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Estimating Paleoenvironments Utilizing Foraminiferal Fossils from the Toyohama Formation, Aichi Prefecture, Central Japan

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Summary

The Miocene Morozaki Group spreads across the Chita Peninsula in Aichi prefecture, Central Honshu, Japan, and was deposited between 18 to 15 Ma. Using foraminiferal archives contained in samples from the Katana outcrop at the tip of the Chita Peninsula, we aimed to verify whether the Chita Peninsula used to be in the deep ocean. We used various techniques such as the planktonic / total ratio (P/T) method and faunal analysis. Faunal analysis on mollusks from the same outcrop was also undertaken in order to obtain better data. From these experiments, we estimate the paleodepth of the Morozaki Group to have been between 100 to 2000 meters below sea level, and that the Chita Peninsula sediments were deposited in the deep ocean.

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Introduction

Microfossil assemblages in marine archives represent a powerful tool to estimate prehistoric marine environments (1). Microfossil usually refers to fossils that requires to observe through microscopes and are compared to macrofossils. Microfossils, including foraminiferal fossils, are more likely to dissolve chemically, but are physically stronger and much more abundant than many macrofossils. Foraminifers are a type of protist and has a calcareous shell. They vary in size; most are around 0.1 mm but some can grow up to nearly 5 cm. A large number of microfossils are often contained in sediments, making them a very significant tool for various paleoceanographic reconstructions (1).

The stratum observed in the Katana outcrop (E136°58’14”, N34°42’47”) is included in the Toyohama formation, Morozaki Group (**Figure 1A and 1B**). The Morozaki Group formed from the Early to Middle Miocene in the Neogene (2). This group belongs to the Setouchi Miocene Series, which was formed in deeper parts of the ocean compared with other strata such as the Ichishi, Fujiwara, and Mizunami Group, which formed at the same time (3). The group is composed of the Himaka, Toyohama, Yamami and Utumi formations, in ascending order.

The Morozaki Group is mainly composed of sandstone, mudstone, and tuff. Many fossils of fish and mollusks are found. However, planktonic foraminifers are scarce because of its siliceous lithofacies — this indicates that the amount of calcium carbonite was scarce when the strata formed (4). Instead, this group is largely composed of turbidites. Turbidites usually form when a large amount of sediment originating in a landslide is transported deeper than 200 meters underwater. This observation has led to the hypothesis that the Morozaki Group formed in the deep ocean (2). Since the deep ocean receives only minor impacts from currents and waves, muddy sediments would form more slowly compared to sandy sediment. This is visible in the Katana outcrop which has clear differences between each layer.

Previous reports suggest the depth of the Chita Peninsula was once between 200 to 600 meters (5) or deeper than 500 meters (6), based on macrofossil

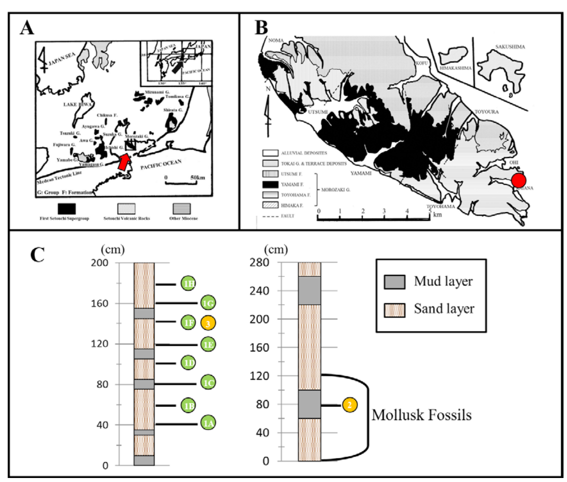

Figure 1: Study Sampling Points. A) Geological map of central Japan (modified from Yoshida, 1991). The red arrow shows Chita peninsula. B) Geological map of the study area (modified from Yamaoka, 1993). The red dot shows Katana outcrop. C) Geological column of the sampling point. The Y-axis shows the height of the sampling point in cm and the column on the right is 10 meters below the column on the left.

Sample	Circular	Sphere	Stick shape	Total
1-A	0	1	2	3
1-B	0	4	16	20
1-C	0	6	1	7
1-D	1	0	1	2
1-E	3	0	1	4
1-F	1	0	7	8
1-G	0	9	0	9
1-H	0	18	20	38

Table 1: Fossil classification by shape.

assemblages such as mollusks. Furthermore, while researchers have studied foraminiferal fossils from the Morozaki Group, no one has tried to estimate the paleodepth of the Chita Peninsula utilizing this approach. In this study, we estimated the paleoenvironment, in particular the depth of the Chita Peninsula, utilizing foraminiferal assemblage. We utilized the planktonic / total (P/T) method, and faunal analysis, described below:

The P/T method estimates the depth of the ocean using the ratio of planktonic foraminifers to total number of foraminifers. After figuring out the ratio of the planktonic foraminifera, the result is fitted into a P/T graph, which shows the depth of the deposit site. This P/T graph was made accordance with P/T rations at various depths from the Gulf of Mexico (7). Although there is a slight difference in the depth between different parts of the ocean, this type of graph has been used in many experiments to estimate the depth of sediments using foraminiferal ratios.

In contrast to the P/T method, faunal analysis is a method used to estimate the paleoenvironment from the habitat of the detected fossil species. The habitats — such as depth and climate — are estimated utilizing results from previous research.

We utilized foraminiferal fossils to estimate the environment which the Morozaki Group formed. We analyzed one set of foraminiferal fossil samples using the P/T method, and two samples using faunal analysis. In addition, faunal analysis was carried out using mollusks from the same outcrop.

As a result, we estimated the paleodepth of the Morozaki Group to be 100 to 2000 meters. The research also showed that the strata formed at least 17.54 Ma, at a time when there could have been two kinds of ocean currents in the region and a possible suboxic environment.

Results

The depth at which samples 1-H, 1-B and 1-D (**Figure 1C**) were deposited was estimated utilizing the P/T method, and the depth for samples 2 and 3 was done utilizing the faunal analysis. We first sorted fossils found in samples 1-A to 1-H (**Figure 1C**) by shape. Stick shaped fossils tended to be more abundant compared to circular and spherical fossils. Sample 1-H contained the most fossils, followed by sample 1-B (**Table 1**). These results provided insights into which sample contained the most fossils. From the results, samples 1-H, 1-B, and 1-D were further observed.

We found 327 fossils in sample 1-H, which included benthic species (31%) such as *Ammonia* sp., *Buccella* sp., *Elphidium* sp., and *Uvigerina* sp.; and planktonic species (69%) such as *Globigerina* sp., *Globigerinoides* sp., and *Orbulina* sp. (**Table 2**). Sample 1-B had a similar species composition with 44% benthic species and 56% planktonic species and a total of 248 fossils. (**Table 2**) The estimated depth from the P/T method was approximately 200 meters from sample 1-H, and 150 meters from sample 1-B (**Figure 2**). In addition, 687 fossils were found in sample 1-D, with benthic species (16%) such as *Ammonia* sp. and *Elphidium* sp., and planktonic species (84%) such as *Globigerina* sp., *Globigerinoides* sp. and

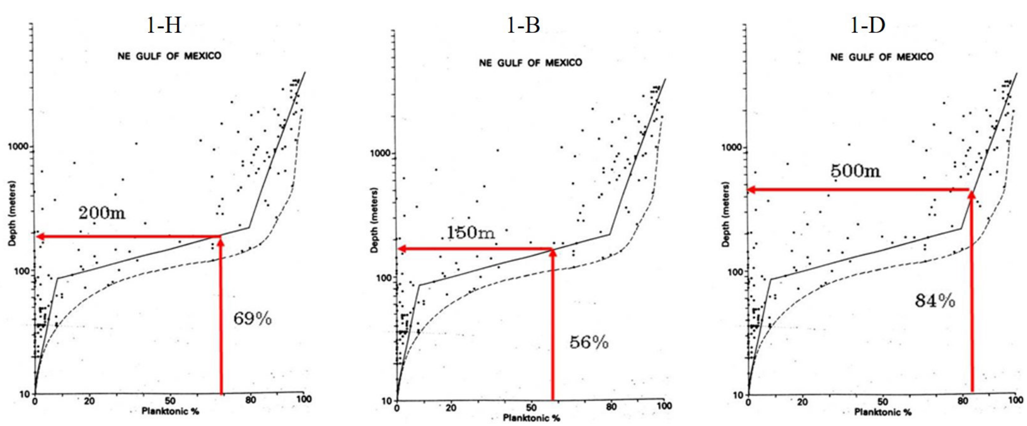

Figure 2: Depth Estimation using Foraminiferal Fossils. Showing collection of samples 1-H, 1-B, and 1-D, according to the P/T method (7). It was inferred from the graphs that the deposited depths were 200 meters, 150 meters and 500 meters respectively.

	Scientific name	1-H			1-B			1-D		
		Numbers	Total	Ratio	Numbers	Total	Ratio	Numbers	Total	Ratio
	Ammonia sp.	67			94			4		
	Bolivina sp.	0			5			0		
Benthic	*Buccella* sp.	3	100	31%	0	108	44%	0	107	16%
	Dentalina sp.	0			6			0		
	Elphidium sp.	28			2			103		
	Uvigerina sp.	2			1			0		
	Globigerina sp.	14			95			2		
Planktonic	*Globigerinoides* sp.	4	227	69%	10	140	56%	2	580	84%
	Orbulina sp.	209			35			576		
Total		327		100	248		100	687		100

Table 2: Further classification of fossils from samples 1-H, 1-B and 1-D. Fossils were classified by genus level. (*Orbulina* sp. later turned out to be radiolarian)

Orbulina sp. (**Table 2**). The estimated depth from the P/T graph is approximately 500 meters (**Figure 2**)

From sample 2, a total of 74 foraminiferal fossils were found (**Table 3**), including *Ammonia tochigiensis*, *Discorbis opercularis* and *Nonion kidoharaense* which lived in the Inner Sublittoral zone and Pullenia aperture, which lived in the Upper Bathyal zone (8). The Inner Sublittoral zone is approximately 0 – 50 meters and the Upper Bathyal zone is 150 – 400 meters, respectively (9). Therefore, the estimated paleodepth is restricted to between 0 – 400 meters based on the present faunal analysis. A total of 168 fossils were found from sample 3 (**Table 3**), including *A. tochigiensis* and *N. kidoharaense* of the Inner Sublittoral components, *Lenticulina rotulata* of the Upper Bathyal components and *Uvigerina* cf. *hootsi* of the Middle Bathyal component (8). The Middle Bathyal zone is approximately 400 – 2000 meters (9). Therefore, we estimated the paleodepth to be from 0 – 2000 meters.

Mollusk fossils from the same outcrop as sample 2 were also taken into consideration utilizing the faunal analysis. A total of 24 mollusk fossils were found (**Table 4**), and after classifying fossils into species (**Figure 3**), we estimated the paleodepth using previously published estimates of mollusk habitat depths (5). Using this approach, we estimated the paleodepth to be 0 – 870 meters (**Table 4**).

Discussion

We identified several kinds of paleoenvironmental information for the Morozaki Group through this experiment. Since radiolarian fossils were counted as *Orbulina* sp. in samples 1-H, 1-B and 1-D, the paleoenvironment was estimated using the results from samples 2 and 3.

Depth of the Past Ocean

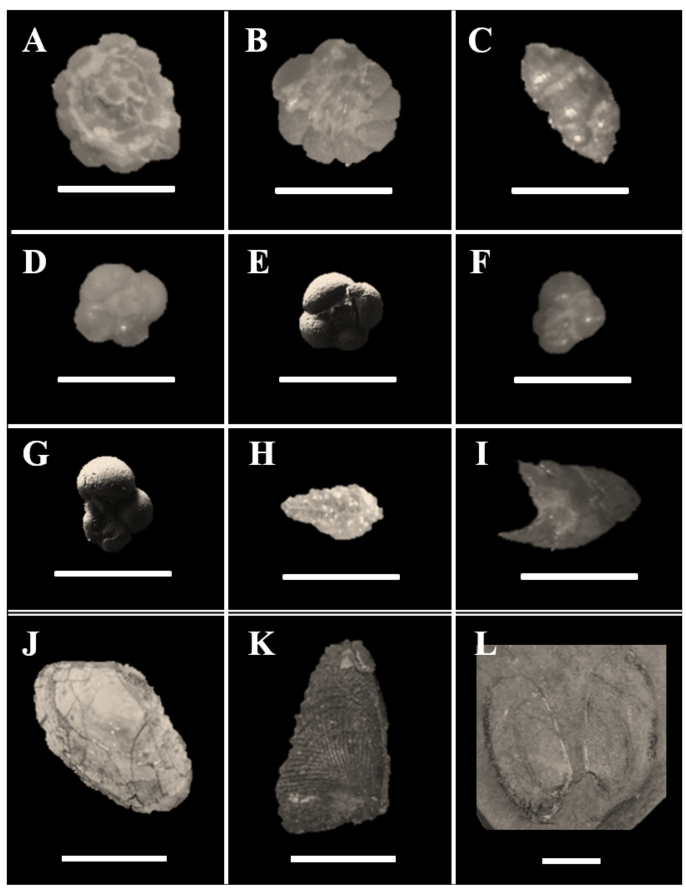

Figure 3: Foraminiferal Fossils and Mollusks Found. Foraminiferal fossils include A, B) *Ammonia tochigiensis*, C) *Uvigerina* cf. *hootsi*, D, E) *Catapsydrax dissimilis*, F, G) *Globigerina praebulloides*, and H, I) *Bolivina* sp. Mollusk fossils found in the experiment include J) *Bathymalletia inermis*, K) Acila picutulata, and L) *Calyptogena chitanii.* Scalebars represent 500 μm for foraminiferal fossils (A – I) and 1 cm for mollusk fossils (J – L).

	Scientific name	Sample 2		Sample 3		Habitat
		Numbers	Ratio	Numbers	Ratio	
Benthic	*Ammonia* sp	12	16%	80	31%	
	Ammonia tochigiensis	4	5%	6	2%	Inner Sublittoral
	Bolivina sp.	19	26%	1	0%	
	Lagenta costata	18	24%	22	9%	
	Leniticulina rotulata	0	0%	3	1%	Upper Bathyal
	Nonion kidoharaense	7	9%	18	7%	Inner Sublittoral
	Nonion sp.	3	4%	14	6%	
	Pullenia apertura	3	4%	0	0%	Upper Bathyal
	Quinqueloculina sp.	0	0%	2	1%	
	Uvigerina cf. *hootsi*	0	0%	2	1%	Middle Bathyal
Planktonic	*Catapsydrax* cf. *dissimilis*	0	0%	50	20%	
	Globigerina praebulloides	0	0%	14	6%	
	Globigerina sp.	0	0%	20	8%	
	Globigerinoides diminutus	0	0%	10	4%	
	Globigerinoides sp.	5	7%	0	0%	
Unknown		3	4%	12	5%	
Total		74	100	254	100	

Table 3: Classification of fossils from sample 2 and 3. Fossils were classified into species.

Scientific name	Numbers	Habitat	Ratio
Acila picutulata	3	0m~870m	13%
Bathymalletia inermis	13	50~200m	54%
Calyptogena chitanii	1	100~750m	4%
Cryptonatica ichishiana	5		21%
Propeamussium tateiwai	2	20~300m	8%
Total	24		100

Table 4: Classification of mollusks from sample 2. Fossils were classified into species.

From the results on foraminifera, we estimated the depth of the Morozaki Group to range from 0 – 2000 meters. Analyses of samples 2 and 3 indicate that there could be two different environments: namely, the Inner Sublittoral zone and the Upper to the Middle Bathyal zones. Previous research suggests that the Inner Sublittoral zone is equivalent to 0 – 50 meters underwater and the Upper to the Middle Bathyal zones is equivalent to 150 – 2000 meters (9).

Additionally, *Ammonia tochigiensis* obtained from sample 2 and 3, lived in the inner bay. Since the Morozaki Group is thought to be mainly composed of turbidite, this means that most of the sediments originated from a shallower part of the ocean, before descending in a landslide (2). Therefore, it is possible that some of the fossils came with the sediments from a shallower part of the ocean.

On the other hand, the results from mollusk fossils show that the estimated depth is approximately 100 – 870 meters. Although some of the fossils may have been carried by turbidites, many fossils were found with both valves attached. This indicates that the mollusks were most likely buried alive by the sediments forming the turbidites, rather than carried by them. However, there are many theories on the mollusks found. For example, Shibata reported that all of the mollusks found in this experiment belong to the *Acilana* assemblage, which lived at a depth of 100 – 3000 meters (10).

Moreover, the strata showed no signs of littoral indicators, such as ripple deposits and lamina. This suggests that the site was deeper than 100 meters, where there are normally no waves or currents.

Given all the evidence above, we estimate that the Morozaki Group formed at 100 – 2000 meters underwater with sediments originating from an inner bay 0 – 50 meters deep.

Geologic Age Determination

Catapsydrax cf. *dissimilis* is an index fossil and had existed until the Early Miocene Zone N. 6 (11). We recognized *C.* cf. *dissimillis* in sample 3. According to The Geologic Time Scale 2012, the upper boundary of the zone is 17.54 Ma. Therefore, assuming that the fossils have not been disturbed, the Morozaki Group may have formed at least 17.54 Ma.

Catapsydrax cf. *dissimilis* have been found in the upper layer of the Toyohama formation (4), and diatom fossils from planktonic foraminiferal Zone N. 6 to N. 7 have also been detected in the sediments from the middle and upper part of the Toyohama formation (12). Therefore, these findings support our upper age boundary of the Morozaki Group.

Water Temperature

Previous research has shown that *Ammonia tochigiensis* lived in tropical and subtropical oceans (13). *Catapsydrax dissimilis* and *Globigerina praebulloides* also lived in tropical to temperate oceans (11).

However, *Acila picutulata* and *Bathymalletia inermis* are also present in these samples and are associated with subarctic oceans. Therefore, they may have traveled to the region in a cold southerly current (14).

Since *Ammonia tochigiensis* lived in the inner bay while *Catapsydrax dissimilis* and *Globigerina praebulloides* are Planktonic foraminifera, the shallow part of the ocean may have had a strong warm current. On the other hand, *Acila picutulata* and *Bathymalletia inermis* are known to live in deeper parts of the ocean. Therefore, there could have been a cold current in the deeper part of the ocean.

In the present day, off the shores of Eastern Japan, a warm current (the Kuroshio Current) flows north at the surface, and a cold current (the Oyashio Current) flows south under the warm current. The faunal evidence suggests that there could have been a similar kind of current when the Morozaki Group formed.

Given the evidence presented above, this research suggests the possibility of warm currents heading north at the surface and cold currents heading south in the deeper parts of the ocean (14).

Marine Environment

Bolivina sp. can survive in a marine environment with less oxygen, and just like other species from the *Calyptogena*, *Calyptogena chitanii* breeds sulfur-reducing bacteria in their bodies, making them able to live in suboxic conditions. Therefore, when these foraminifers thrived, oxygen levels may have fluctuated to lower values from time to time.

Such fluctuations are mainly caused by volcanic activity, and the subsequent appearance of a hypoxic environment. Another possibility is that the surface productivity increased over time, reducing the amount of oxygen in the deeper parts of the ocean.

The Morozaki Group has many more fish fossils than other strata near the Morozaki group (6), supporting the hypothesis that hypoxia was caused by high surface production due to the increase in the number of animals at the surface.

Conclusions

Utilizing the information provided in microfossil assemblages, combined with the P/T method and faunal analysis, we suggest the environment in which the Morozaki Group formed to be as follows: 1) The Morozaki Group was formed between 100 – 2000 meters below sea level. However, due to underwater landslides, sediments were carried from 0 – 50 meters deep, and were associated with some of the foraminiferal fossils. 2) The sediments of the obtained samples originated at least 17.54 Ma. 3) There may have been a strong warm current heading north at the surface, and a strong cold current heading south in the middle layer during this time period. This may also be the reason why the Morozaki Group has so many different species. Finally, 4) the Morozaki Group may have experienced some periods of hypoxia, making it difficult for most of the animals to survive.

To further support our conclusions, further work should analyze greater numbers of samples and collect microfossils from other layers within the Morozaki Group. To confirm that the sediments came from 0 – 50 meters and to further investigate questions regarding ocean currents and oxygen levels, these same kinds of experiment must be performed at different outcrops in the Morozaki Group. By doing this, it may be possible to find out what kind of depositional process the strata represent.

In addition, it is important to perform the same kinds of experiments with different marine archives. In particular, fossils of other animals such as sea urchins, crabs, sea stars, radiolarians and many kinds of fish come from this group (6). By using different kinds of marine archives, it may be possible to establish the depth and time intervals more precisely. It may also be possible to establish whether there was hypoxia, and if so the reasons for it.

Methods

Sample Collection

Sample collections were carried out three times from 19th April 2014 to 3rd May 2016 (**Figure 1**). The first set of eight samples was collected at 20-cm intervals from the bottom of the cliff in the Katana outcrop. Each sample was named as sample 1-A to sample 1-H from the bottom. The other two samples were collected between sandstone and mudstone layers since there was a better chance that the sampling points were not contaminated by turbidites. Sample 2 was collected from a different sampling point, 10 meters below the first and third sets of samples. The mollusk fossils were also collected from the same sampling point as sample 2. Sample 3, on the other hand, was collected from the same sampling point as sample 1-F.

Fossil Extraction

The fossils in sample 2 were extracted using the sodium sulfate method. In this method, the fossils were extracted using saturated sodium sulfate (15). Sodium sulfate breaks the rocks as it crystallizes inside them. In addition to sodium sulfate method, the fossils from the first set of samples and sample 3 were extracted using also the naphtha method. In the naphtha method, naphtha (a type of gasoline) breaks the rock as it turns into gas when it is being boiled. Since naphtha penetrates into rocks better than water, the naphtha method is more efficient compared to the sodium sulfate method.

Sample Sorting and Identification

All the samples were then sorted using 60 metersesh (250-μm opening), 120 metersesh (125-μm opening) and 230 metersesh (63-μm opening) sieves, and dried. After fossil extraction, a spoonful of specimens (5 ml in volume) from each sample (1-A to 1-H) was observed. The fossils were then sorted by shapes, and were further classified to genus level if a section contained greater than 20 fossils.

The fossils found in samples 1-H, 1-B, and 1-D were classified into species, and fossils found in samples 2 and 3 were classified to genus level. Both were sorted according to previously published methods (16).

The mollusk fossils were classified into species according to Yamaoka (14). Their habitats were estimated using reports by Shikama and Kase (5).

Depth Estimation

The ratio of each genus in the fossils was calculated, and used to estimate the depth using either faunal analysis or the P/T method.

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