering off toward the rim of the crater. A notably sharper tapering is observed in the ^{207}Bi results, from high values west of center to nearly undetectable levels at the crater edges. The ^{137}Cs data display a decrease by the northeastern crater edge; however, the overall levels of ^{137}Cs are substantially lower on average than all but the ^{238}Pu results. The ^{241}Am data correlate quite strongly with the $^{239,240}\text{Pu}$ data; this is a topic for future study.

The presence of coral, alive and dead, and notably grainy sand at the crater rim as well as the washout from weather events in shallower regions could affect and decrease the apparent activity. Some radionuclides, such as ^{137}Cs , are well known to interact chemically with the environment.

Compared with other regions in the northern Marshall Islands (Table 3), we find the largest extent of radionuclide activity to be in the Bravo crater. Compared with the lagoon near Bikini and Enyu Islands on the eastern side of Bikini Atoll, the values are an order of magnitude higher. In Utirik Atoll, ~500 km away, we find no presence of residual radioactivity to within the precision of our measurement uncertainty. Interestingly, there is also a significant difference between the lagoon near Bikini versus

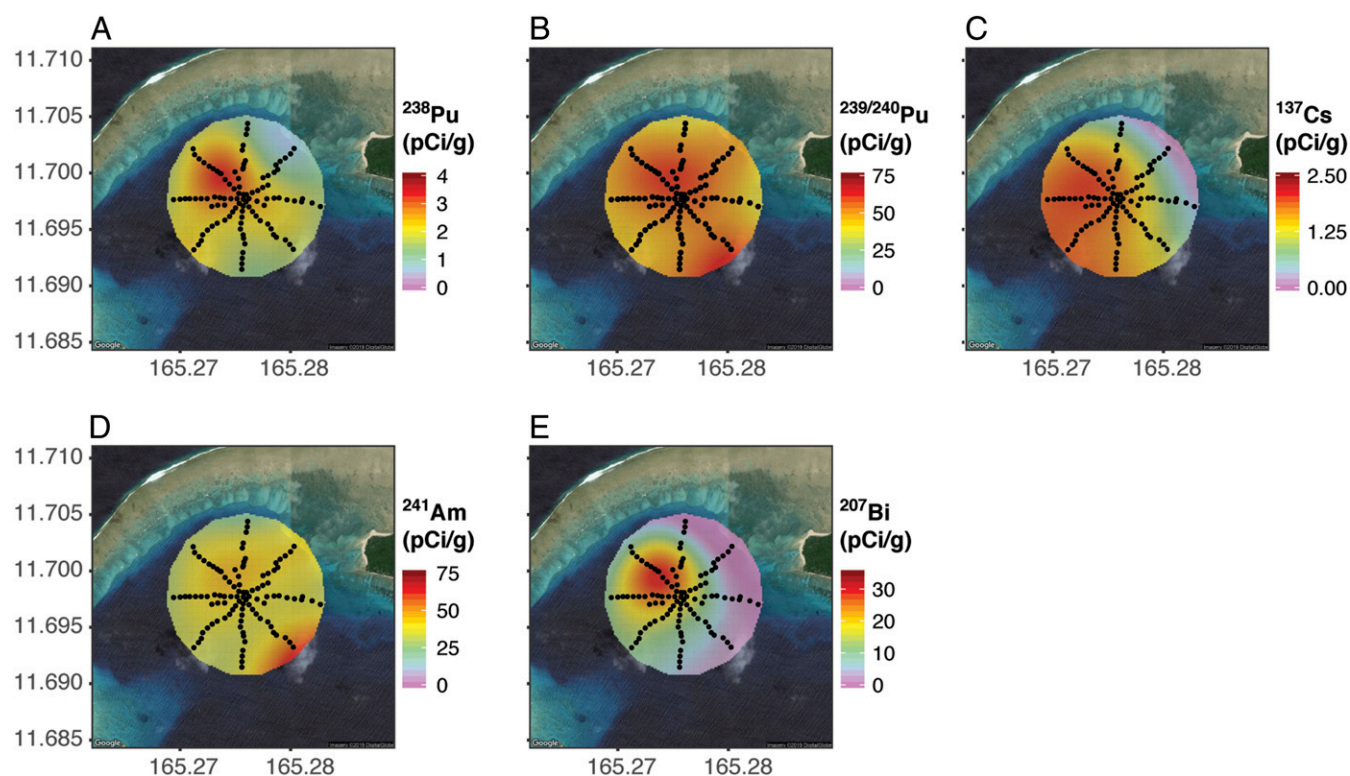


Fig. 4. Radiation levels of 5 different radionuclides in the top 25 cm of surface sediment of the Bravo crater. (A) ^{238}Pu . (B) $^{239/240}\text{Pu}$. (C) ^{137}Cs . (D) ^{241}Am . (E) ^{207}Bi . All activity concentrations are given in units of picocuries per gram.

Table 3. Activity levels for 5 radionuclides collected from individual cores adjacent to islands in the northern Marshall Islands

Radionuclide	Bravo	Bikini	Enyu	Rongelap	Utirik	Medren	Runit
Plutonium-239,240	54	2.3	0.45	0.23	0	0.17	6.2
Americium-241	40	1.5	0.4	0	0	0.2	1.0
Plutonium-238	2.3	0.2	0	0	0	0	2.0
Bismuth-207	15	0	0	0	0	0	0
Cesium-137	1.6	0	0	0	0	0	0.6

The Bravo results come from an average over 108 cores. Results are given in pCi/gm.

Enyu Island, with Enyu displaying noticeably smaller values for $^{239,240}\text{Pu}$, for example. Although we did not collect core samples from other thermonuclear bomb craters, we did collect a few samples from a fission bomb crater neighboring Runit Island in Enewetak Atoll. The Runit crater has an order of magnitude less $^{239,240}\text{Pu}$ contamination, but interestingly still has a concentration of ^{238}Pu comparable to the Bravo crater.

Compared with the recent handful of cores collected by the Buessler et al. (8), our average results are in good agreement. We find an average value of 56 picocuries per gram (pCi/gm) for $^{239,240}\text{Pu}$ activities in the Bravo crater, relative to 49 pCi/g (1,820 Bq/kg) from the top sediment of craters noted in the Buessler et al. study.

There are uncertainties in the results from the present study, some pertaining to the cores themselves and some related to the chemical analysis. The sediment was collected down to 25-cm depth from its surface. For the majority of the cores, the sediment analyzed corresponded to depths between ~15 and 25 cm deep. However, some of the cores, especially those near the Bravo rim, were not packed as tightly, so there could have been mixing between different sediment depths. It is likely that the average true sampled sediment depth coming from cores collected near the Bravo crater rim is shallower than the depth from cores collected near the Bravo crater center. A more systematic comparison of cores in which the core depth information is kept strictly intact would be valuable in future studies, as has been done previously (8, 12).

The crater appears to be filling in at a rate of approximately a meter every 3 y, so the measurement of the radioactive contamination performed today is only a crude approximation to what it was at the time of the Bravo test, 65 y ago. Contamination from neighboring nuclear tests, such as Romeo and Poplar, also cannot be excluded as contributing to the overall contamination in the Bravo crater lagoon sediment. The existence of these additional tests underscores the complexities in terms of estimating lagoon sediment contamination from individual nuclear weapons tests. The properties of the individual weapon tests also play a large role in the ultimate radionuclide deposition.

In regard to studies of nuclear weapon bomb craters in ocean environments, an important issue is the recovery of, in this case, lagoon life. Some studies addressing these issues have been done in Bikini Atoll (13, 14). On the edges of the crater at shallow depths, this pertains primarily to the coral regrowth. At deep depths, the sediment composition from nuclear weapons testing is dramatically altered, and a much finer grain and silty sediment remains. Bacteria and sea cucumbers are ubiquitous. Studies of the morphology have been performed (15). Correlating residual radioactivity and sediment conditions with lagoon life impact would be an interesting future study.

Studying the Bravo crater and collecting ocean sediment was a large undertaking that involved deep technical scuba diving and the use of advanced scuba equipment and technologies. The zero-visibility conditions at deep depths presented a particularly

difficult challenge. Follow-up studies of the thermonuclear bomb crater environments would best be conducted in shallower conditions. For example, working in the Ivy Mike crater, whose depth is on the order of 35 m, as shown in Fig. 5, offers numerous advantages. Although still formally within the depths defined by technical scuba diving, the requirements on the diver would be eased substantially. Similarly, fission bomb craters, such as those found near Runit Island in Enewetak Atoll, are shallow and may be easier to study from a data collection perspective.

In summary, there is still residual contamination of radionuclides throughout the Bravo bomb crater, from center to rim. We find that the radionuclide distribution is fairly uniform across the crater with some tapering off toward the crater rim, the most dramatic change being in ^{207}Bi . Although the lagoon is gradually filling in over time, contamination levels from residual long-lived radioactive isotopes, such as plutonium and americium, will likely last for centuries. The nuclear weapon tests caused a dramatic change in sediment composition. Additional studies to determine what the impact on life is in the lagoon craters, especially at the deeper depths, would be valuable.

Methods

Crater Depth Mapping. To plan the dive program, the first step was to map the crater. The 23-m Indies Trader *Indies Surveyor* ship was equipped with a JMC V108 video echo sonar installed underneath its hull. The sonar determined the lagoon depth over a series of evenly spaced positions. From these measurements, we generated a depth map using a kriging fit implemented with the R programming language (9). Mapping of the Bravo and Mike craters, using the Surveyor, took several hours each.

Sediment Core Collection. Sediment cores were collected in 5-cm-diameter, 25-cm-long cylindrical clear plastic PVC tubes. The tubes had machined teeth on 1 edge, which were screwed into the top layer of the lagoon sediment during the collection process. Once the cores were filled, a vacuum-tight seal was screwed onto the exposed end of the sediment core. The core was then lifted and retrieved from the sediment floor and immediately capped. The task was performed at depths down to ~60 m in low-visibility conditions. Collecting the sediment disturbed the lagoon floor and rapidly generated a large silt cloud over most of the Bravo crater. Minimal sediment was lost during the retrieval process due to the strong suction from the first seal. Once the cores were capped, they were immediately sent to the surface using lift bags.

Once a sediment core was collected by a pair of divers, the dive team navigated underwater to a neighboring point, typically 60 m away, using a compass and a single Minnus-Traveler DPV made by the Submerge Scooters

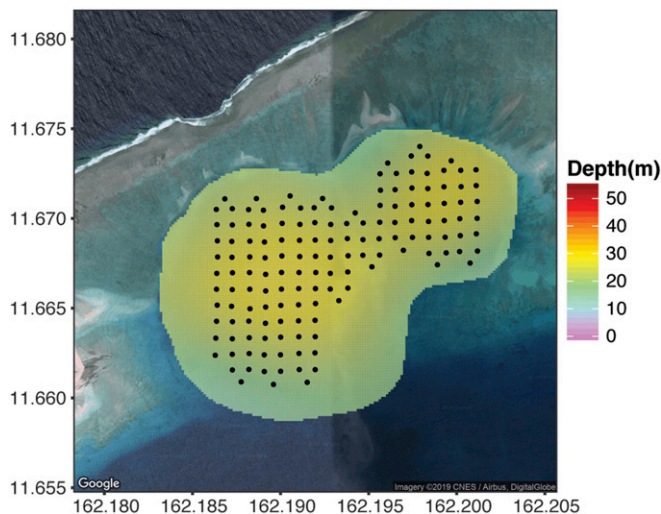


Fig. 5. Interpolated depth map of the Ivy Mike crater based on echo sonar measurements (black dots).

Company. The DPV used a NiMH battery so that it could be transported on a commercial aircraft. The scooter was able to rapidly transport a pair of divers at depth. Five advanced technical divers performed the crater sediment collection for the radiation mapping project over an 8-d period.

GPS Measurements. A GPS record was taken on the surface by hand using a Garmin etrex 30x by researchers operating on a small motor boat. Multiple GPS measurements were taken by the team on the boat for redundancy. The Garmin GPS measurement is quoted by the company as being accurate to a distance of ± 12 m. A dedicated study was performed in which multiple cores were sent from the same location at deep depths in rapid succession, and the GPS point was measured on the surface, under windy conditions. From this systematic study, we found a reproducibility of the core location to be good to within a couple of meters. The relative precision of the core GPS measurement appears to be significantly better than the absolute position uncertainty quoted by the Garmin Company. Although on a few windy days the surface of the water in the lagoon became quite choppy, there was essentially no current in the Bravo crater throughout the project.

Subsample Preparation. Once collected, cores were transported intact back to Columbia University. Subsamples of sediment were removed from the deep end of the core, corresponding to 15 and 25 cm from the lagoon sediment surface. Subsamples were transferred to a 100-mL plastic centrifuge tube. All subsamples were mailed as a batch to Gel Laboratories for isotopic analysis. Although sediment mixing throughout the 25-cm depth is certainly possible, it did appear that for the vast majority of the core samples the solid hard mud, with pulverized consistency of the lagoon sediment, is more likely not to have mixed. Therefore, it is likely more accurate to assume that the samples in this study are represented by considering that the composition originated from sediment located between 15 and 25 cm from the sediment surface rather

than closer to the surface. However, the sediment composition over the majority of the Bravo crater did differ significantly from the composition near the edges. Samples collected near the crater edges were more grainy; therefore, these samples are more likely to have sediment mixing from differing sediment depths (ranging, at most, over the full 0 to 25 cm).

Radiochemical Analysis. Gel Laboratories performed the radiochemical analysis of the core sediment samples. The subsample precipitate was dissolved in acid, and the elements were subsequently separated by ion exchange resins. After radiochemical separation, concentrations were determined by isotopic alpha emission (16). Minimum detection limits for alpha emission are estimated to be 1 pCi/g. Measurements of ^{137}Cs activity were performed using gamma detection techniques, and minimum detection limits for this process are estimated to be 0.1 pCi/g.

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