Late Miocene ostracods from the Fujikotogawa Formation, northern Japan – with reference to cold water species involved with trans-Arctic interchange

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ABSTRACT - Seventy-eight ostracod species belonging to 38 genera are recognized from the late Miocene Fujikotogawa Formation (c. 7–8 Ma), 40 km NE of Akita City, northern Japan. Some 30–40% of the ostracod species belong to the cold water groups (circumpolar and cryophilic species) reported from Plio-Pleistocene formations yielding the Omma-Manganji Fauna, the name given by Otuka (1939) to the Pliocene Japanese cold water molluscan fauna. This study demonstrates that most ostracod species distinguished in deposits yielding the Omma-Manganji Fauna had already appeared in the late Miocene. At least 13 of the ostracod species have been reported from both the Arctic and northern Atlantic Oceans, implying migration from the Pacific to the northern Atlantic through the Arctic after the Bering Strait had been breached. The 13 circumpolar, nine cryophilic and four endemic cold water species are illustrated, with brief taxonomic notes. J. Micropalaeontology 13(1): 3–15, September 1994.

INTRODUCTION
One of the most significant geological events in the late Neogene of high northern latitudes is the Pliocene opening of the Bering Strait. It is thought to have brought about a drastic faunal change in northern oceans. In order to investigate the dynamics of ostracod species in relation to the opening of the Bering Strait, it is important to compare Miocene to Recent ostracod assemblages from Arctic, northern Atlantic and northern Pacific Provinces. Ostracod species inhabiting such frigid to cold water environments as the Arctic and northern Atlantic have been reported long since by many workers. In recent years, Hazel (1967, 1970) and Hazel & Valentine (1969) investigated detailed distributions of many ostracod species from off northeastern North America; Neale & Howe (1973, 1975) studied ostracod assemblages from high latitude seas such as Novaya Zemlia; Siddiqui & Grigg (1975) investigated Recent ostracods from Nova Scotia, North America and Canada; Penney (1989) investigated Recent ostracods of the Ikersuak (Bredefjord) District in southwestern Greenland; Hartmann (1992) reported living and subfossil ostracods of the Liefdefjorden (North Spitsbergen). Late Neogene fossil ostracods in eastern North America, northern Europe, and the Arctic have also been studied by a large number of workers (Swain, 1963; Hazel, 1968; Cronin, 1981, 1988, 1991a, b; Cronin & Dowsett, 1990; Marincovich et al., 1990; Brouwers et al., 1991).

On the other hand, in northern Japan many cold water ostracod species have been reported by many workers from Plio-Pleistocene formations yielding the Omma-Manganji Fauna, which was assigned to cold water fossil molluscan assemblages in the Pliocene of the Japan Sea side by Otuka (1939). Hanai (1957a, b, c, 1959a, b, 1970) conducted the taxonomic work of typical high latitude genera such as Palmenella, Cythere and Semicythereura from the Plio-Pleistocene Setana and Sawane Formations (a and c in Fig. 1). Okada (1979) and Ishizaki & Matoba (1985) showed some cold water ostracods from Plio-Pleistocene formations in Akita Prefecture. Tabuki (1986) recognized some genera and species, reported from the north Atlantic to Arctic Provinces, in the Plio-Pleistocene Daishaka Formation (c in Fig. 1). Hanai & Yamaguchi (1987) also found those species in the early Pleistocene Hamada Formation (b in Fig. 1). Cronin & Ikeya (1987) presented a preliminary report of ostracod assemblages from the representative formations yielding the Omma-Manganji Fauna and distinguished three different species groups: 26 circumpolar and 21 cryophilic species in the northwestern Pacific, and the remaining temperate endemic species. Hayashi (1988) discussed a palaeoenvironment during deposition of the Plio-Pleistocene Setana Formation by means of fossil ostracod assemblages. Irizuki (1989b) investigated ostracods from the late Pliocene Sasaoka Formation (d in Fig. 1) and suggested that 20–40% of the assemblages were species inhabiting cold waters. Ishizaki et al. (1993) reported ostracod assemblages from the Omma Formation distributed in the type locality (f in Fig. 1) and delineated vertical environmental changes during early to middle Pleistocene time. As a result, some of these ostracod species in the Plio-Pleistocene are common to those in the Arctic and north Atlantic, which suggests that species in the Arctic and/or those in the northwestern Pacific migrated through the Bering Strait.

In Japan, only a few attempts have so far been made at the study of ostracod assemblages of pre-opening of the Bering Strait. The Fujikotogawa Formation is almost the only deposit yielding abundant late Miocene shallow water calcareous fossils on the Sea of Japan side of northern Japan. The purpose of the present study is to report some ostracod species which inhabit the Arctic and northern Atlantic and had already appeared during late Miocene time (pre-opening of the Bering Strait) in the northwestern Pacific and to discuss the origin of such cold water ostracods and their migration during the late Neogene.

GEOLOGICAL SETTING
The Fujikotogawa Formation is located approximately 40 km NE of Akita City, northern Japan (Figs 1 & 2); its
Irizuki

Fig. 2. Map showing the geology and sample localities of the Fujikotogawa Formation. O: Obinai Formation; W: Iwaya Formation; F: Fujikotogawa Formation (FC: calcareous sandstone; FS: fine sandstone; FA: alternations of sandstone and mudstone; FM: mudstone). Revised from Sumi & Moritani (1973).

Fig. 1. Locality of the Fujikotogawa Formation, some Plio-Pleistocene formations yielding the Omma-Manganji Fauna (a to f) and the Tatsunokuchi Formation (g). a: Setana Formation; b: Hamada Formation; c: Daishaka Formation; d: Sasaoka Formation; e: Sawane Formation; f: Omma Formation.

geology was investigated in detail by Sumi & Moritani (1973) and Ogasawara et al. (1986). It overlies conformably the Iwaya Formation. The Lower Fujikotogawa Formation can be divided into four parts on the basis of lithology: a lower part consisting of fine to medium calcareous black sandstone yielding many calcareous fossils (FC in Fig. 2); this is succeeded by fine sandstone (FS); followed by alternations of sandstone and black mudstone (FA); the upper part consists of black mudstone rich in siliceous fossils (FM). The lower Fujikotogawa Formation is assigned to the late Miocene and correlated with the Funakawa Formation distributed around Akita City. Saito & Izawa (1988) reported such planktonic foraminifers as *Globorotalia praemargaritae* Catalan & Sprovieri and *Globorotaloides falconariae* Giannelli & Salvatorini, which indicate zone N.17 of Blow (1969) from the Fujikotogawa Formation. Izawa (pers. comm.) reported a nannofossil species, *Discosta quirqueramas* Gartner, showing zone CN.9 of Okada & Bukry (1980) from sandstones of the lower part (near sample FC-11). The age of the lower part of this formation is thus suggested to be 7–8 Ma.

MATERIALS AND METHODS

Fifteen rock samples were collected from the lowest part of the Fujikotogawa Formation (FC in Fig. 2). However, only five samples yielded sufficient numbers of ostracod specimens for study (FC-11 to 15) (Fig. 2). Eighty-gram sediments were disaggregated by using a saturated sodium sulfate solution and naphtha, washed through a 200 mesh sieve screen, and dried. A fraction coarser than 125 μm (15 mesh) was sieved and divided by a sample splitter into aliquot parts, from which 200-odd specimens of ostracods were picked and placed on an assemblage slide.

FOSSIL OSTRACOD ASSEMBLAGES

Seventy-eight ostracod species belonging to 38 genera were discriminated in the five samples (calcareous fine sandstone) of the lower Fujikotogawa Formation (Table 1), but many
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| Fossil ostracods from the Fujikotogawa F. | 11 | 12 | 13 | 14 | 15 |
|------------------------------------------|----|----|----|----|----|
| *Acanthocythereis duneimensis* (Norman)  |    |    |    |    |    |
| *Aurila* cf. corniculata Okubo           | 9  | 3  | 3  | 3  | 18 |
| *Aurila* sp. A                          | 7  | 11| 4  | 6  | 6  |
| *Baffinicythere* sp. 1                   | 1  |    |    |    |    |
| *Baffinicythere* sp. 2                   | 1  | 1  | 2  |    |    |
| *Callicythere* setamensis Hanai           |    |    |    |    |    |
| *Callicythere* undulatifacialis Hanai     | 3  | 1  | 3  | 2  | 1  |
| *Callistocythere* sp.                    | 3  | 1  | 3  |    |    |
| *Callistocythere* sp.                    | 1  |    |    |    |    |
| *Caudoites* posteroceostata (Ishizaki)   | 6  | 13| 7  | 4  | 9  |
| *Clithia clathae Neale                   | 1  |    |    |    |    |
| *Carnicoquima* monlweisii (Ishizaki)     | 6  | 3  | 2  | 3  | 4  |
| *Carnicoquima* saltol (Ishizaki)         | 12 | 4  | 2  | 4  | 1  |
| *Cythere kamikojanicnsis* Tsukagoshi & Ikeya | 9  | 37| 35| 15 | 13 |
| *Cythere* sp.                           | 1  |    |    |    |    |
| *Cythereopteron* cf. angulaturn Brady & Robertson | 1 | 1 | 1 | 3 |    |
| *Cythereopteron* cf. reticulurn Hanai & Howe | 4 | 3 | 5  | 3  |
| *Cythereopteron* eremiturn Hanai         | 2  |    |    |    |    |
| *Cythereopteron* miureense Hanai         | 2  | 6  | 1  |    |    |
| *Cythereopteron* cf. nodosoolaturn Hanai & Howe | 1 |    |    |    |    |
| *Cythereopteron* sawamense Hanai         | 11 | 32| 33| 22| 26| 124 |
| *Cythereopteron* sp.                     | 1  |    |    |    |    |
| *Elonsonella* concinna (Jones)           | 1  | 4  | 2  | 3  | 10 |
| *Eucythere* sp.                          | 1  |    |    |    |    |
| *Eucythereura* neoalae (Ishizaki)        | 3  | 2  | 1  | 1  |    |
| Falsobuntoria cf. taiwanica Malz         | 1  |    |    |    |    |
| *Filmarchinea* diishakaenensis Tabuki     | 1  | 2  | 3  |    |    |
| *Filmarchinea* hanaii Okada              | 1  | 2  | 5  | 4  | 16 |
| *Filmarchinea* japonica (Ishizaki)       | 29 | 47| 25| 9  | 15| 125 |
| *Hannabohocrella* triangularis (Hanai)   | 1  |    |    |    |    |
| *Hemicythere* emarginata (Sars)          | 1  | 1  | 2  |    |    |
| *Hemicythere* aff. gurjanovae Schornikov | 45| 26| 16| 22| 39| 148 |
| *Hemicythere* kitampiconica (Tabuki)     | 25 | 11| 26| 16| 18| 96  |
| *Hemicythere* ochotensis Schornikov      | 1  | 5  | 4  |    |    |
| *Hemicythereura* clathrata (Sars)        | 1  |    |    |    |    |
| *Hemicythereura* cuneata Hanai          | 2  | 3  | 3  | 3  |
| Howenia neoloticythereidea (Ishizaki)    | 10 | 9  | 8  | 4  | 41 |
| *Kotorecythere* sp.                      | 1  | 9  | 2  |    | 14 |
| *Laxococoncha* subkotoforuma Ishizaki    | 3  | 6  | 9  |    |    |
| *Laxococoncha* sp.                       | 2  | 3  | 5  |    |    |
| *Laxocorniculum* kotoroforumz ishizaki  | 8  | 9  | 9  | 4  | 35 |
| *Laxocorniculum* sp. 1                   | 17 | 6  | 4  | 10 | 43 |
| *Laxocorniculum* sp. 2                   | 1  | 1  |    |    |    |
| *Munseyella* hatatatensis Ishizaki       | 1  | 3  |    |    |    |
| *Munseyella* japonica (Hanai)            | 2  | 1  | 3  |    |    |
| *Neomuniceratina* japonica (Ishizaki)    | 3  |    |    |    |    |
| *Neonesidea* sp.                         | 1  |    |    |    |    |
| *Pacambocythere* sp.                     | 1  |    |    |    |    |
| *Painnella* ilicica (Norman)             | 3  | 2  | 2  |    | 10 |
| *Painnella* saboyamensis (Ishizaki)      | 2  | 3  | 2  | 1  |    |
| *Paracythereidea* neolongicauda Ishizaki | 1  | 10| 6  | 9  | 3  |
| *Patagonocythere* sp. 1                  | 1  |    |    |    |    |
| *Patagonocythere* sp. 2                  | 1  |    |    |    |    |
| *Petrocycythe* diishakaenensis Tabuki     | 1  |    |    |    |    |
| *Robertsonites* hanai Hanai Tabuki       | 2  |    |    |    |    |
| *Robertsonites* reticuliforma (Ishizaki) | 2  | 1  | 3  | 11| 17 |
| *Rotundocythere* sp.                     | 10 | 1  | 6  | 3  | 12 |
| *Schizocythere* kishinoueyi (Kajiyama)   | 24 | 46| 31| 23| 123 |
| *Semicythereura* henryhowel Hanai & Ikeya| 8  | 7  | 7  | 10 | 39 |
| *Semicythereura* aff. henryhowel Hanai & Ikeya| 5  | 1  | 1  | 7  |    |
| *Semicythereura* cf. hiberna Okubo       | 2  | 4  | 1  | 7  |    |
| *Semicythereura* mainensis (Haze & Valentine) | 4  | 5  | 7  | 4  | 3  |
| *Semicythereura* skippa (Hanai)          | 1  |    |    |    |    |
| *Semicythereura* subundata (Hanai)       | 5  | 7  | 10 | 5  | 34 |
| *Semicythereura* sp. 1                   | 2  | 1  | 3  |    |    |
| *Semicythereura* sp. 2                   | 1  | 2  | 1  | 4  | 10 |
| *Semicythereura* sp. 3                   | 2  | 8  | 5  | 4  | 26 |
| *Semicythereura* sp. 4                   | 5  | 9  | 3  | 7  | 29 |
| *Semicythereura* sp. 5                   | 2  | 9  | 1  | 2  | 10 |
| *Semicythereura* sp. 6                   | 1  | 1  |    |    |    |
| *Semicythereura* sp.                     | 1  |    |    |    |    |
| *Tyrhocythere* sp. 1                     | 1  |    |    |    |    |
| *Urocythereis* gorokuensis Ishizaki      | 2  | 1  | 3  |    |    |
| *Urocythereis* cf. gorokuensis Ishizaki  | 2  |    |    |    |    |
| *Urocythereis* sp.                       | 1  | 3  |    |    |    |
| *Xestoleberis* sp. 1                     | 1  | 1  | 2  |    |    |
| *Xestoleberis* sp. 2                     | 3  | 3  |    |    |    |
| Gen. et sp. indet.                       |    |    |    |    |    |
| number of speciments                     | 600| 388| 327| 227| 282| 1524 |
| number of species                        | 50 | 53 | 44 | 44 | 45 | 78 |
| number of circumpolar species            | 49 | 72 | 56 | 25 | 35 | 237 |
| number of cryophilic species             | 77 | 58 | 55 | 45 | 79 | 334 |
| number of other species                   | 174| 258| 216| 157| 168| 973 |

Table 1. Ostracod species from the late Miocene Fujikotogawa Formation.

* : circumpolar species, *~ : cryophilic species.
specimens were poorly preserved. There were 44 to 53 species per sample. In order to determine the structure of the ostracod assemblages, the Shannon-Weaver's information function, revised by Buzas & Gibson (1969), was used. Diversity and equitability of fossil ostracod assemblages from the Fujikotogawa Formation were relatively high (Table 1; Fig. 3). Recent ostracod death assemblages in some bay areas have lower values of diversity and equitability (Ishizaki, 1979), whereas those in open sea areas have higher values (Ishizaki, 1979; Iriizuki, 1989a; Ikeya & Itoh, 1991; Ikeya & Suzuki, 1992). For example, recent ostracod assemblages on the sublittoral (60–90 m in depth) sandy bottom of Toyama Bay, central Japan, show a diversity value of about 3.5 and equitability of 0.6 (Iriizuki, 1989a). These values approximate those of the Fujikotogawa Formation. Thus, ostracod assemblages from the Fujikotogawa Formation may represent an open sublittoral setting. Dominant species are Schizocythere kishinouyei, Hemicythere aff. gurjanovae (= Hemicythere gurjanovae of Cronin & Ikeya, 1987), Finmarchinella japonica, Cytheropteron sawanense and Cythere kamikoanensis. The total number of specimens of these species is more than 100. These species are also representative of sublittoral open seas. On the other hand, Ogawara et al. (1986) reported some benthic foraminifers having various depth ranges (inner sublittoral to upper bathyal) from the lower Fujikotogawa Formation, thus there is a possibility that those fossil assemblages include displaced specimens from shallower areas.

Cronin & Ikeya (1987) recognized 26 circumpolar species which are known as fossil and/or inhabitants in high-latitude northern hemisphere seas, and 21 cryophilic species typically occurring with circumpolar species in Plio-Pleistocene formations of northeastern Japan. In the present study, at least 13 circumpolar and ten cryophilic species were recognized from the Fujikotogawa Formation. Previously, three circumpolar species (Finmarchinella japonica = Finmarchinella angulata of Cronin & Ikeya, 1987, Munseyella hatatatensis Ishizaki = Munseyella mananensis (Hazel & Valentine), and Palmenella limicola (Norman)) and four cryophilic species (Finmarchinella hanaii, Finmarchinella nealei, Hemicythere kitainipponica = Hemicythere? sp. of Yajima (1988) and Robertsonites reticuliforma) were reported from some Miocene formations (Ishizaki, 1966; Yajima, 1988). According to Yajima (1988), Finmarchinella hanaii and Palmenella limicola appeared in Blow's planktonic foraminiferal zone N. 9 (early Middle Miocene). Finmarchinella japonica (Cronin & Ikeya, 1987) thought that Finmarchinella japonica is conspecific to Finmarchinella angulata (Sars)) was reported from the Hatatate Formation corresponding to N. 13 zone (middle Middle Miocene) (Ishizaki, 1966). Ten circumpolar species are as follows: Acanthocythereis danae, Cytheropteron cf. nadossoalatum, Eoflosonella concina, Finmarchinella japonica (Finmarchinella angulata of Cronin & Ikeya, 1987), Hemicythere emarginata, Hemicytherura clathrata, Munseyella hatatatensis, Palmenella limicola, Semicytherura mainensis and Semicytherura subundata. Additionally, Cytheropteron cf. angulatum (= Cytheropteron tsugaruense Tabuki, 1986), Cytheropteron cf. arcticum, and Cluthia clathae also inhabit the Arctic and north Atlantic (Neale, 1973; Neale & Howe, 1973, 1975; Whatley & Masson, 1979).

Ten cryophilic species are as follows: Baffinicythere sp. 1, B. sp. 2, Finmarchinella daishakanaensis, F. hanaii, Hemicythere aff. gurjanovae, H. kitainipponica, H. ochotensis, Kotoracythere sp., Robertsonites hanaii and R. reticuliforma. Baffinicythere sp. 1 and B. sp. 2 are very closely related to B. howei Hazel. Iriizuki (in prep.) discusses the morphological relationships among species of the genus Baffinicythere. All these lines of evidence indicate that many high latitude species lived around northern Japan during the late Miocene. Figure 4 shows the percentages of circumpolar, cryophilic and temperate species in each sample from the Fujikotogawa Formation. All samples contain about 30–40% cold water ostracod species (circumpolar + cryophilic species of Cronin & Ikeya (1987) and this study). Many diversified species of the genus Semicytherura closely related to S. undata, which lives around the Arctic (Neale & Howe, 1975; Siddiqui & Grigg, 1975; Penney, 1989), occur in the Fujikotogawa Formation (Pl. 3). All these species can be recognized in the Omma-Mangaji Fauna suggesting cold water environments in the Pliocene of Japan (Cronin & Ikeya, 1987). Such species as Callistocythere setanensis, Cytheropteron sawanense, Howeina neoleptocytheroida,
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Patagovacythere sasakoiensis and Urocythereis? gorokuensis are endemic or are confined to a cold water environment in northern Japan. It is true, however, that there coexist such warm water species as Palsobuntonia cf. taiwanica, Loxocorniculum spp., Pacamboicyste sp., Paracytheridea neolongicaudata and Typhlocythere sp. They live in shallow water under the influence of the warm Kuroshio and Tsushima Currents.

DISCUSSION

Extensive studies on the origin of the molluscan Omma-Manganji Fauna and its migration have been made by many workers (e.g. Ogasawara, 1986). Durham & MacNeil (1967) cited more than 125 megainvertebrates of Pacific origin which entered the Arctic–Atlantic region, while only 16 Arctic–Atlantic taxa occur widely in the North Pacific late Neogene strata. Recently, Vermeij (1991) identified 295 molluscan species that either took part in the trans-Arctic interchange or are derived from stocks that so did, and suggested that out of these species, 261 are of Pacific origin, whereas only 34 are of Arctic–Atlantic origin. The first appearance of Pacific molluscs in the Atlantic region has been reported from a late Pliocene formation (Serripes groenlandicus zone) in Iceland, which is correlated to the Red Crag of England (MacNeil, 1973; Gladenkov, 1981). MacNeil (1973) mentioned that the northern Atlantic Ocean was abnormally cool in preglacial time and that the earliest migration of Pacific molluscs across the Arctic, and probably the first opening of the Bering Strait, took place in late Miocene time and the first great migration took place in early Pleistocene time. The date of the first opening of the Bering Strait is now problematical, but it is considered in general to have been about 3.0 Ma (Marincovich et al., 1990). More recently, Gladenkov et al. (1991) studied the stratigraphy and palaeoceanography of Pliocene deposits of Karaginsky Island, off eastern Kamchatka, Russia, and concluded on account of the occurrence of several marine species of Arctic and Atlantic origin in contemporary deposits that the proto-Bering Strait may have opened, at least temporarily, by 4.0 Ma. They suggested, in addition, that a second migration of marine species occurred about 3.6–3.2 Ma which is coeval with the migration of many marine species from the Pacific to the Atlantic through the Arctic. Cronin (1991b) investigated fossil ostracods from Tjörnes, Iceland, and mentioned that the first appearance of a Pacific species, Palmenella limicola, was found in the Cytheridea zone (molluscan Serripes zone) assigned to 2.8 Ma. This is concordant with the result from the molluscan study of MacNeil (1973). Moreover, he mentioned that such high latitude ostracods as Robertsonites tuberculata (Sars), Eofsonella concinna, Acanthocythereis danelmensis, Palmenella limicola and Finmarchinella spp. occur in pre-3.0 Ma deposits of the Limimtevayamian suite of Karaginsky Island, off eastern Kamchatka, Russia. He pointed out that these species migrated through the Arctic into the Atlantic once the Bering land barrier was breached. According to the ostracod list given by Gladenkov et al. (1991), the Limimtevayamian suite contains some ostracods common to the Fujikotogawa Formation. The present study supports the possibility that Acanthocythereis danelmensis, Eofsonella concinna and Palmenella limicola migrated from the Pacific to the Arctic. In addition, other species such as Cytheropteron cf. arcticum, Cytheropteron cf. nodososalatum, Hemicythere emarginata, Hemicytherura clathrata, Semicytherura mainensis, Semicytherura subunata and Munseyella hatatansis are thought to have migrated to the Arctic–Atlantic Provinces through the Bering Strait. Some hemicytherin ostracods such as Baflincythere howei, some Finmarchinella species (e.g. F. logani (Brady & Crosskey), F. barentzovoensis (Mandelstam), etc.) and Hemicythere villosa (Sars), are representative species ranging in age from late Pliocene (e.g. Red Crag of England, Tjörnes in Iceland) to Recent in the Arctic and northern Atlantic Provinces, but they have never been reported from northeastern Japan. Several different congeneric species are found in the late Miocene Fujikotogawa Formation, which suggests that some species migrated from the northwestern Pacific to the Arctic–Atlantic to evolve into new species after 3.0 Ma.

Whether water temperature around northeastern Japan at the time when the Fujikotogawa Formation was deposited (about 7–8 Ma) was warmer or colder than today is yet to be determined. This question will be dispelled by further investigations in combination with isotope measurements.

Fossil assemblages from the Fujikotogawa Formation are correlated with those from Plio-Pleistocene formations yielding the Omma-Manganji Fauna based on Cronin & Ikeya (1987), Hayashi (1988), Ishizaki & Matoba (1985), Irizuki (1989b), Okada (1979), Tabuki (1986) and unpublished data. About 90% of ostracod species from the Fujikotogawa Formation are common to those of Plio-Pleistocene formations. This indicates that the species composition of the Fujikotogawa Formation is very similar to that of Plio-Pleistocene sediments yielding the Omma-
Manganji Fauna, but generally the ratio of circumpolar and cryophilic species is higher in Plio-Pleistocene deposits than that in the Fujikotogawa Formation (see Cronin & Ikeya, 1987).

CONCLUSIONS
The late Miocene Fujikotogawa Formation yields important ostracod species for discussing the origin of cold water ostracod faunas and their migration. Major conclusions from the present study are as follows:
1. At least 13 sublittoral species from the Fujikotogawa Formation are found in the Arctic and northern Atlantic, suggesting migration from the Pacific through the Bering Strait (Table 1).
2. Atlantic species belonging to three hemicytherin genera, Baffinicythere, Finmarchinella and Hemicythere, may be descended from Pacific ancestors.
3. Ostracods such as Hemicythere and Semicytherura were already diversified during the late Miocene and most ostracod species from the Fujikotogawa Formation are found common to the Plio-Pleistocene of northern Japan.

TAXONOMIC NOTES
Some aspects of 13 circumpolar (+), nine cryophilic (+) and four endemic cold water species (−) are briefly discussed below. Specimens are deposited in the Department of Geoenvironmental Science, Faculty of Science, Tohoku University (IGPS).

Suborder Podocopa Sars, 1886
Family Cytheridae Sars, 1925
Genus Kotorocythere Ishizaki, 1966
+ Kotorocythere sp.
(Pl. 1, fig. 1)

Remarks. This species has been widely reported from the Plio-Pleistocene formations in northern Japan (Ishizaki & Matoba, 1985; Tabuki, 1986; Cronin & Ikeya, 1987).

Genus Munseyella van den Bold, 1957
* Munseyella hatatatensis Ishizaki, 1966
(Pl. 1, fig. 2)

Remarks. Cronin & Ikeya (1987) thought that M. hatatatensis is conspecific with M. mananensis Hazel & Valentine, 1969. M. hatatatensis was first described from the Middle Miocene (Blow's (1969) N. 13) Hatatate Formation in Sendai (Ishizaki, 1966) and its valves are found in Toyama Bay at depth of 50–300 m (Ishizaki & Irizuki, 1990).

Family Leptocytheridae Hanai, 1957
Genus Cluthia Neale, 1973
* Cluthia clutheae Neale, 1973
(Pl. 1, fig. 3)

Remarks. A specimen from the Fujikotogawa Formation resembles Cluthia japonica (Tabuki, 1986) reported from the Pliocene Daishaka Formation, northern Japan, but differs from the latter in having two distinct swellings in the anterocentral area. This species is distributed in Recent sediments of the northwestern Atlantic to Arctic and its fossils were reported around Great Britain (Neale, 1973). Brouwers (1990) recognized it from the middle sublittoral zone of the northeast Gulf of Alaska.

Family Cytheridae Baird, 1850
Genus Palmenella Hirschmann, 1916
* Palmenella limicola (Norman, 1865)
(Pl. 1, fig. 4)

Remarks. This species shows no morphological differences between the North Pacific and North Atlantic.

Family Hemicytheridae Pur, 1953
Genus Hemicythere Sars, 1925
* Hemicythere emarginata (Sars, 1865)
(Pl. 1, fig. 7)

Remarks. Hazel (1967) assigned this species to the genus Baffinicythere, but Horne & Whittaker (1983) suggested that emarginata should come under the genus Hemicythere because it has conspicuous ductus ejaculatorius and two frontal muscle scars as opposed to three in Baffinicythere. Specimens from the Fujikotogawa Formation have more rectangular valves, each with a less conspicuous vertical rim in the dorsal portion.

+ Hemicythere aff. gurjanovae Schornikov, 1974
(Pl. 1, figs 5, 6)

Remarks. Cronin & Ikeya (1987) recognized this species in some Plio-Pleistocene formations of northern Japan. Hemicythere gurjanovae from the intertidal zone of the Kuril Islands (Schornikov, 1974) differs in having robust anterior and posterior rims.

+ Hemicythere kitanipponica (Tabuki, 1986)
(Pl. 1, figs 8, 9)

Remarks. Tabuki (1986) assigned this species to the genus Ambrostracon, but Hemicythere seems more appropriate because it has two frontal muscle scars and normal and marginal pore patterns similar to some species of the genus Hemicythere (e.g. H. emarginata and H. orientalis).
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Schornikov) (Irizuki, 1993). Yajima (1988) also recognized this species from the Fujikotogawa Formation as *Hemicythere?* sp.

+ *Hemicythere ochotensis* Schornikov, 1974  
(Pl. 1, fig. 10)

**Remarks.** This species resembles *Hemicythere quadriodosa* Schornikov, 1974 but the former has a posterior rim as opposed to a tubercle in the latter.

Genus *Baffinicythere* Hazel, 1967  
+ *Baffinicythere* sp. 2  
(Pl. 1, fig. 11)

**Remarks.** Poorly-preserved specimens from the Fujikotogawa Formation seem to be assigned to *Baffinicythere* sp. 2 of Irizuki (1993) and Irizuki & Sasaki (1993). Irizuki (in press) studied reticulation patterns of this species.

Genus *Elofonella* Pokorny, 1955

* *Elofonella concinna* (Jones, 1856)  
(Pl. 1, fig. 12)

**Remarks.** The type specimen of *Elofonella concinna* is a pitted form with a conspicuous anterior marginal rim, but specimens from the Fujikotogawa Formation are notably reticulate, with a less conspicuous anterior marginal rim. Bassiouni (1965) assigned pitted and reticulate forms respectively to *E. concinna* and *E. neoconcinnna*, but Hazel (1967) thought that both types are conspecific because of the existence of intermediate forms.

Genus *Finmarchinella* Swain, 1963

+ *Finmarchinella daishakaensis* Tabuki, 1986  
(Pl. 1, fig. 13)

**Remarks.** This species was first described from the Plio-Pleistocene Daishaka Formation by Tabuki (1986). Only juvenile specimens were found in the Fujikotogawa Formation.

+ *Finmarchinella hanaii* Okada, 1979  
(Pl. 1, fig. 14)

**Remarks.** This species has widely been reported from Plio-Pleistocene formations yielding the Omma-Manganji Fauna. Its valves are recognized in shallow sediments from the Sea of Japan around the Noto Peninsula (Irizuki, 1989a).

* *Finmarchinella japonica* (Ishizaki, 1966)  
(Pl. 1, fig. 15)

**Remarks.** This differs from *F. angulata* (Sars) in having an anterior tubercle and more prominent posterior nodules. It is a matter of argument, however, whether these differences of characters represent intraspecific variation or geographically separate subspecies, which is now being studied by the author.

Genus *Patagonacythere* Hartmann, 1962

− *Patagonacythere sasaokensis* Irizuki, 1993  
(Pl. 2, fig. 1)

**Remarks.** This species was reported by Irizuki (1989b) from the Pliocene Sasaoka Formation, northern Japan as *Urocythereis?* sp. B. Irizuki (1993) studied pore distributional patterns of this species.

Genus *Urocythereis* Ruggieri, 1950

− *Urocythereis? gorokuenensis* Ishizaki, 1966  
(Pl. 2, fig. 2)

**Remarks.** This species was first described from the Pliocene Tatsunokuchi Formation in northern Japan (g in Fig. 1), where the Tatsunokuchi Fauna, applied to cold shallow water molluscan assemblages in the Japanese Pliocene on the Pacific side, was reported (Nomura, 1938; Otuka, 1941). It was also found in abundance in Plio-Pleistocene formations yielding the Omma-Manganji Fauna.

Family *Trachyleberididae* Sylvester-Bradley, 1948

Genus *Acanthocythereis* Howe, 1963

* *Acanthocythereis danelmensis* (Norman, 1865)  
(Pl. 2, fig. 3)

**Remarks.** Specimens from the Fujikotogawa Formation have more rectangular valves, but the distributional patterns of spines and tubercles are the same as those from the Atlantic.

Genus *Robertsonites* Swain, 1963

+ *Robertsonites hanaii* Tabuki, 1986  
(Pl. 2, fig. 7)

**Remarks.** Specimens from the Fujikotogawa Formation are all juveniles. This species differs from *R. reticuliforma* Ishizaki in having a subcentral tubercle and ridges, and its valve is less protrudent toward the posterior than the latter.

+ *Robertsonites reticuliforma* (Ishizaki, 1966)  
(Pl. 2, figs 4–6)

**Remarks.** This species was first described by Ishizaki (1966) from the middle Miocene Hatatate Formation.

Family *Cytheruridae* Muller, 1894

Genus *Hemicythere* Elofon, 1941

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**Explanation of Plate 2**

Fig. 1. *Patagonacythere sasaokensis* Irizuki, 1993, juvenile left valve, IGPS 102302, FC-11, ×52. Fig. 2. *Urocythereis? gorokuenensis* Ishizaki, 1966, juvenile left valve, IGPS 102303, FC-11, ×71. Fig. 3. *Acanthocythereis danelmensis* (Norman, 1865), female right valve, IGPS 102304, FC-15, ×40. Figs 4–6. *Robertsonites reticuliforma* (Ishizaki, 1966); fig. 4, juvenile right valve, IGPS 102305, FC-15, ×60; fig. 5, female left valve, IGPS 102306, FC-13, ×49; fig. 6, female right valve, IGPS 102307, FC-14, ×49. Fig. 7. *Robertsonites hanaii* Tabuki, 1986, juvenile right valve, IGPS 102308, FC-12, ×85. Fig. 8. *Hemicythereura clathrata* (Sars, 1866), adult left valve, IGPS 102309, FC-14, ×80. Fig. 9. *Semicytherura mainensis* Hazel & Valentine, 1969, adult left valve, IGPS 102310, FC-14, ×80. Figs 10, 11. *Howeina neolepocythereoida* (Ishizaki, 1966); fig. 10, adult left valve, IGPS 102311, FC-11, ×73; fig. 11, adult right valve, IGPS 102312, FC-11, ×73. Fig. 12. *Cythereopteron cf. angulatum* Brady & Robertson, 1872, adult left valve, IGPS 102313, FC-14, ×86. Fig. 13. *Cythereopteron cf. arcticum* Neale & Howe, 1973, juvenile left valve, IGPS 102314, FC-11, ×82. Fig. 14. *Cythereopteron cf. nodosovulatum* Neale & Howe, 1973, juvenile right valve, IGPS 102315, FC-12, ×72. Fig. 15. *Cythereopteron sawanense* Hanai, 1957, adult left valve, IGPS 102316, FC-14, ×82.
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Fujikotogawa Formation and those from the Atlantic have the same reticular and ridge patterns. It is closely related to similar. They also resemble *Semicytherura subundata* (Sars, 1865)

**Remarks.** This has been well illustrated by Neale & Howe (1975) and Hartmann (1992). Specimens from the Fujikotogawa Formation and those from the Atlantic have the same reticular and ridge patterns.

Genus *Howeina* Hanai, 1957

– *Howeina neolepiocytheroides* (Ishizaki, 1966)

**Remarks.** This was first described from the Pliocene Tatsunokuchi Formation mentioned above. It is closely related to *Semicytherura mainensis*.

Genus *Semicytherura* Wagner, 1957

*Semicytherura mainensis* Hazel & Valentine, 1969

**Remarks.** Specimens from the Fujikotogawa Formation have less prominent tubercles on the ala than the type specimens but their ridge patterns are very similar. They also resemble *Howeina higashimyeensis* Ishizaki, 1971, of which type specimens have prominent vertical ridges in the posterior portion, but have curved ridges. According to Hazel & Valentine (1969) and Siddiqui & Grigg (1975), this species ranges from the Pleistocene to Recent around Nova Scotia, eastern Canada and USA.

*Semicytherura subundata* Hanai, 1957

**Remarks.** Most species of the genus *Semicytherura* from the Fujikotogawa Formation are morphologically related to the *S. undata*–*S. subundata* group (see Pl. 3, figs 1–17). *Semicytherura subundata* is characterized by its large valve size and robust ridges. Cronin recognized this species in the Pleistocene of northeastern North America (Cronin & Ikeya, 1987).

Genus *Cytheropteron* Sars, 1865

*Cytheropteron cf. angulatum* Brady & Robertson, 1872

**Remarks.** Specimens from the Fujikotogawa Formation have less prominent tubercles on the ala than the type specimens. Tabuki (1986) also reported this species from the Plio-Pleistocene Daishaka Formation. According to Whatley & Masson (1979), this species ranges from the Pleistocene to Recent in the Arctic and north Atlantic, and Recent specimens occur in boreal, sub-Arctic and Arctic waters on both sides of the Atlantic (15 to 142 fathoms in depth). According to Brouwers' data, this species is also living in the southwestern Gulf of Alaska.

*Cytheropteron cf. arcticum* Neale & Howe, 1973

**Remarks.** The type specimens of *C. arcticum* have fine pitted ornamentation; specimens from the Fujikotogawa Formation have much coarser ornamentation. According to Neale & Howe (1973), this species ranges from the late Pleistocene (Hoxnian) to Recent in Europe. Recent specimens occur in some abundance at Russian Harbour, Novaya Zemlya and at 71°15.0’N, 27°54.0’E (142 fathoms).

*Cytheropteron cf. nodosoaalatum* Neale & Howe, 1973

**Remarks.** A poorly-preserved specimen from the Fujikotogawa Formation resembles the juvenile specimen (paratype) of Neale & Howe (1975).

**Cytheropteron sawanense** Hanai, 1957

**Remarks.** This species has been widely recognized in Plio-Pleistocene formations yielding the Omma-Manganji Fauna in northern Japan (e.g. Hanai, 1957c).

**ACKNOWLEDGEMENTS**

The author expresses his deep gratitude to Professor Kunihiro Ishizaki of the Department of Geoenvironmental Science, Faculty of Science, Tohoku University, for advice and continuous encouragement throughout the course of the present study and critical reading of the manuscript. Deep appreciations are also expressed to Emeritus Professor Yokichi Takayanagi and Professor Tsunemasa Saito of the same university for their assistance, suggestions and discussions concerning various aspects of the study, and reading of the manuscript. The author is indebted to Dr Thomas M. Cronin of the US Geological Survey for constructive discussions and suggestions about North Atlantic ostracod assemblages. Sincere thanks are also due to Professor Kenshiro Ogasawara of Tsukuba University for constructive suggestions concerning the Omma-Manganji Fauna. Acknowledgements are also due to Shohei Otomo and Jun Nemoto of the Department of Geoenvironmental Science, Faculty of Science, Tohoku University, for their photographic assistance. A part of this study is supported financially by the Katayama Memorial Scholarship from Tohoku University.

**Explanation of Plate 3**

Figs 1, 2. *Semicytherura henryhowei* Hanai & Ikeya, 1982: fig. 1, adult left valve, IGPS 102317, FC-14, ×108; fig. 2, adult right valve, IGPS 102318, FC-14, ×108.

Fig. 3. *Semicytherura aff. henryhowei* Hanai & Ikeya, 1982, adult? left valve, IGPS 102319, FC-12, ×99. Figs 4, 5. *Semicytherura subundata* (Hanai, 1957): fig. 4, left exterior view of juvenile? carapace, IGPS 102320, FC-12, ×88; fig. 5, juvenile? right valve, IGPS 102321, FC-14, ×88.

Fig. 6. *Semicytherura* sp. 1, adult? left valve, IGPS 102322, FC-12, ×110. Fig. 7. *Semicytherura* sp. 2, adult? left valve, IGPS 102323, FC-15, ×120. Figs 8–11. *Semicytherura* sp. 3: fig. 8, male left valve, IGPS 102324, FC-13, ×97; fig. 9, male right valve, IGPS 102325, FC-13, ×97; fig. 10, female left valve, IGPS 102326, FC-15, ×97; fig. 11, female right valve, IGPS 102327, FC-15, ×97. Figs 12–15. *Semicytherura* sp. 4: fig. 12, male left valve, IGPS 102328, FC-11, ×94; fig. 13, male right valve, IGPS 102329, FC-11, ×94; fig. 14, female left valve, IGPS 102330, FC-11, ×94; fig. 15, female right valve, IGPS 102331, FC-12, ×94.

Figs 16, 17. *Semicytherura* sp. 5: fig. 16, adult left valve, IGPS 102332, FC-14, ×120; fig. 17, adult right valve, IGPS 102333, FC-14, ×120.

Fig. 18. *Semicytherura* sp. 6, juvenile right valve, IGPS 102334, FC-13, ×133.
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Addendum

Irizuki & Matsubara (1994) reported six circumpolar ostracod taxa (Acanthocythereis danelmensis, Elofsonella cf. concinna, Finnmarcinella japonica, Hemicytherura clathrata, Munseyella hatatatensis, and Palmenella limicola) from the early Middle Miocene (c. 16 Ma) of northern Japan, which, thus far, represent the oldest fossil record of circumpolar species of Japan.

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