Caldera-forming Submarine Pyroclastic Eruption at Myojin Knoll, Izu-Bonin Arc

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A large caldera-forming eruption, having about twice the volume of the famous 1883 Krakatau event, occurred at Myojin Knoll on the Izu-Bonin Arc, about 400km south of Tokyo. The age of the eruption is not known, but it may have occurred in the past several thousand years. The eruption probably took place at water depths of 200-400m, and a caldera 5-6km in diameter and 520-900m deep resulted from edifice collapse into a partly emptied magma reservoir. An estimated $36km^3$ of rhyolite pumice and other debris was erupted. Part of this material is contained in a 130-200m pumice-rich deposit at the top of the caldera wall, which was observed and sampled during three "Shinkai 2000" dives. Much of the erupted material probably traveled downslope in cold submarine pyroclastic flows; additional material was carried in aqueous suspension or floated on the sea surface. Caldera formation likely triggered tsunamis. Because the age and recurrence intervals of large submarine events at this and other nearby volcanoes are so poorly known, societal risks related to events of this type cannot yet be evaluated.

Key words : Submarine caldera, Submarine eruption, Submarine pumice, Tsunami

1. Introduction

This report presents preliminary findings and interpretations of the rhyolitic caldera-forming eruption at Myojin Knoll Volcano. We restrict discussion only to the latest caldera-forming eruption and its products; in addition, we do not consider the geology of the pre-caldera volcanic edifice or the post-caldera dome complex that grew on the caldera floor. Available data include observations made and samples obtained during seven "Shinkai 2000" dives into the caldera, as well as bathymetric coverage of about 60 percent of the volcanic edifice. Because the caldera-forming eruption was not observed and because needed additional data are not yet available, our account of this event is both preliminary and interpretive.

The caldera-forming eruption at Myojin Knoll was a large and important event. The volume of tephra erupted is estimated to have been about twice that of the famous 1883 Krakatau eruption, yet only in recent years has the Myojin Knoll area been recognized as the site of a caldera-forming eruption. In the past few decades, volcanologists worldwide have learned a great deal about large pyroclastic eruptions that take place on land. In contrast, virtually nothing is known about similar eruptions on the sea floor and how they impact the marine environment. Our ongoing studies at Myojin Knoll Caldera represent the first sustained effort to fill this wide gap in knowledge.

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2. Location and general setting

Myojin Knoll Caldera is located along the front of the Izu-Bonin Arc at 32° 06'N, about 400km south of Tokyo (Fig.1). The caldera lies at the summit of a broad volcanic edifice, 15km in diameter. Conspicuous knolls on the flanks and near the top of this edifice are interpreted to mark the summits of small pre-caldera volcanic cones that grew and coalesced to form a larger, "compound" edifice. Rocks making up the pre-caldera cones have been observed in the caldera wall during "Shinkai 2000" dives #555, 624, 696, 734, 735, and 737.

Myojin Knoll Caldera is one of several submarine calderas believed to lie along the Izu-Bonin Arc (Murakami and Ishihara, 1985; Nagaoka et al., 1991; Yuasa et al., 1991). One of these, the Kurose-nishi Hole, has been questioned as a volcanic caldera (Fujioka and Saito, 1992), but most of the other structures are probably of caldera-collapse origin.

3. The Caldera

The Myojin Knoll Caldera is an elliptical structure about 5-6km in diameter (Fig.2). The depth of the caldera rim varies from 500 to 880m, and the flat caldera floor lies at a depth of about 1,400m. The caldera wall therefore varies in height from 520 to 900m. As noted earlier, the bathymetric knolls adjacent to the caldera are interpreted to be the summits of small submarine volcanoes that coalesced to form the pre-caldera volcano edifice. Some of these small volcanoes have been cut by the caldera fault, revealing parts of their interior structure. The post-caldera dome complex on the caldera floor has a volume of at least $0.6km^3$.

We estimate the volume of the caldera collapse to be about $18.1km^3$. Of this total, $13.6km^3$ is represented by the volume of the present-day caldera, $0.7km^3$ by "caldera fill" material eroded from the steep caldera walls and deposited on the caldera floor, and $3.8km^3$ by the missing top of the pre-caldera volcanic edifice. An assumed caldera-fill thickness of only 100m was used in these calculations; this estimate is conservative. The total volume of caldera collapse is therefore probably greater than $18.1km^3$ as stated above.

4. Pumice Deposit

4.1 General Stratigraphy

A deposit rich in rhyolite pumice, ranging in thickness from 130 to about 200m, is exposed at the top of the caldera wall. It is probable that this same deposit blankets the lower slopes of the Myojin Knoll Volcano and the surrounding sea floor. This deposit was traversed completely in the upper caldera wall during "Shinkai 2000" dives 555, 696, and 734. In addition, the lower several meters of the deposit were likely observed during "Shinkai 2000" dive 737. The contact marking the base of the deposit is shown schematically on the cross section in Fig.2.

The detailed stratigraphy of the pumice deposit is not yet known, and "Shinkai 2000" traverses made thus far show deposit to be rather poorly exposed. Several coherent outcrops 2-5m high were observed in each of dives 555, 696 and 734, but most areas are partly or completely covered with manganese-coated

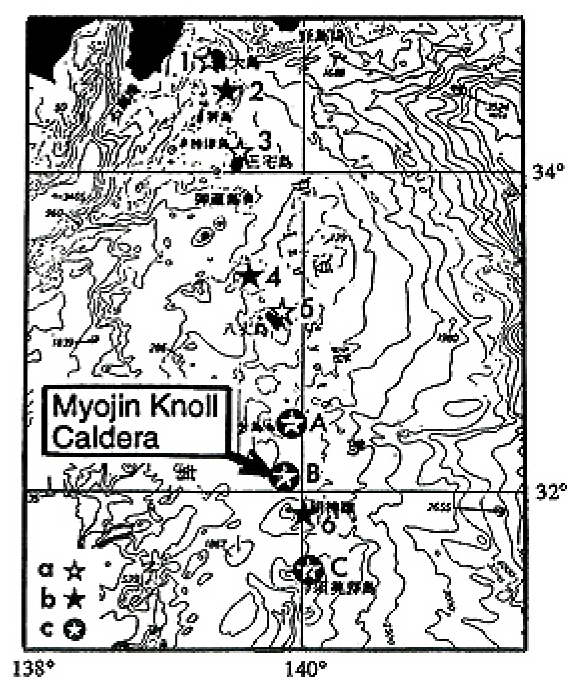

Fig.1 Map of northern Izu-Bonin Arc (Murakami and Ishihara, 1985). Myojin Knoll Caldera is one of several recognized calderas.

pumice blocks that rolled downslope from the caldera rim. Crude bedding was observed in places, usually defined by the subhorizontal alignment of dark clasts enclosed in lighter colored pumice. A superficial look at these pumiceous outcrops might suggest that the deposit is poorly sorted, and it is true that clasts larger than about 1 cm in diameter occur in a wide range of sizes. Closer inspection, however, shows that fine-grained matrix is virtually absent, and the deposits everywhere observed has an intact framework of clasts. No welding or sintering was observed.

The upper surface of the pumice deposit is exposed at the top of the caldera wall, and everywhere observed it is littered with large blocks of pumice coated with manganese oxide. These blocks, a few tens of centimeters to more than 2m in diameter, were deposited as a result of late-stage submarine fallout.

4. 2 Chemistry

Table 1 shows major and trace element analyses of pumices collected from "Shinkai 2000" dives 555 and 696. Also shown are major element analyses of four small lithic fragments collected from the thick pumice deposit during the "Shinkai 2000" dive 734 to the north caldera wall. All of these samples are rhyolitic in composition; in addition, the pumices are noteworthy for their low contents of K20.

4. 3 Pumice densities

We collected several hundred pumice lapilli and kept them submerged in sea water upon returning to the surface. In the laboratory, we determined the density of 203 individual lapilli, still water saturated. We then dried these same lapilli and determined their

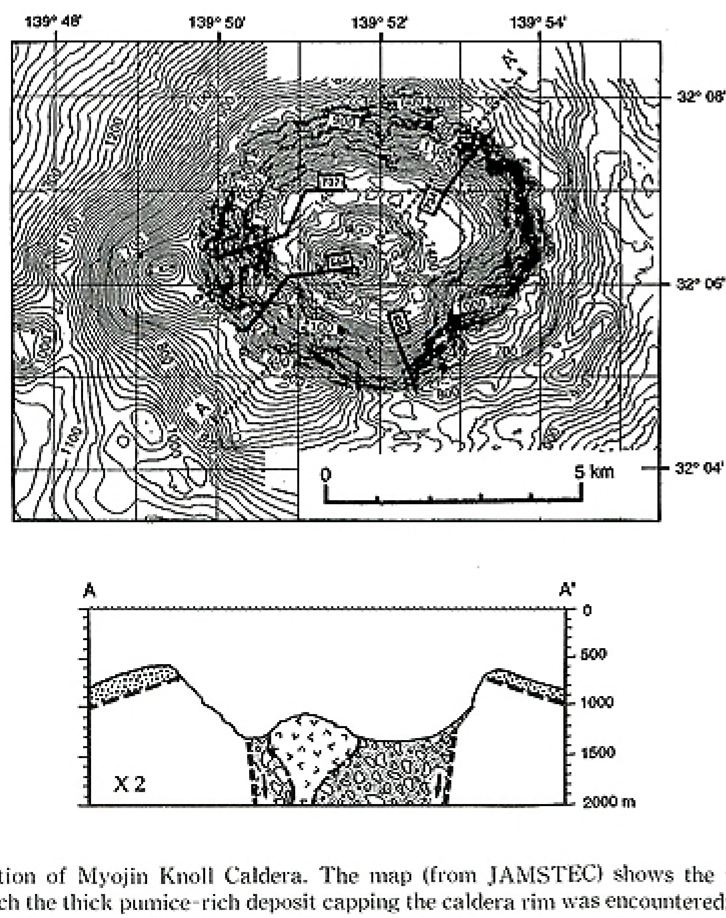

Fig.2 Map and cross section of Myojin Knoll Caldera. The map (from JAMSTEC) shows the four "Shinkai 2000" traverses along which the thick pumice-rich deposit capping the caldera rim was encountered; depth in meters. The interpretive cross section shows the pumice-rich deposit (stippled), the pre-caldera edifice (nonpatterned), the caldera fill (rubbly pattern), and the post-caldera dome complex (checked pattern).

Table 1 Chemical analyses of pumices and accessory lithics from the thick deposit capping the caldera wall. Major element analyses normalized to 100% anhydrous. "Orig. Sum" is the analysis before normalization. FeO determined by titration. All samples analyzed with a Phillips model PW 1,480 x-ray spectrometer. Analyses by V. Avery, Smithsonian Institution.

Description / Location	Pumice, SW Caldera Wall			Pumice, S Caldera Wall		Lithics, N Caldera Wall				
Sample	555-6	555-7	555-8	696-5	696-6	734-4L1	734-4L1 Dupe	734-4L3	734-4L4	734-4L6
SiO2	74.54	75.02	74.53	73.64	71.74	74.25	74.15	74.83	74.55	73.93
TiO2	0.31	0.32	0.32	0.32	0.38	0.38	0.39	0.26	0.33	0.32
Al2O3	13.51	13.43	13.50	13.29	13.74	13.69	13.86	13.52	13.51	13.82
Fe2O3	0.86	0.83	0.94	0.67	*3.80	0.87	0.79	0.90	0.58	0.96
FeO	1.93	1.75	1.94	2.52	0.00	2.11	2.12	1.60	1.87	1.52
MnO	0.11	0.10	0.11	0.15	0.13	0.09	0.09	0.09	0.07	0.07
MgO	0.63	0.54	0.61	0.53	0.86	1.42	1.40	0.65	0.60	0.59
CaO	2.76	2.63	2.74	2.72	3.25	2.51	2.52	2.15	3.01	3.02
Na2O	4.42	4.49	4.41	5.18	5.21	4.27	4.27	5.10	3.95	4.34
K2O	0.63	0.81	0.84	0.90	0.79	0.32	0.32	0.95	1.45	1.36
Cr2O3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P2O5	0.09	0.08	0.07	0.08	0.09	0.09	0.09	0.06	0.07	0.06
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Orig. Sum	100.50	100.66	100.65	100.68	100.32	100.94	100.49	100.23	100.90	100.70
Ba	171	186	167	150	117					
Co	<5	<5	<5	<5	<5					
Cr	<10	<10	<10	<10	<10					
Cu	21	35	27	11	6					
Nb	10	3	7	<2	<5					
Ni	7	13	13	4	<5					
Rb	10	9	11	11	10					
Sr	133	127	132	139	139					
V	16	11	14	<10	11					
Y	34	34	34	47	41					
Zn	69	80	65	82	98					
Zr	127	126	131	129	102					

Major element analyses normalized to 100% anhydrous. "Orig. Sum" is the analysis sum before normalization. FeO determined by titration. All rocks analyzed with a Philips model PW 1480 x-ray spectrometer. Analyses by V. Avery, Smithsonian Institution.
*All Fe as Fe2O3

densities again. The results of these measurements are shown in Fig.3.

Both histograms show that the studied pumices have a wide range of densities, whether water-saturated or dry, and this is due to variations in vesicularity from sample to sample. It is clear, however, that most of the water-saturated pumices have densities ranging from 1.3 to 1.6g/cm^3. These same pumices, when dried, have densities clustering in the range 0.5 to 1.1g/cm^3.

We interpret these relations to indicate that much of the caldera-related eruption column remained below sea level, where steam-inflated pumice quenched and ingested sea water, quickly transforming most individual pumice lapilli from "floaters" to "sinkers," a process first described by Kato (1987). The rapid fallback of this material to the upper slopes of the volcano can explain the thick pumice deposit observed in the upper part of the caldera wall.

If the eruption column broke through sea level, as it probably did, much pumice could have cooled in air. Quenching in this environment resulted in air being ingested, and, as suggested by the data presented in Fig. 3B, these pumices would have floated on the sea surface. The combined effect of ocean currents and wind could have transported this pumice far from the volcano.

5. Caldera-forming eruption

Many details of the caldera-forming eruption will never be known, but we can comment briefly on a few eruption-related interpretations:

5.1 Location of eruptive vents

The thick pumice deposits observed along the three "Shinkai 2000" traverses did not appear to be disturbed by immediately adjacent eruptive activity. The precise location of the eruptive vents is not known, but they were probably located within the area now occupied by the caldera.

5. 2 Depth of eruption

Upward extrapolation of the volcano's slopes suggests that the shallowest part of the pre-caldera volcano lay at about 200m below sea level. Nearby summit areas may have been at depths of up to 400m. The eruptive vent, or vents, were probably located somewhere in the summit area, at water depths of 200-400m.

5. 3 Variations in eruption intensity

The vague stratification defined by local concentrations of lithic clasts, as well as bedding within the pumice itself, suggests that the eruption varied in intensity. The local concentrations of lithic clasts may indicate that phreatomagmatic explosions, which tore fragments from the pre-caldera edifice, punctuated the eruption of pumice.

5. 4 Eruption through sea level

It is likely that the eruption was sufficiently energetic to break through the sea surface and rise into the air. Pumice that cooled in a resulting subaerial eruption column would tend to ingest air. As discussed above, much of this material therefore floated. Ocean currents and wind could have transported this material to great distances from the volcano.

5. 5 Location of caldera faults

Caldera faults have not been observed. The cliffs forming the upper walls of the present-day caldera have doubtless been eroded back, chiefly as a result of small post-caldera avalanches and erosion. These processes have built extensive talus cones that blanket the lower caldera wall, especially along the south and northwest parts of the structure. It is likely that the caldera fault, or faults, are buried beneath this talus. We have shown the approximate location of this fault in the cross section in Fig.2.

6. Proximal deposits

We arbitrarily define proximal deposits as those laid down on the sea floor within 20km of the Myojin Knoll. The makeup of this material is not yet known, but much of it was likely transported in submarine pyroclastic flows that traveled down the 16°-20° slopes of the volcano and continued outward over the sea floor. Once off the slopes of the volcano, these pyroclastic flows would likely have spread outward in all directions, hugging the sea floor as they traveled. As outlined above, we have interpreted that the pumice contained in these pyroclastic flows was water-saturated, and therefore "cold" when transported and deposited. It is therefore unlikely that any of these deposits are welded or sintered.

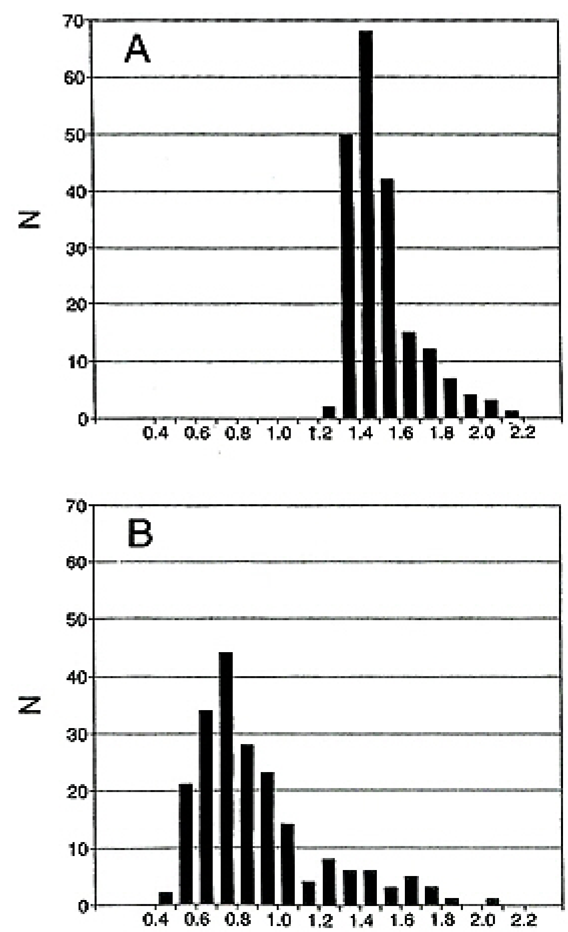

Fig.3 Bulk densities (g/cc^3) of 203 pumice lapilli recovered from the deposit at the caldera rim. (A) Densities of water-saturated pumice. (B) Densities of same pumices when dried. These differences are interpreted to reflect the environment in which the pumices cooled: submarine (A), and subaerial (B).

The thickness of the proximal deposits is unknown. Future coring, or perhaps shallow seismic refraction studies, may ultimately provide some thickness information. In the meantime, simple volume-area calculations provide a basis for estimating very approximate thickness values. As noted above, the volume of the Myojin Knoll Caldera is about $18km^3$. If we assume, as is the convention, that the volume of tephra erupted is twice the volume of the caldera collapse, then about $36km^3$ of pyroclastic debris was erupted into the local marine environment. Again, assuming that 95 percent of this material was deposited within 20km of the Myojin Knoll summit, the average tephra thickness within this area is about 27m. The deposits closer to the volcano would of course tend to be thicker, and those farther away would be thinner. In any case, it is likely that the sea floor near Myojin Knoll was abruptly blanketed a layer of tephra a few tens of meters thick. Other thick layers of deep-sea pumice have been documented elsewhere along the Izu-Bonin Arc by Nishimura et al. (1992).

Large volumes of slower-settling pumice, mostly in the form of large blocks, must also have been deposited proximally. As noted earlier, such material was observed to cap the thick pumiceous deposit at the top of the caldera rim. These blocks, inflated by steam and other magmatic gases at the time of the eruption, may have temporarily floated on the sea surface until ingestion of sea water gradually increased their bulk density to the point where they sank toward the sea floor. Ocean currents would have influenced the fallout trajectories of these blocks, carrying them kilometers laterally before they were deposited. The characteristics of this pumice-block deposit awaits the availability of deep-sea photography and other data. It is likely that maps showing average block diameter, when available, will show the same kind of lobe-like pattern that is characteristic of fallout deposits laid down on land.

7. Distal deposits

Virtually nothing is known about the distal deposits associated with the caldera-forming eruption (those deposited at distances greater than 20km from Myojin Knoll), but we suggest they probably represent an important component of the debris produced during and soon after the caldera-forming eruption. These deposits, composed of slower settling particles, are likely composed of two chief components: 1) material related directly to the eruption that was transported in suspension, and 2) material related to post-eruption convective upwelling from the newly-formed caldera.

Material related directly to the eruption that was carried in suspension and deposited at >20km from the volcano would have to be material having low values of fallout terminal velocity (low VT's). Much of this material probably consisted of fine grained ash, having VT's of 10 cm/sec or less, produced by fragmentation of pumice and other debris during the eruption. An unknown amount, however, probably consists of coarse pumice blocks that floated temporarily and saturated with sea water very slowly, similar to the material contained in the proximal coarse-pumice facies discussed above.

Post-eruption convective upwelling probably also contributed significant material to the distal facies of the Myojin Knoll tephra deposit. The collapse of the Myojin Knoll caldera, and disruption of associated hot rocks at shallow levels in the throat of the volcano, probably set up large convection cells that permitted large volumes of sea water to circulate through the hot rubbly debris of the caldera fill and then rise toward the sea surface. Similar convection cells at other volcanoes, such as at times between explosions at Myojin-sho in 1952-1953, produced turbid plumes that transported slowly-settling material far from the volcano (Morimoto and Ossaka, 1955). The same general process must have operated at Myojin Knoll, but probably more vigorously, because of the much larger size of the caldera-forming event. The transported debris was probably fine grained and had low VT's , enabling it to be carried great distances by ocean currents before being deposited on the sea floor. Traces of such material from this and other eruptions are probably contained in deep-sea sediments over a wide area of the nearby ocean floor, perhaps forming a component of the tephras described by Fujioka et al. (1992) and Nishimura and Murakami (1988).

8. Age

The caldera is geologically young, but we do not know its absolute age. Observations from "Shinkai 2000" show that much of the caldera wall is nearly vertical, implying that the structure formed recently. There has been sufficient time, however, for debris falling from this scarp to build the large talus cone that rests against the southern, eastern, and northeastern caldera wall. In addition, post-caldera time was of sufficient duration to allow the eruption of the thick rhyolite flows that make up the dome complex on the caldera floor. As noted above, studied samples of rock and pumice are low in potassium, and, in addition, they contain no observable potassium feldspar, indicating that accurate 40Ar/39Ar ages will be difficult, if not impossible, to obtain.

Alternatively, the age of the caldera-forming eruption might be obtained by studying deep-sea sediment cores collected 50 or 100km from the caldera. Fine grained tephra, from the caldera-forming eruption itself or from the convective upwelling that likely persisted for months or years afterward, could have been transported long distances by ocean currents and deposited in quiet deep-sea conditions. The age of this tephra, if it can be recognized, might be bracketed by paleontologic dating or other studies of the overlying and underlying sediment.

9. Hazards and risks

As noted earlier, the caldera-forming eruption at Myojin Knoll was a very large event. The resulting hazards are fairly straightforward to identify; the risks that such events pose are more difficult to assess.

9. 1 Hazards

Tsunamis. It is not known whether the Myojin Knoll caldera collapsed abruptly (within a few minutes or hours), or whether it collapsed more slowly in a piecemeal mode (taking a few days, weeks, or months). In the former case, it is likely that tsunamis would have been generated by the collapse process. The abrupt collapse of the Krakatau caldera in 1883, which has about half the volume of the Myojin Knoll structure, produced 30-m high tsunamis that devastated the coast of Java, 60-70km away (Simkin and Fiske, 1983). It is likely that tsunamis formed by caldera collapse at Myojin Knoll reached the island of Aogashima, just 40km away. It is also possible that these tsunamis traveled even farther, reaching more distant islands along the Izu-Bonin arc, or perhaps even parts of mainland Japan. Evidence for these tsunamis is probably difficult to recognize today, and might consist only of scattered calcareous debris torn from the adjacent shallow sea floor and deposited on the flanks of an island. Similar evidence was used to document giant Pleistocene tsunamis on the islands of Lanai and Molokai, in Hawaii (Moore and Moore, 1984; Bryan and others, 1993). The former tsunami ran up the side of Lanai to an elevation of about 375m above sea level.

Airborne tephra and floating pumice. If the submarine eruption column formed at the time of the caldera-forming eruption broke through the sea surface, it is likely that airborne tephra was scattered over a very wide area. This tephra must have blanketed islands located along its fallout trajectory, and floating rafts of pumice likely choked the sea surface. Ocean currents and wind carried the floating pumice away.

9. 2 Risks

The risks posed by the hazards discussed above are more difficult to assess. The age of the Myojin Knoll Caldera is not yet known, nor is the possible recurrence interval of other large explosive eruptions at that caldera. Very little is known about the eruptive histories of other submarine volcanic centers along the northern part of the Izu-Bonin arc, so there is currently little basis for quantifying the risk from submarine volcanic eruptions in this area.

This lack of knowledge, however, should not be confused with a lack of risk. An eruption of the size that produced the Myojin Knoll Caldera would likely be a destructive event. Additional information is needed about the frequencies and characteristics of submarine eruptions along the northern Izu-Bonin Arc.

10. Conclusions

An estimated 36km^3 of rhyolite pumice and associated lithic debris was erupted at ocean depths of 200-400m to form Myojin Knoll Caldera. Much of this pumice was quenched by sea water and fell back to the flanks of the volcano. Some pumice may have been carried into the air by eruption columns that broke through the sea surface. Much of this material ingested air and floated, producing huge rafts of floating pumice. The age of the caldera-forming eruption is not known, but it probably occurred in the recent geologic past. Future eruptions of this type will pose significant risks.

Acknowledgments

We extend sincere thanks to JAMSTEC and to the Operations Team of the "Shinkai 2000" and the crew of the R/V "Natsushima".

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(Manuscript received 22 June 1995)