TEM study on magnetotactic bacteria and contained magnetite grains as biogenic minerals, mainly from Hokuriku-Niigata region, Japan

by

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Abstract

Sediments and water samples were collected mainly from Hokuriku-Niigata region, Japan , stored in the laboratory for several weeks and naturally enriched magnetotactic bacteria and the magnetite grains contained in the bacterial cells were examined. Various shapes of the magnetotactic bacteria were found in many localities. From some localities where coarse sediments are dominant, non-eutrophic environments are characteristic and/or pH of the water is comparatively acidic, magnetotactic bacteria were not found in this method. Changes of the bacterial diversities in Lake Sagata were found: the diversity of bacteria apparently enhanced in spring (March to May) and especially in autumn (October to December), and coccoid bacteria were found in all seasons. Mineralogical characteristics, such as shape, size, twinning, elongation direction, development of crystal faces and so on were also examined and described. TEM images of the cell division were taken. It was clarified that cell division proceeded by dividing vertically to the long axis and the same number of magnetosome chains belonged to the daughter cells , although the number of magnetite crystals is reduced in half. Swimming direction tests of the bacteria were carried out and it was found from the preliminary results that magnetotactic bacteria relatively easily adopt themselves to the magnetic field change after a few months. The specimens from the other localities containing Australia were also described.

Keywords : Magnetotactic bacteria, magnetosomes, magnetite, biogenic magnetite, biomineralization, TEM, Hokuriku, Niigata, Japan

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Intorduction

Magnetotactic bacteria contain intracellular magneite grains which are arranged in one or more chains and are called as magnetosomes (Blakemore, 1975). The magnetite grains are characteristic in their sizes, compositions, and shapes. Various types of magnetic minerals in magnetotactic bacteria are distinguished such as octahedral, hexagonal prism and tear-drop type (Stolz *et al*.,1990; Mann *et al*.,1991). Recently, magnetotactic bacteria are considered to be ubiquitous and the occurrences of them in various environments are reported (e.g., Mann, *et al*.,1990) . Biomineralization processes , in general, can be classified into the following two types (Stolz *et al*., 1990; Lowenstam ,1981; Mann ,1986) : "Biologically-Induced Mineralization (BIM)" which means by-product mineralization for organism and "Biologically Controlled Mineralization " (BCM) in which minerals are formed under strict biological control.

Strain GS-15, which is an example of BIM type mineralization (Blakemore and Blakemore,1991; Stolz *et al*.,1990; Mann 1986) produces extracellular magnetic minerals. BCM is also called as "organic matrix-mediated mineralization," (Lowenstam,1981). The bacteria (e.g., generally microaerophilic) require small amount of oxygen. The optimum value may not exceed 5 % within 1 % for magnetite production (Blakemore *et al*.,1989; Stolz *et al*.1990). An example of such natural environment is the water-sediment interface.

Aquaspirillum magnetotacticum (*Magnetospirillum magnetotacticum*) strain MS-12, (Blakemore and Blakemore,1991) is the first isolated and cultured magnetotactic bacterium from fresh water. The growth of this organism, which often occurs in stagnant and fresh water environments, is disturbed and grown under the conditions of above 5 % oxygen or anaerobical conditions. *Bilophococcus magnetotacticus* (*Magnetococcus*),(Blakemore *et al*. 1989; Blakemore and Blakemore,1991) which is aerotolerant, was isolated and observed in suboxic sediments under fresh water condition. However, they were not cultured axenically. This coccus contains intracellular sulfur rich inclusions, probably closely related to sulfidic sediments.

On the contrary, Bazylinski (1991) discovered strain MV-1, which is vibrioid and isolated from marine sulfide rich water and sediment. The MV-1 produces intracellular magnetite under strict anaerobic conditions. Not only magnetite, but also pyrrhotite(Farina *et al*.,1990) and greigite (Mann *et al*.,1990) are the magnetic minerals contained in the bacterial cells living in such environment. It is reported that these bacteria, sometimes containing pyrite, inhabit the environment of brackish and sulfidic salt marsh pools emitting strong odor of H_2S. Magnetite within the bacteria has also been mineralogically examined especially by TEM (e.g., Mann *et al*., 1991; Sparks, 1991; Matsuda *et al*., 1983; Akai *et al*., 1991 and 1993).

Bacterial magnetite found as fossils are called as "magnetofossils"(Petersen, *et al*., 1986; Vali *et al*., 1987). In general, two types of fossils are known: facies fossils and index (leading) fossils. The former indicates an environment where the organisms have lived, and the latter indicates a specific age of strata. Detailed knowledges are necessary for bacterial fossil to be used for such facies-indicative fossils. Especially, detailed information on an environments where the magnetotactic bacteria live and flourish is essential for the use of them as facies fossils.

So, the detailed data on the bacteria is essential, but almost no systematic data about this have been known in Japan. Furthermore, fundamental mineralogical characteristic of biogenic magnetite is also the target of interest mainly from the stand point of biomineralization.

In this study, we obtained samples of magnetotactic bacteria from Japan and western Australia, and found the various shapes and the seasonal changes of predominance in bacteria species and so on. The main objective of this paper is to describe the essential data on magnetotactic bacteria and biogenic magnetite grains (magnetosomes) in the bacteria mainly from the stand point of biomineralization and geoscience.

2. Samples & Methods

Sediments and water samples were collected from the upper sediment layers of aquatic environments (mainly eutrophic freshwater lakes, ponds and so on) in a water depth of 100 - 30cm. Vessels (15 cm in diameter and 8 cm in height) were filled with the sediments and water from each lake. After several weeks of storage in the laboratory, magnetotactic bacteria naturally enriched just beneath the water-sediment interface. They were further condensed with Sm-Co magnet due to their magnetotaxis. Fig.1 shows the magnetotactic bacteria aggregates by swiming toward the magnet under the optical microscope. The enriched bacteria were observed without any special treatment under the optical microscope. A few water drops containing bacteria cells were deposited on carbon-coated, formvar-covered

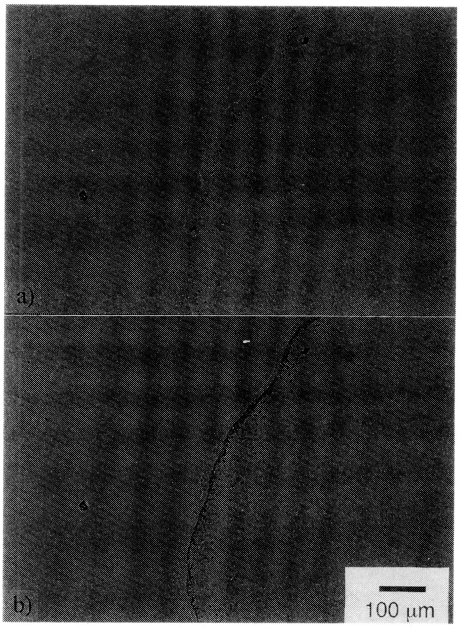
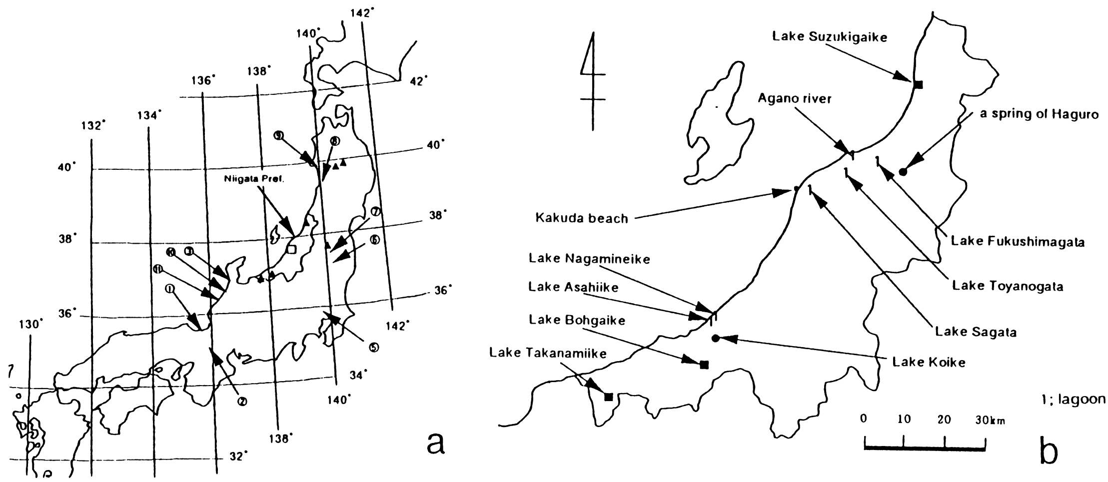


Fig.1. Optical micrographs of magnetotactic bacteria swimingtoward the Sm-Co magnet in the water drop.
a: Immediately after magnet setting.
b: 5 minutes after magnet setting.



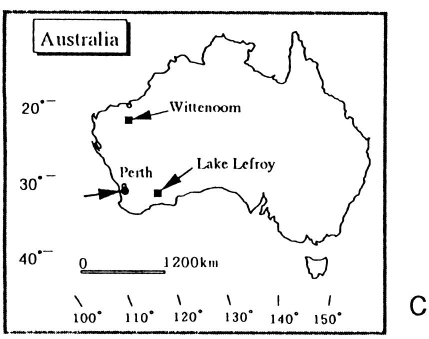


Fig.2. Maps indicating localities where presence of the magnetotactic bacteria wes checked.
a: Localities in Japan except for Niigata Prefecture(1:Lake Sugako; 2:Lake Biwa; 3:Lake Ochigata; 5:pond in Nogawa Park; 6:Lake Inawashiro; 7:Sohara; 8:Ohtsuzutsumi ; 9:Lake Ogata; 10: Kibagata; 11: Kitakata; ▲: Lakes & ponds where magnetotactic.bacteria were not found)
b: Samples in Niigata Prefecture (Lake Haguro is very near Fukushimagata)
c: Sampling sites in Australia

grids or microgrids for electron microscopic observation. They were air-dried and observed by TEM (JEM 200CX with energy dispersive spectrometer of TN2000). Minerals contained were identified based on SAED patterns and the EDS analytical results.

3. Results

3.1 Magnetotacitc bacteria and their environments

In Fig.2 a,b and c show the locality maps suggesting where the magnetotactic bacteria are found. Table 1 also summarizes the localities where magnetotactic bacteria were found . It was estimated that the localities where magnetotactic bacteria were found were characterized by comparatively eutrophic environments. Typical bacteria found in each locality are shown in Plate I to VI. On the other hand, this method did not detect such bacteria in non-eutrophic environments (Table 2) , where

Table 1. Typical localities where magnetotactic bacteria were found in this study.

No.	locality	lakes,rivers	sediment	depth(m)	others
0	West Australia	a pond near Perth	sand	0.5	Stromatolite
1	Niigata Pref.	L. Sagata	sand	0.5	Lagoon
2	Niigata Pref.	L. Fukushimagata	sand	0.3	Lagoon
3	Niigata Pref.	L. Asahiike	sand	0.2	Lagoon
4	Niigata Pref.	L. Koike	mud	0.3	Artificial
5	Niigata Pref.	L. Nagamineike	sand	0.3	Lagoon
6	Niigata Pref.	L. Toyanogata	sand	1.0	Lagoon
7	Niigata Pref.	Kakuda beach	sand	0.5	Tidal pool
8	Niigata Pref.	Agano river	sand	0.3	River side
9	Tokyo	L. Nogawa	mud	0.2	Artificial
10	Ishikawa Pref.	L. Ohchigata	sand	0.5	Lagoon
11	Fukui Pref.	L. Sugako	sand	0.3	Lagoon
12	Shiga Pref.	L. Biwako	pebble	0.3	Lagoon
13	Fukushima Pref.	L. Inawashiroko	sand	0.3	Lagoon
14	Akita Pref.	L. Ohdzutsumi	sand	0.5	Artificial
15	Fukushima Pref.	a pond of Sohara	mud	0.3	Bog

Table 2. Some localities where magnetotactic bacteria were not found in this study.

No.	locality	name	sediments	depths (m)	others
1	Australia	a river of Wittenoom	sand	0.3	Iron ore region
2	Australia	L. Lefroy	mud	0.3	Salt lake
3	Niigata	L. Suzukigaike	mud (consolidated)	0.5	Artificial lake
4	Niigata	L. Bohgaike	mud (consolidated)	0.5	Innutritious
5	Niigata	L. Takanamiike	sand	0.5	Innutritious
6	Fukui	L. Suigtsu	pebble	0.5	freshwater (artificially)
7	Akita	L. Tazawa	mud	0.5	Caldera lake
8	Iwate	stream (Matsuo Mine)	pebbly	0.2	Acidic
9	Akita	L. Ohyachi	mud (consolidated)	0.5	Innutritious

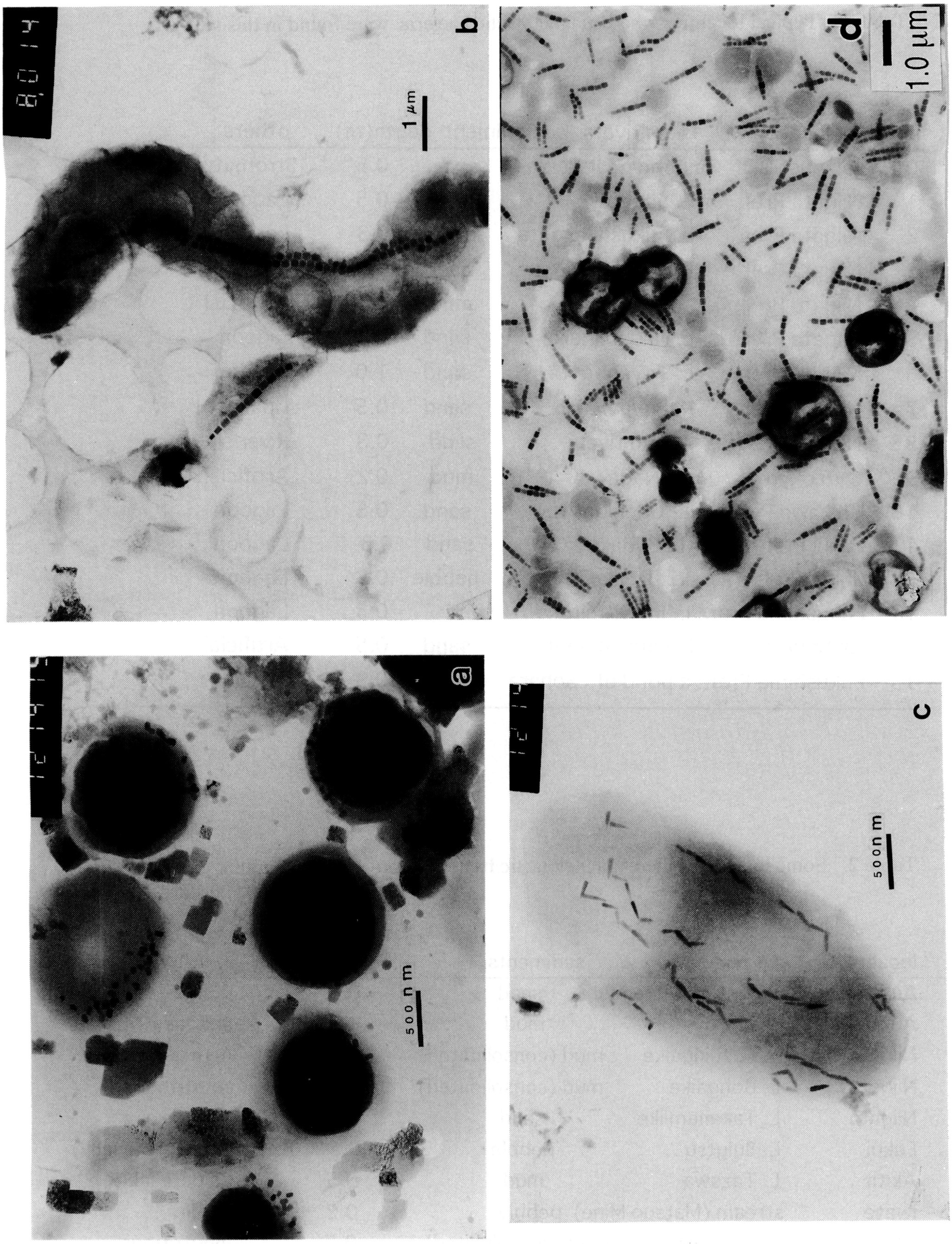


Fig.3. TEM images of varieties of morphological forms of magnetotactic bacteria.
a : coccus (Lake Toyanogata) **b :** spirillum (Lake Fukusimagata)
c : bacillus (roddish) (Lake Fukusimagata) **d :** aggregated bacteria and magnetosomes (Lake Ochigata)

coarse sediments are dominant and characteristic. The pH of the water in which bacteria lived is usually about 6.5-7.2 and the bacteria were not found in comparatively acidic lakes. These results do not necessarily indicate an absence of magnetotactic bacteria ; instead, this method did not detect the bacteria. In marine environments, magnetotactic bacteria were not easily observed in sandy or rocky seashore such as strongly waving intertidal zone. However they were obtained from fine sediments of tidal pool inside rocky shore.

Various shapes of magnetotactic bacteria, such as spirillum, were observed on sandy bottom part in Lake Sagata and they did not developed the other inclusions in the cell. On humus muddy part, coccoid bacteria were comparatively predominant type. Most of the cocci developed remarkably the intracellular inclusions, especially during summer and autumn.

3.2 Morphological diversity of magnetotactic bacteria and inclusions

Varieties of morphological forms of magnetotactic bacteria were observed. Most typical three types are shown in Fig. 3a,b and c . Relative seasonal abundances in the types of form were found. Fig. 3a shows dominant cocci collected in Lake Toyanogata in June. In Fig. 3b, the TEM image shows dominant spirillium bacterium collected from Lake Fukushimagata in June. In Fig. 3c bacilli (roddish) sampled in Lake Fukushimagata in June is shown. Apparently widely different shapes of the magnetototactic bacteria were thus distinguished . Observed TEM images of bacteria and magnetite inclusions are fundamental data, so these basic data of typical TEM images taken for each of lakes and ponds are summarized in Plate I to VI. Octahedral types are shown in 5,28,32 in Plate I to VI, hexagonal prism type in 1, 2, 3, 6-23, 25, -27, 29-31 in Plate I to VI, tear-drop type in 4, 24, 33, 34 in Plate I to VI.

It was found that magnetotactic bacterium often contains granule-like sulfur crystal in the cell. Its detailed description containing mineralogy of the sulfur is given in another paper in this volume. From Lake Sagata , a few sulfur granules were found in coccoid bacteria sampled in April and vibrio-like bacteria in August were found. The former, a remarkable type of bacteria, is predominant at this lake in April. On the other hand, the inclusions were also observed in the bacteria cultured in laboratory until October for six months.

3.3 Observed changes of magnetotactic bacteria for three years

The samples were collected monthly in Lake Sagata for about three years. They were examined to find some changes in morphological diversity and the assemblages. Procedure of sample preparation and examination is the same as in 3.1. So, the results indicate only apparent change with restriction by this method. Table 3 shows the results summarized. The diversity of bacteria apparently enhanced in spring and autumn (March- May:27,28; September- November: 31,32 in Plates) , but not in summer and winter (June-August: 29,30 ; December- February: 33,34 in Plates). It was found that in the samples in summer a few of kind of coccoid bacteria were predominant (29,30, in Plates). On the

Table 3. Changes in diversity of bacteria in Lake Sagata.

Date	Coccus	Spirillum	Bacillus	major	Sulfur inclusions
1992 April	1			Coccus	Sulfur inclusion
1992 May	——	——	——	——	
1992 June	2	1		Coccus	
1992 July	2			Coccus	
1992 August	3			Coccus	
1992 September	1			Coccus	
1992 October	1	5	1	Coccus	Sulfur inclusion
1992 November	1	1	1	Coccus	Sullfur inclusion
1992 December	1	2	1	Coccus	
1993 January	1	1		Spirillum	
1993 February	3			Coccus	
1993 March	2			Coccus	
1993 April	6	1		Coccus	Sullfur inclusion
1993 May	1	1		Spirillum	
1993 June	——	——	——	——	
1993 July	2			Coccus	
1993 August	1			Coccus	
1993 September	4			Coccus	
1993 October	1	3		Spirillum	
1993 November	3			Coccus	Sulfur inclusion
1993 December	4			Coccus	
1994 January	3			Coccus	
1994 February	2	1		Coccus	
1994 March	1			Coccus	
1994 April	1	2		Coccus	
1994 May	4			Coccus	
1994 June	2			Coccus	
1994 July	3			Coccus	
1994 August	4	3		Coccus	Sulfur inclusion
1994 September	4	2		Coccus	Sulfur inclusion
1994 October	1	3		Coccus	
1994 November	4	1		Coccus	

Colum, "major" indicates major abundant type of bacteria in its number in the specimen. Colums "coccus"," spirillum","bacillus" indicate kinds of apparent coccus, spirillum and bacillus types, respectively.

contrary they decreased in winter. These coccoid bacteria often developed sulfur inclusions in the cells as stated above briefly . Coccoid bacteria were observed in every season. Based on apparent differences in shapes and sizes, more than ten types of coccus, about ten types of spirillum and a few types of bacillus seem to be distinguished in Lake Sagata.

3.4 Division of magnetotactic bacteria

TEM images showing proceeding of magnetotactic bacteria division were obtained (Fig. 4). It was suggested that the bacteria usualy form a septum perpendicular to long axis as shown in Fig.4 and subsequently divided along the long axis. It was observed that each magnetosome chain was simultaneously partitioned into two chains and that the chains were succeeded to each daughter cell. Consequently, it is concluded that the same number of magnetosome chains may always belong to the cells of magnetotactic bacteria, although the number of magnetite crystals belonging to a single chain is reduced in half. This fact seems to be common to the magnetotactic bacteria obtained in this study.

3.5 Magnetotaxis and polarities of magnetotactic bacteria

Swimming direction test in the bacteria using Sm-Co magnet was carried out (Fig.5).

The samples collected in Lake Biwa, Lake Sagata and Lake Fukushimagata were cultured in a vessel for some months (Lake Biwa : one month; Lake Sagata: one month and four months; Lake Fukushimagata : four months), then a few drops of water containing bacteria were placed on the slide glass, then small Sm-Co magnet was placed near the drop and the bacteria were observed under the optical microscope. It was found that the south-seeking bacteria appeared in these samples (Fig.5: Lake Sagata, one month). Furthermore, it was found that north-seeking bacteria appearred in the Australian samples which were stored and cultures for 5 months in Japan in a vessel in which very local south-hemisphere magnetic environment was produced using small Sm-Co magnet beneath the vessel.

Thus, from these preliminary experiments it was estimated that magnetotactic bacteria relatively easily adopt themselves to the magnetic field change after a few months. It was also found that the south-seeking bacteria with crystalline sulfur granules were less frequent than any other bacteria.

3.6 Types of magnetite forms in magnetotactic bacteria

Major three types of bacterial magnetite forms are known and the schematic figures of the typical three magnetite grains are shown in Fig.6 . Fig.7 shows typical ED pattern of the bacterial magnetite obtained ,which is same to that of JCPDS data. Size distribution patterns of magnetite grains in each type are shown in Butler and Banerjee (1975) diagram (Fig.8) on which magnetic domain type is distinguished. Size distribution in the tear-drop type is concentrated in narrower single domain region than the other two types, so it may indicate that this type is more effective in obtaining strong magnetic moment per unit volume of magnetite. In the following, each type of magnetite form is explained in detail. Some diversity was also found in the same type of magnetosomes as shown in Plate I to VII.

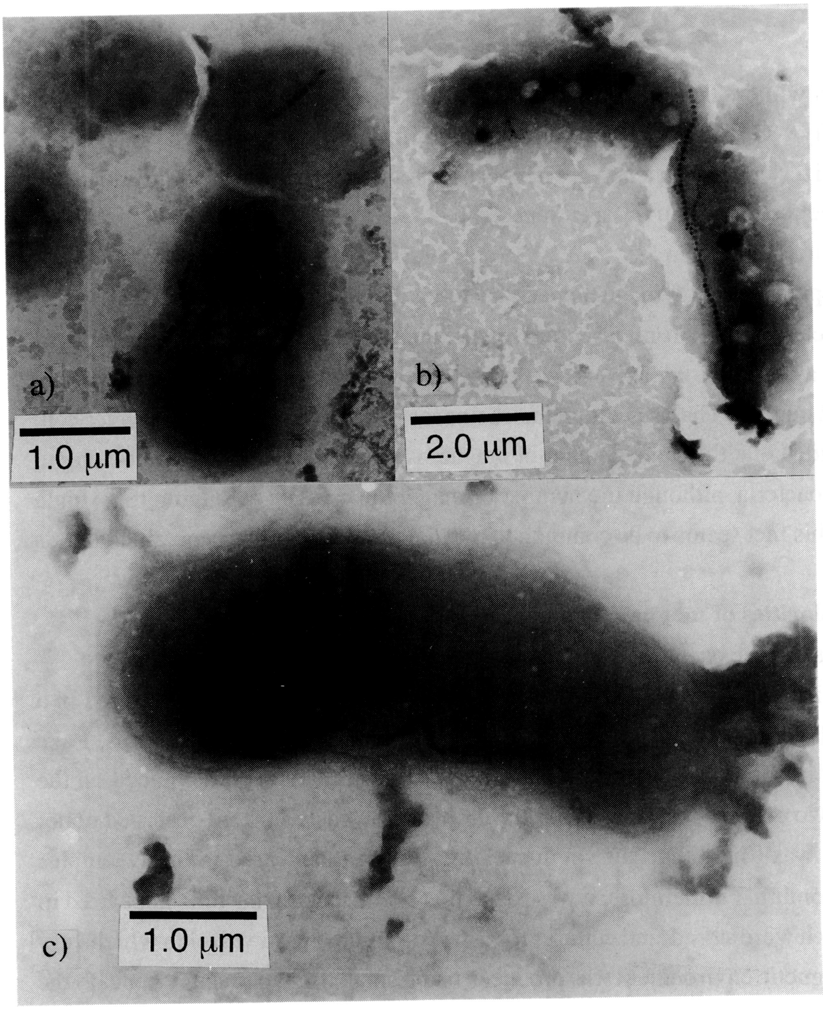
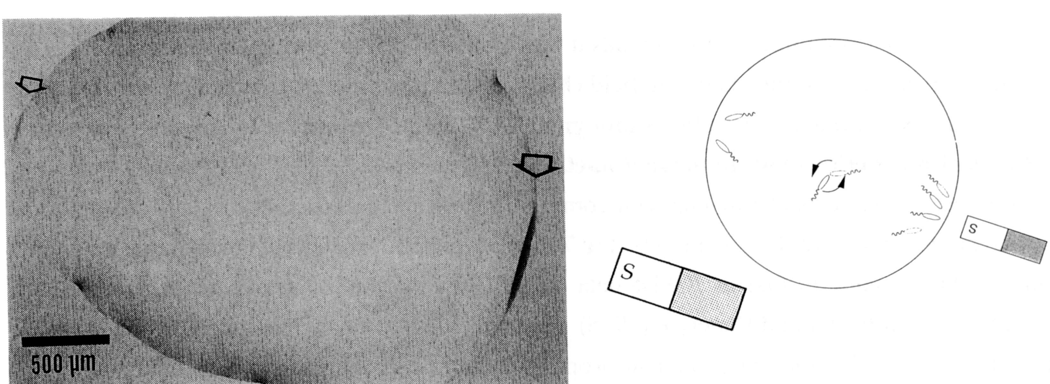


Fig.4. TEM image suggesting division of magnetotactic bacteria.
a: coccus (Lake Sagata,)
b: spirillum (Lake Sagata)
c: spirillum (Lake Sugako)



a)

Fig.5. Optical Micrograph of swimming tests in magnetotactic bacteria.
(Lake Sagata specimen, 4 weeks)

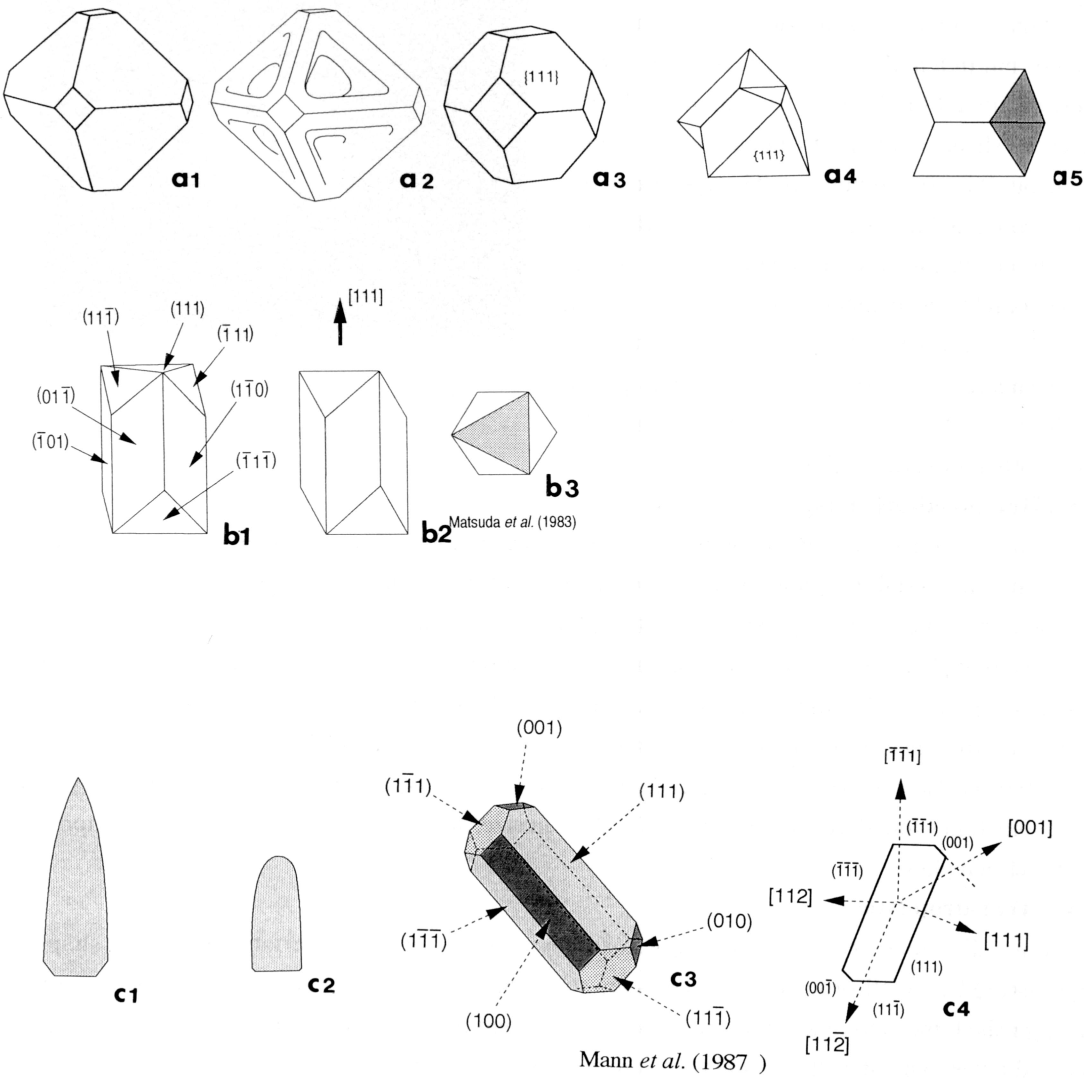


Fig.6. Schematic mineralogical explanation and varieties of three main types of magnetosomes (bacterial magnetite grains). Explanations by Matsuda *et al.* (1983) and Man *et al.*(1987) are slso added.
a1 ~ a5: octahedral type crystals (a2: skeletal crystal)
b1 ~ b3: hexagonal prisum type crystals
c1 ~ c4: tear drop type crystals (lower part in c1 indicate well defined crystallographic planes in the rear parts of the magnetosomes)

3.6.1 Octahedral type

Magnetosomes of octahedral type are usually 70-120 nm in length (Fig.9a) . It is composed of well-defined {111} faces truncated by {100} faces. Its shape is similar to the inorganic magnetite habit. It is often found that this type of magnetite is contained in large or slender helical bacteria. The crystals were aligned with the [111] direction parallel to the magnetosome chain axis. When crystals are growing, the {100} faces tend to become smaller in comparison to the devolopment of the {111} faces. Twinned crystals were relatively often observed in this type.

Fig.7. ED pattern on magnetite grains in magnetotactic bacteria.

3.6.2 Hexagonal-prism type

Hexagonal prism type of magnetosome (Fig.9b) is commonly observed in various types of bacteria, while the crystal morphology is composed of {111} planes and some {110} planes which are truncated by other {111}, {100} and {110} planes.This elongated habit corresponds to uniaxial growth along [111] axes which are well known "easy direction" of magnetization in magnetite. The magnetite grains easily align in the direction along the long axis of magnetosome chain. Two morphologies for this type are sometimes found: dumbbell-like and spindle- like in shape. Hexagonal prism type is also classified into long type, small type, normal type and short type. Twinned crystals were sometimes found. Smaller crystals, 10-30 nm in size, are similar to cube-like and /or comprised of ill-defined planes.

3.6.3 Tear-drop type

Generally, tear-drop type of magnetosomes consists of characteristic tear-drop shaped crystals(Fig.9c). Well-ordered {111} faces are sometimes found in the rear part. They can be easily distinguished morphologically from any other types and inorganic one. Measuring crystasl length and width it is found that the crystal width are generally constant ranging within 30-50 nm. The long axis of the crystal usually elongates up to about 300 nm at maximum. Crystallographic direction of the elongation is often [111] direction or [100] direction. Same tendency has also been known in the magnetite grains from the Japan Sea (Akai, *et al* ., 1991). More detailed examination showed that tear-drop type rarely elongates along the directions [110]. The elongations along [111] direction are typically characteristic in the teardrop type with rounded anterior part.

This type of magnetosome indicates the three patterns of the arrangement; straight type and a zigzag type against the long axis of grains and a bundle type with remarkable kinked and curved crystals.

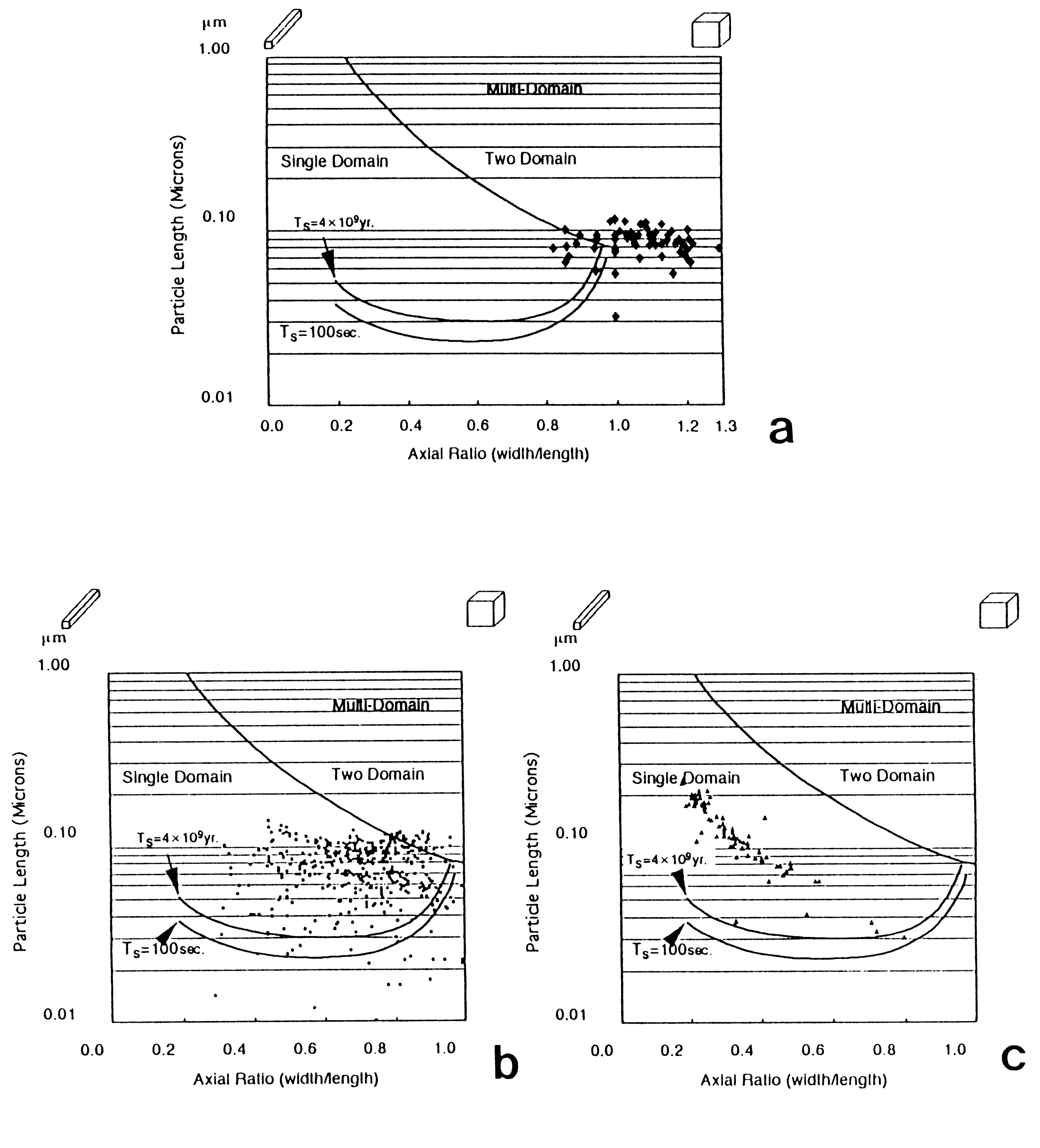


Fig.8. Size distribution of bacterial magnetite grains in each type of magnetosomes plotted on Butler and Banerjee(1975) diagrams.

a: octahedral type.
b: hexagonal prism type.
c: tear-drop type.

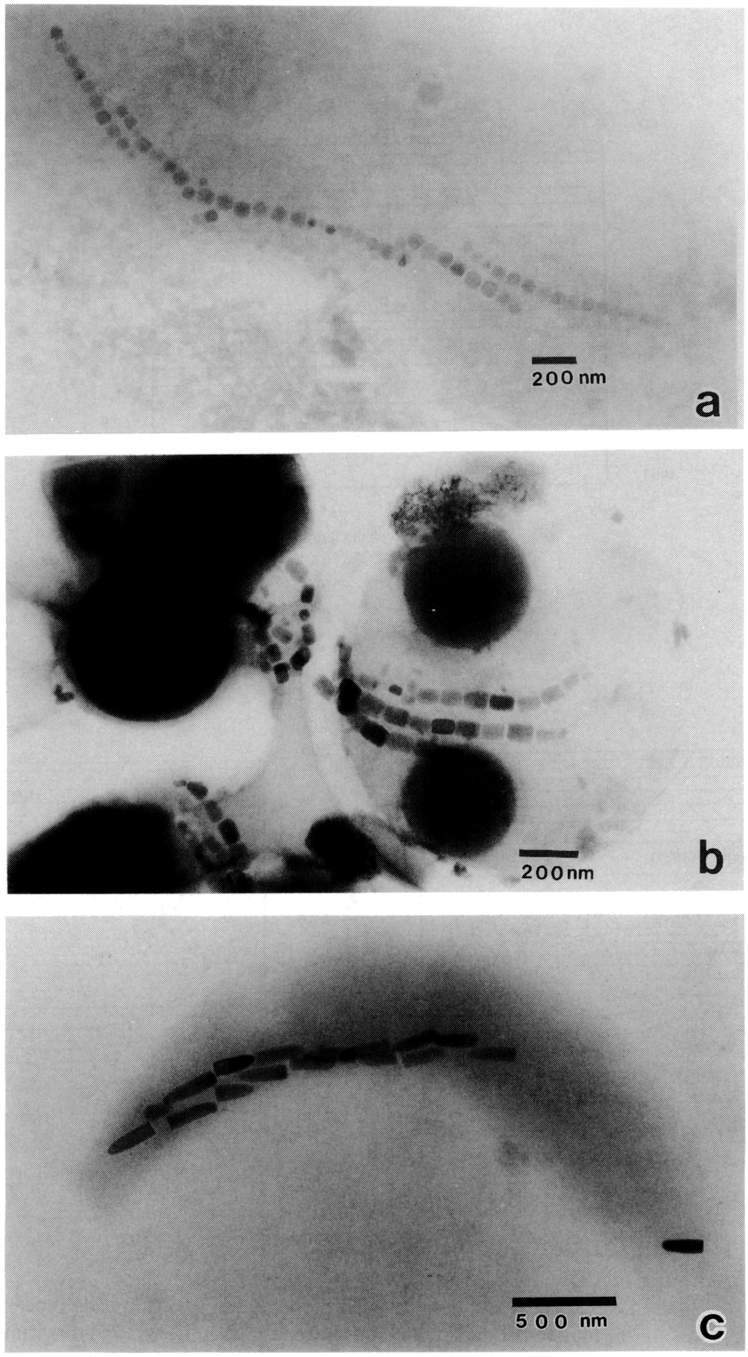


Fig.9. Three types magnetosomes contained in the magnetotactic bacteria.
a: Octahedral type magnetite (Lake Sagata, December)
b: Hexagonal prism type magnetite (Lake Sagata, September)
c: Tear-drop type magnetite (Lake Asahiike)

4. Discussions and summary

In an aqua planet, the earth , iron often exists as oxide or hydroxide form in the earth surface conditions. Iron is the fourth abundent element in the crust and it is very reactive element. Iron biomineralization is also one of important procces in the earth surface environments (Schwertmann and Fitzpatrick,1992). Magnetosome (magnetite) which is formed within magnetotactic bacteria is one of typical products of BCM processes. However, the detail of the bacteria and contained magnetite of magnetosomes has not been well established : Almost no detailed and systematic report on the bacteria and the cotained magnetite in Japan has been present until now. Fundamental data on the bacteria and the magnetite are essentially important from the stand point of the earth science. They may be related to facies fossil, biomineralization process, mineralogy itself, and so on.

In this study we obtained basic data on the bacteria which are related to fundamental questions : where are they living in Japan,?, what types of bacteria enriched in storage?, what types of magnetosomes are found in different environment?, how is the crystallographic characteristics?, and so on. These fundamental questions were tested in Japan in this study.

Some lakes and ponds in north eastern Japan especially Hokuriku-Niigata region were tested. From many localities, magnetotactic bacteria were found, but from some localities they could not be found. They were usually found in common aquatic environments especially in eutrophic environments . But in some special water environments where coarse sediments are dominant, none eutrophic environments are characteristic and/or the pH of the water is comparatively acidic, magnetotactic bacteria were not observed in this method. These results do not always mean absence of the bacteria directly. In marine environments, magnetotactic bacteria were also observed in this study. In sandy or rocky seashore the bacteria were not found easily in this study.

Apparent seasonal changes of magnetotactic bacteria species in Lake Sagata for three years were examined by the same method of bacteria-storage for several weeks. It was found that the diversity of bacteria enhanced in spring (March to May) and especially in autumn (October to December). This change may correspond to increasing of chlorophyl-a in spring and autumn. Coccoid bacteria were found in all seasons. Crystalline inclusion of sulfur were also found. They were found in spring or autumn and not in all seasons. Fukuhara and Fukui(1986) , and Fukuhara *et al*. (1990) reported the physicochemical environmental factors in the Lake Sagata : the Eh in the surface of sediments is approximately -200 to +50 mV, pH is about 7, they contain about 2 mg/l on average in concentration of H_2S, 26-41 mg/l in salinity and 4 mg/l in dissolved oxygen. These data indicate that the environment of Sagata is similar to the environment for *Bilophococcus magnetotacticus* to live (Bazylinski *et al* .,1991). It is, therefore, probable that the observed bacteria adapt similar metabolic cycle to *Bilophococcus magnetotacticus*. These environmental conditions may be closely related to the formation of sulfur inclusions although the detail is not known. All these data may become key for these bacteria and the contained magnetosomes to be used in environmental analysis, for example, in testing of the magnetosomes as facies fossils.

Types of magnetite forms were also observed in detail. Major three types of bacterial magnetite forms were also confirmed in this study. However, some diversity was found even in the same type of magnetosomes. It is still in question whether these minor differences depend on differences in species or only on modification within the same species. The presence of such varieties wake up interest to survey magnetofossils from this point of view.

Results on swimming direction tests in the bacteria was also interesting. These results suggest relatively easy adoptation to the reversed magnetic field although its mechanism and process are not yet so clear. It may be closely related to survival of the bacteria under geomagnetic reversal accidents in the earth history. These basic data obtained may be essential for geological and mineralogical sciences.

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References

Akai, J., Sato,T. and Okusa, S. (1991) : TEM study on biogenic magnetite in deep sea sediments from the Japan Sea and the western Pacific Ocean *Journ. Electron Microsc*, **40**, 110-117.

Akai, J.,(1993) : Mineralogical study on bacterial magneite by TEM.*Journ. Jap.Soc.Elec. Micr.(Densikenbikyo)* (in Japanese) **27**, 225-234.

Bazylinski, D.A.(1991) : Anaerobic production of single-domain magnetite by the marine, magnetotactic bacterium, strain MV-1. In: Frankel R B, Blakemore R P, ed. *Iron Biominerals*. New York, Plenum Press, 69-77.

Blakemore, R. P. (1975) : Magnetotactic Bacteria. *Science*, **190**, 377-379.

Blakemore, R. B., Blakemore, N. A., Bazylinski, D. A. and Moench. T. T. (1989) : Magnetotactic Bacteria. In Stanley J T, Bryant M P, Pfennig N, Holt J G, ed. *Bergey's Manual of Systematic Bacteriology*, **3**, Baltimore, Williams & Wilkins 1882-1888.

Blakemore, R. P., and Blakemore, N. A. (1991) : Magnetotactic magnetogens, In: Frankel, R. B., Blakemore, R. P., ed. *Iron Biominerals*. New York, Plenum Press, 51-67.

Butler, and Banerjee.(1975) : Theoretical single-domain grain size range in magnetite and titanomagnetite.*Journ. Geophys. Res.*, **80**, 29, 4049-4058.

Farina, M., Esquivel, D. M. S., Lins de Barros, H. G. P. (1990) : Magnetic iron-sulphur crystals from a magnetotactic microorganism. *Nature,* **343**, 256-258.

Fukuhara, H. and Fukui, M. (1986) : Limnological studies of lakes in Niigata, Prefecture Ⅲ. Seasonal abundance of sulfate- reducing bacteria in Lake Sagata, Niigata, Japan,*Memoirs of the Faculty of Education. Niigata University,* **28** (1).

Fukuhara, H., Ohtaka, A., Tomita, N., Nakamura, T. and Higashide, T. (1990) : Limnological studies of lakes in Niigata Prefecture Ⅳ. Limnological studies of Lake Sagata, with special reference to the Seasonal changes in nutrients and the macrophyte biomass. *Memoirs of the Faculty of Education. Niigata University*, **32** (1).

Lowenstam, H. A. (1981) : Minerals formed by organisms, *Science*, **211**, 1126-1131

Mann, S. (1986) : On the nature of boundary-organized biomineralization (BOB). *Journ. Inorg. Chem.*, **28**, 363-371.

Mann, S., Sparks, N. H. C. and Blakemore, R. P. (1987) : Structure, morpholgy and Crystal growth of anisotropic wagnetite Crystals in magunetotactic bacteria. *Proc. Roy. Soc. London,* **B231**, 477-487.

Mann,S.,Sparks, N. H. C., Frankel, R. B., Bazylinski,D. A., Jannasch,H.W.(1990) : Biomineralization of ferrimagnetic greigite (Fe_3S_4) and iron pyrite (FeS_2) in a magnetotactc bacterium. *Nature* , **343**, 258-261.

Mann, S., Sparks, N. H. C., Wade, V. J. (1991) : Crystallochemical control of iron oxide biomineralization, In: Frankel R B, Blakemore R P, ed. *Iron Biominerals*. New York: Plenum Press, 21-49.

Matsuda , T., Endo, J., Osakabe, N and Tonomura, A. (1983) : Morphology and structure of biogenic magnetite particles. *Nature* , **302**, 411-412.

Petersen, N. ,von Doveneck, T. and Vali, H. (1986) : Fossil bacterial magnetite in deep sea sediments from the South Atlantic Ocean, *Nature*, **320**, 611-615.

Schwertmann,U. and Fitzpatrick, R.W.(1992) : Iron minerals in surface environments In Skinner,H.C.W. and Fitzpatrick, R.ed.*Biomineralization processes of iron and manganese*, 7-30.

Sparks, N. (1991) : Structural and morphological characterization of biogenic magnetite crystal. In: Frankel R B, Blakemore R P, ed. *Iron Biominerals*. New York: Plenum Press, 167-178.

Stolz, J. F., Lovley, D. R.and Haggerty, S. E. (1990) : Biogenic magnetite and the magnetization of sediments.*Journ., Geophys. Res.*, **B495**, 4355- 4361.

Vali, H., Foerster, O. and Petersen, N. (1987) : Magnetotactic bacteria and their magnetofossil in sediments, *Earth Planet. Sci. Lett.*, **86**, 389-40.

Lake Kibagata	木場潟	Matsuo	松尾
Lake Sugako	菅湖	Lake Nagamineike	長峰池
Ohzutsumi	大堤	Lake Asahiike	朝日池
Lake Kitakatako	北潟湖	Lake Fukushimagata	福島潟
Sohara	曽原	Lake Sagata	佐潟
Lake Inawashiro	猪苗代湖	Lake Suzukigaike	鱸ケ池
Lake Biwa	琵琶湖	Lake Bohgaike	坊ケ池
Kakuda	角田	Lake Takanamiike	高浪池
Lake Ohchigata	邑知潟	Lake Koike	小池
Nogawa	野川	Lake Nagamineike	長峰池
Agano River	阿賀野川	Lake Hibarako	桧原湖
Lake Toyanogata	鳥屋野潟	Haguro	羽黒

Explanation of Plates
Plate I ~ Plate VI < Photographs No. 1 ~No.34>

1,2 Specimens from Lake Kibagata (Ishikawa Pref.April 1994) (Coccus with hexagonal prism type magnetosomes and inclusion)
3,4 Specimens from Lake Sugako (Fukui Pref.April,1994) (3:Coccus with double hex.pr. type magnetosomes ; 4: characteristic shaped bacteria with tear drop type magnetosomes)
5 Specimen from Ohzutsumi (Akita Pref.August 1994) (Small Spirillum with small octahedral type magentosomes whose {100} planes are developing.
6 Specimens from Lake Kitakatako (Akita Pref. April 1994) (Coccus with double chians of hexagonal prism type of magnetosomes)
7 Specimens from Sohara (Fukushima Pref. August 1994) (Coccus with hexagonal prism type of magnetosome)
8 Specimens from Marsh near Lake Hibarako (Fukushima Pref. August 1994) (Coccus bacteria with single chain of hexagonal prism type of magnetosomes)
9,10 Specimens from Small pond near Perth, Australia (August,1993) (Coccus type bacteria with single chain of hexagonal prism type of magnetosomes .
11 Specimens from Haguro (Niigata Pref. October 1994) (Coccus bacteria with hexagonal prism type magnetosomes)
12,13 Specimens from Kakuda Beach (Niigata Pref. June 1992) (12:Coccus with single chain of hexagonal prism type of magnetosomes; 13:Large coccus bacteria with elongated hexagonal prism type of magnetosomes whose chain arrangement is broken)
14,15 Specimens from Agano River (Niigata Pref. September 1994) (Coccus with hexagonal magnetosomes chain) (16 : crystalline sulfur inclusion is found)
16,17 Specimens from Lake Toyanogata (Niigata Pref. June 1992) (16: Coccus with hexagonal prism type of magnetosomes ; 17 some inclusion is found)
18 Specimens from Lake Nagamineike (Niigata Pref. October, 1992) (Spirillum with hex. prism type of magnetosomes and the other type bacteria with bundle of tear-drop type magnetosomes)
19,20 Specimens from Lake Asahiike (Niigata Pref. October, 1992) (19: Large coccus with hex. prism type of magnetosomes ;20:Reniform coccus with hexagonal prism type magentosomes)
21 Specimens from Lake Inawashiro (Fukushima Pref. August 1994) (Magnetotactic bacteria from sandy sediments. Two types of bacteria are found)
22 Specimens from Lake Fukushimagata (Niigata Pref. June, 1992) (Typical coccus group with a few hexagonal prism type magnetosomes chains)
23,24 Specimens from Lake Biwa (Shiga Pref.April,1994) (23:Bacteria whose magnetotacsis converted reverse. ; 24 : Bacteria whose magnetotaxis did not converted. They contain Sulfur inclusion)
25,26 Specimens from Pond in Nogawa (Tokyo, May ,1992) (25: Coccus with hexagonal prism type of magnetosomes; 26: Spirillum with hexagonal prism type magnetosomes)
27,28 March - May Specimens from Lake Sagata, Niigata Pref., (27:Bacteria with hexagonal prism type magnetosomes;28: Slender spirillum with small octahedral type of magnetosomes)
29,30 June - August specimens from Lake Sagata, Niigata Pref.,(Bacteria with hexagonal prism type of magnetosomes)
31,32 September - November specimens from,Lake Sagata ,Niigata Pref.(31:Coccus with hexagonal prism type of magnetosomes; 32: Roddish bacteria with tear-drop type of magnetosomes)
33,34 December- Feburary specimens from Lake sagata, Niigata Pref. (33: Nontypically shaped type magnetosomes in the bacteria; 34: Small spirillum with small octahedral type of magnetite grains)

Plate I

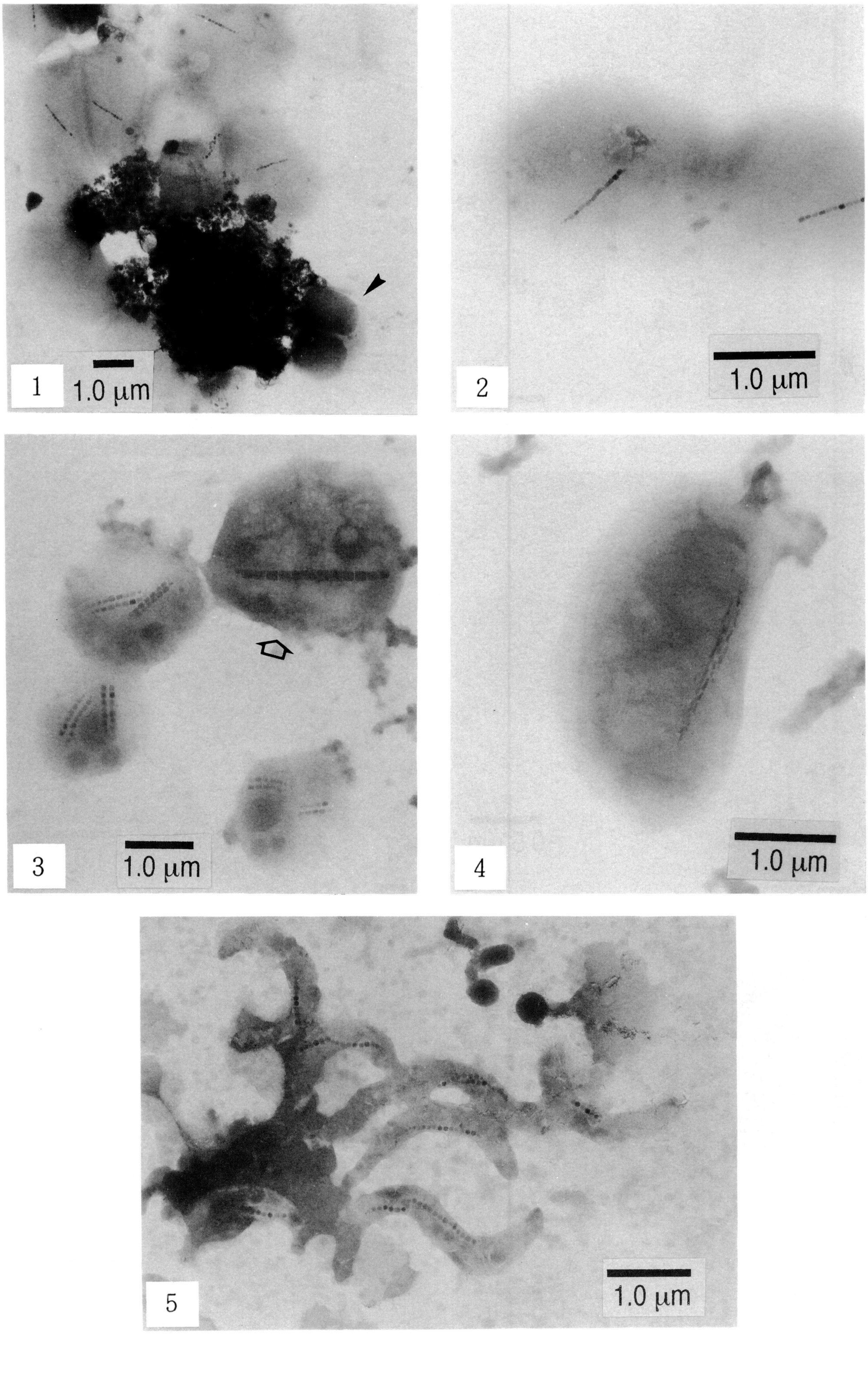


Plate II

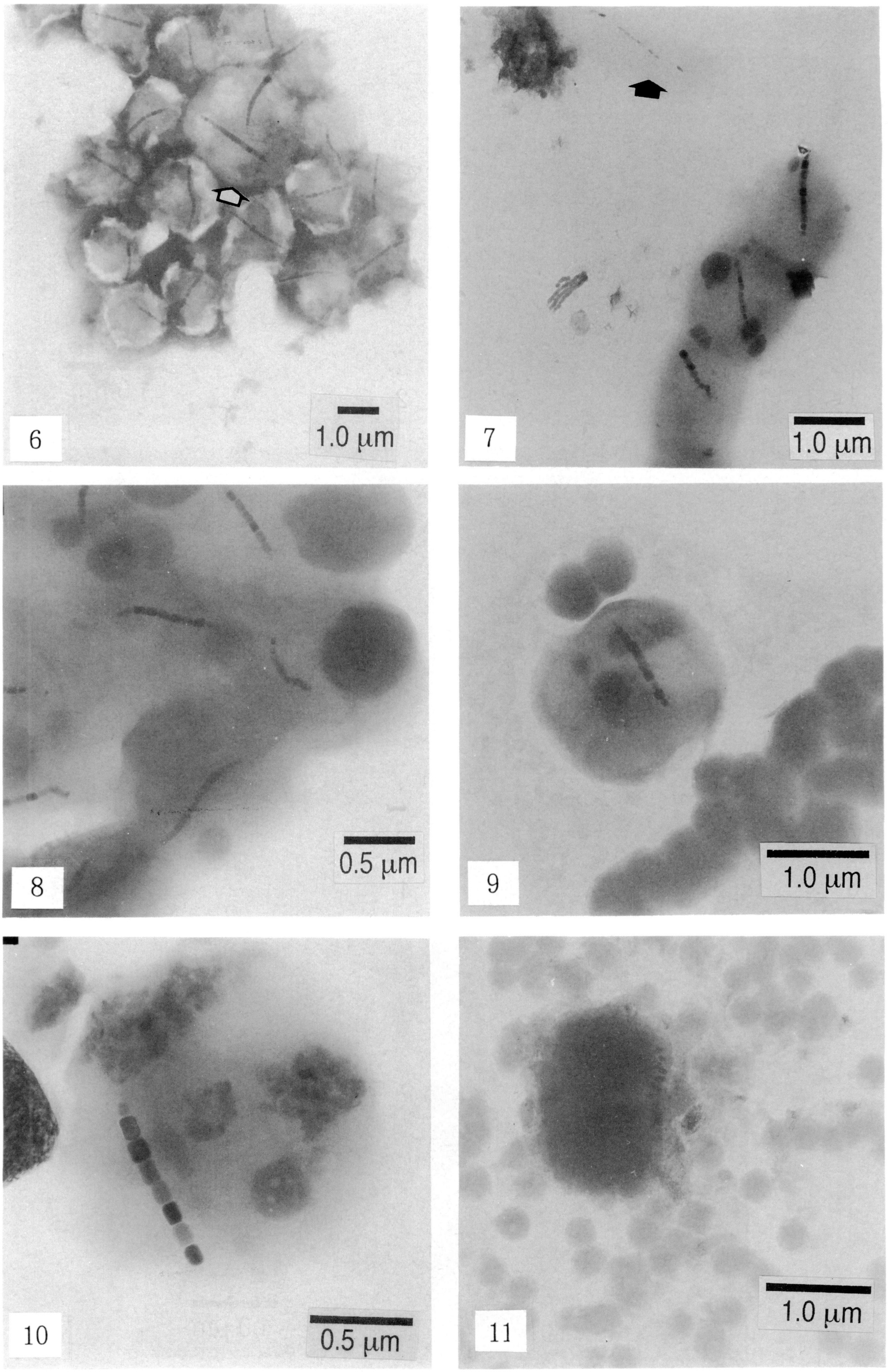
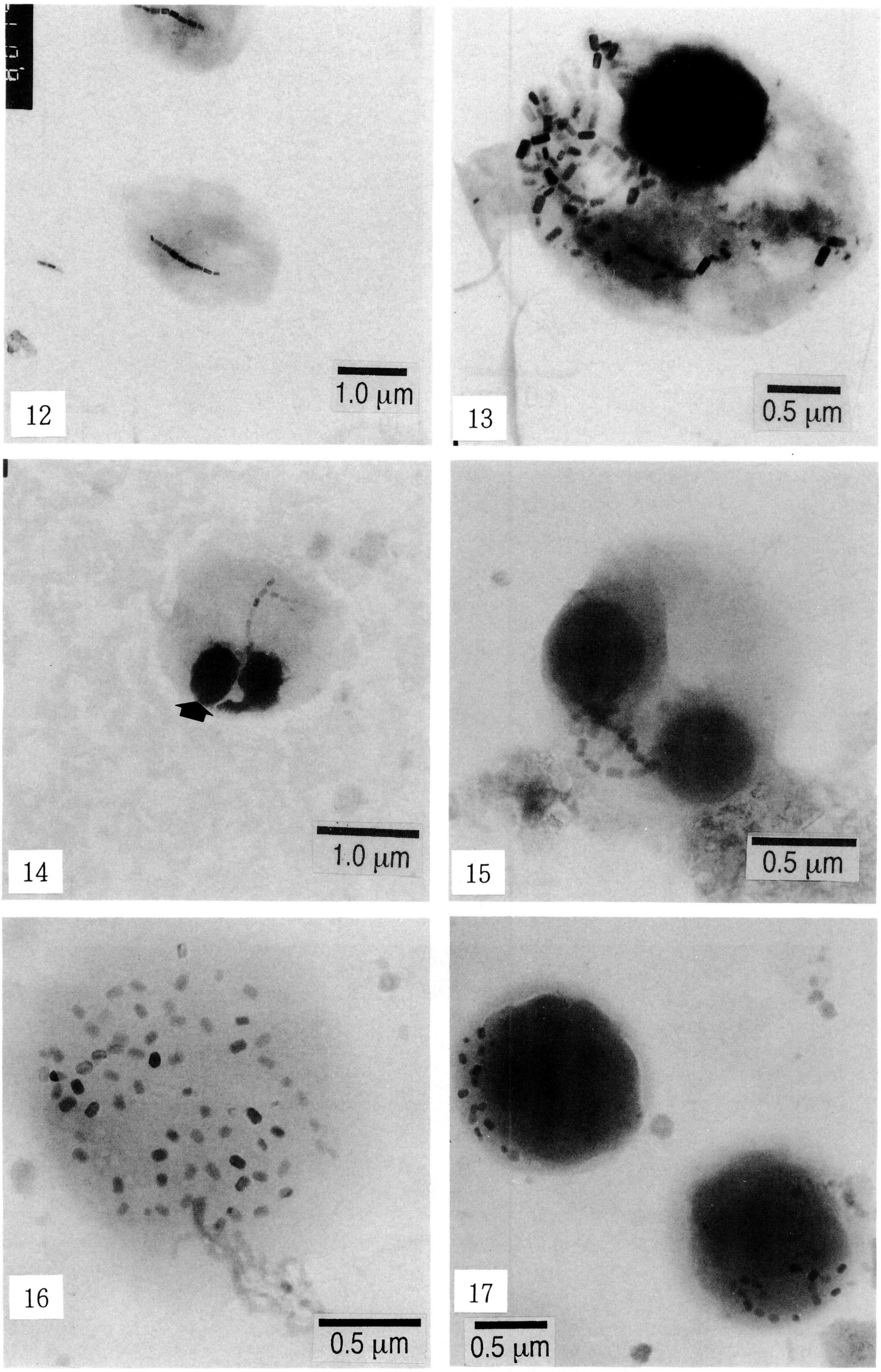


Plate III



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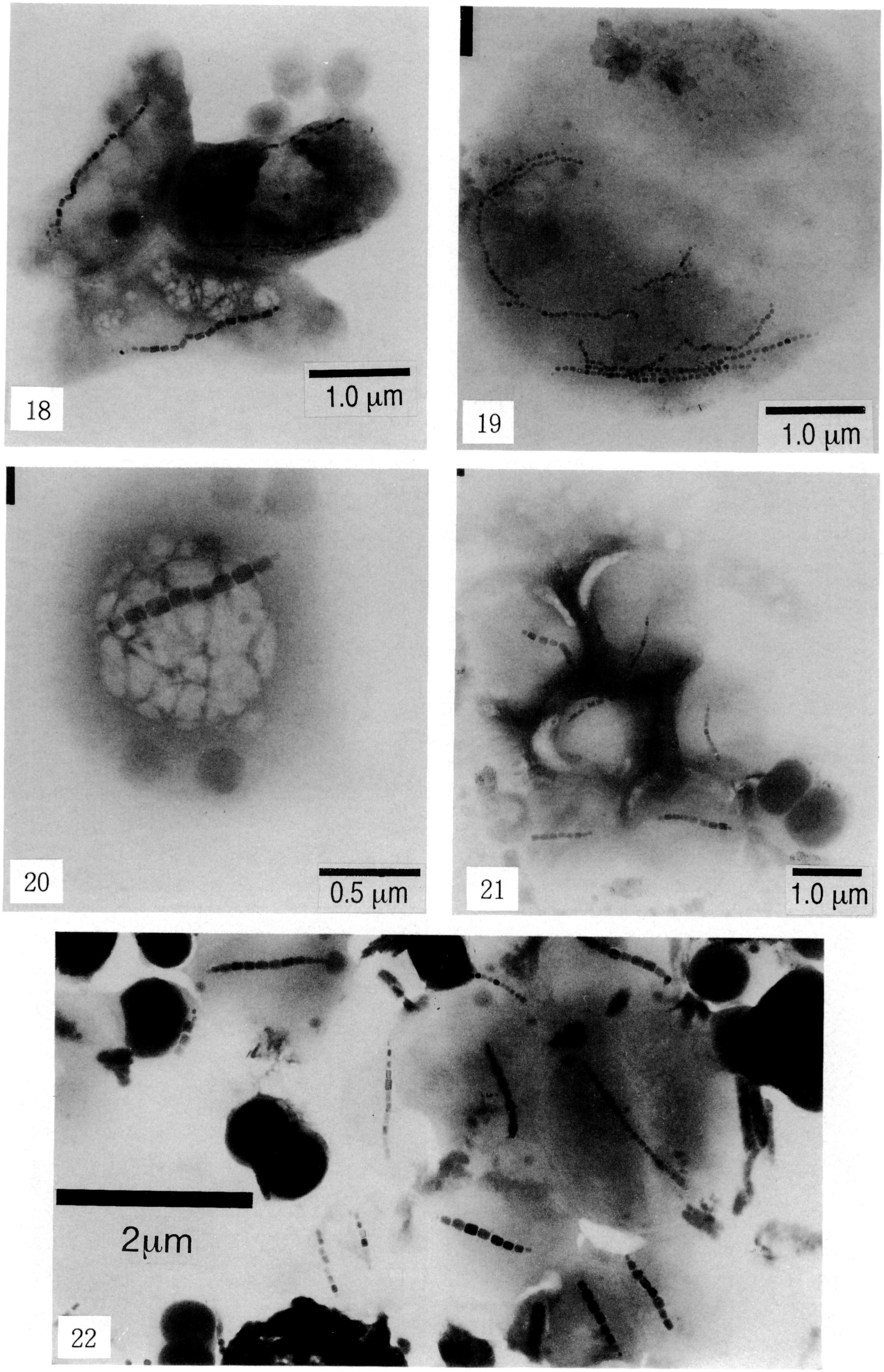

Plate V

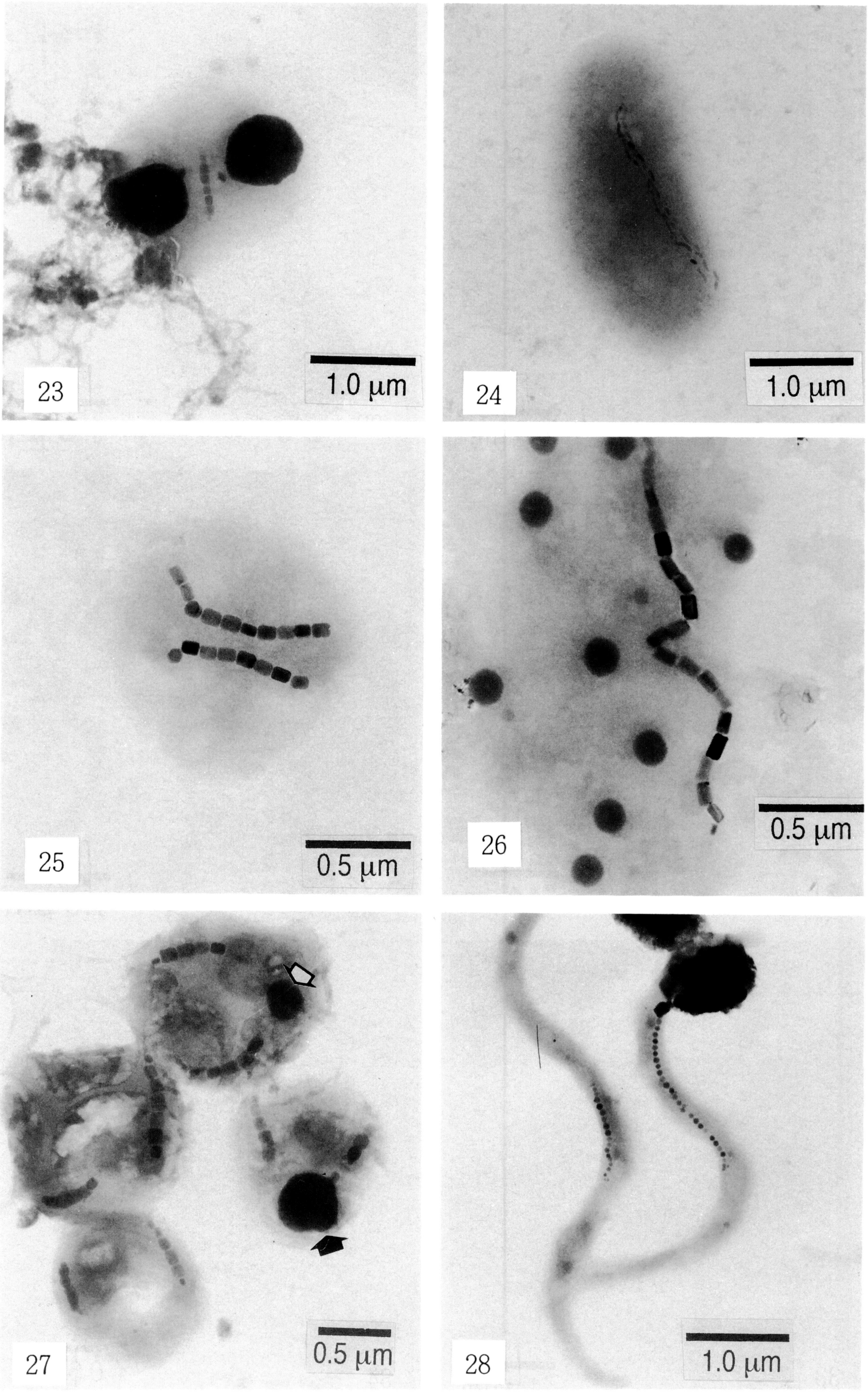

Plate VI