Cenozoic molluscan faunas and climatic changes in the northern Pacific related to Pacific gateways: review and perspective

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Abstract: Through the scientific results of IGCP Project 355, which studied Pacific gateways, the timing of onset or closure of each gateway has been defined. Some geological and paleontological events recognized in local areas took place as a result of gateway events. For instance, the appearance of siliceous biomarkers during the earliest Miocene in Sakhalin, northwestern Pacific, is coeval with the opening of Drake Passage during the earliest Miocene (23 Ma), and the invasion event of *Hataiarca*, an extinct Miocene bivalve, at 16.4 Ma in the Japanese Islands, is coeval with the closure of the Indonesian seaway. This closure indicates the first distinct appearance of the paleo-Kuroshio Current around the Philippine Islands.

Japanese Paleogene faunas have been compiled recently from the biochronological aspect, and Miocene molluscan faunas are now divided into the subtropical Akeyo-Kunugidaira fauna (20-16.4 Ma), the tropical and/or subtropical Yatsuo-Kadonosawa fauna (16.4-15.3 Ma), the subtropical and/or warm temperate Moniwa fauna (15.3-15 Ma), the warm-temperate Older Shiobara-Yama fauna (15-11 Ma) and the mild-temperate and/or cool-temperate Younger Shiobara-Yama fauna (11-5.3 Ma). These faunas can be considered as responses to stepwise cooling stages from tropical to cool-temperate realms, respectively.

Opening and closure of the Bering Strait during the Neogene was recently precisely redefined using diatom biochronology and fossil records of the bivalve *Astarte*. However, sea-water cooling is obvious after 6 Ma in high-latitude areas and tends to remain distinct until 2.5 Ma. The modern sub-arctic cold water-mass may have first appeared around 1 Ma as indicated by the first fossil record of the *Chlamys islandica* group in Hokkaido, Japan.

It is important to consider that some kinds of geological events recognized in a local and/or regional area might have taken place in response to global events. In addition, the precise age determination of related geological events is very important for the consideration of the cause and effect of events.

Keywords: Neogene events, Drake Passage, Indonesian seaway, *Hataiarca* invasion, Bering Strait, Yatsuo-Kadonosawa fauna, Shiobara-Yama fauna, paleoclimate, Miocene, Pliocene

1. Introduction

Concerned with the origin and migration of Japanese Cenozoic mollusks, Kotaka (1986, ed.) published many data including most molluscan families. Many studies have been also carried out on biotic migration across the Bering land bridge and seaways through it since Durham and MacNeil (1967) pointed out and discussed the migration of Neogene molluscan species (Hopkins, 1972; Kontrimavichus 1986, ed.; Kafanov, 1982; Masuda, 1986; Marincovich *et al.*, 1990; Vermeij, 1991, 2001; Basilyian *et al.*, 1993; Marincovich and Gladenkov, 1999; Marincovich *et al.*, 2002).

Recently Amano (2005) discussed the migration history of late Cenozoic cold-water mollusks in the North Pacific as exemplified by *Boreotrophon*, *Japelion*,

Sulcosipho species, and so on. He suggested that some cold-water species originated in the temperate zone of the North Pacific in response to the terminal Eocene events.

The timing of opening and closure of the Pacific gateways has been well studied as the main target of IGCP Project 355, corresponding to progress on the above-cited studies. In relation to these Pacific gateways, the cause and effect of events recognized in some local areas should be considered from the aspect of the linkage between local and global events. In addition to recognition of geological events, the precise age determination of events using methods such as integrated microfossil biostratigraphy, Sr stratigraphy, and Ar-Ar dating, are very important for the correlation of events of global aspect.

In this paper, recent progress in the study of Cenozoic events and paleoclimate is reviewed and discussed, main-

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ly based on molluscan studies of the Japanese Islands.

2. New data on Cenozoic biostratigraphy

Kafanov and Amano (1997) and Kafanov *et al.* (1999, 2000, 2001, 2002) have compiled a checklist of the Cenozoic Bivalvia in the Russian Far East. Owing to these data, molluscan biostratigraphy and bivalve biogeographical distribution are now well understood in the northwestern Pacific region (Kafanov and Ogasawara, 2003a, b, 2004, 2005, 2006a, b). Also, the databases of Japanese fossil type specimens described during the 20th Century have been published (Ikeya *et al.*, 2001-2004, eds.). Among these, for instance, more than 2,600 species of Cenozoic Gastropoda and 1,500 species of Cenozoic Bivalvia are compiled from systematic and geological aspects.

Recently, Early Miocene biostratigraphy has been advanced using groups such as diatoms, dinoflagellates and silicoflagellates (Barron and Gladenkov, 1995; Gladenkov and Barron, 1995; Gladenkov, 1998; Yanagisawa and Akiba, 1998; Kurita *et al.*, 2000; Yanagisawa, 2002) in conjunction with numerical age determinations and Sr stratigraphy (Ito, 1993; Ito *et al.*, 1998; Ogasawara *et al.*, 2003b; Kurihara *et al.*, 2005, Kano *et al.*, 2006).

Concerned with Paleogene stratigraphy and geological correlation of the Northwestern Pacific region between Kamchatka and Sakhalin, Gladenkov (1997, 2001) and Gladenkov, Y., *et al.* (2002, 2005) have compiled the stratigraphy of these areas mainly based on new geological data. The Japanese Paleogene molluscan faunas have also been compiled recently by Shuto (1993), Suto *et al.* (2005) and Takashima *et al.* (2008MS), corresponding to the new time-scale of the Cenozoic Era compiled from Cenozoic biozonations of microfossils (Gradstein *et al.*, 2004).

3. Pacific gateways

Ogasawara (2002) compiled the Cenozoic history of the Pacific Ocean, which can be divided into 7 stages. He also discussed the relationship between global events and Japanese Cenozoic molluscan faunas (Ogasawara, 2001). For instance, in relation to the closure of the Indonesian Seaway, which took place at 17 Ma (Nishimura and Suparka, 1997), Ogasawara and Noda (1996) discussed the cause of the invasion event of *Hataiarca*, which provides an indicator of tropical and/or subtropical mangrove tidal flats, into the Japanese Islands. This event in the tropics apparently resulted from the recent formation of the Kuroshio Current off the Philippine Islands.

In addition, a more obvious closure of the Indonesian seaway is apparent during Late Miocene time (ca. 8 Ma) from planktic foraminifera (Kennett *et al.*, 1985). However, this Late Miocene event is obscure in the molluscan fauna in southwestern Japan, and should be the next target to investigate.

Although the first step of studies of gateway events have been discussed by many workers, a more detailed relationship between gateway events and geological and paleontological events should be considered during the next step.

4. Recent progress on age assignment and stratigraphic correlation

In addition to microfossil biochronology, Sr stratigraphy has been used as a good age determination tool, mainly for Early Miocene rocks, because an obvious increase in Sr content can be recognized through this series, as shown by Ito (1993). Some Early Miocene Sr contents of molluscan shells have been studied from strata whose age determination has been controversial in the Japanese Islands.

Although geological correlation between the Paleogene strata of the Joban coal field of Honshu and the Kushiro and Yubari coal-fields of Hokkaido has been discussed previously, Suto *et al.* (2005) proposed a new correlation among these Paleogene strata, including Early Miocene biozones of the Joban coal field, as a result of recent progress on diatom biochronology (Barron and Gladenkov, 1995; Gladenkov and Barron, 1995; Gladenkov, 1998; Yanagisawa, 2002).

The stratigraphy and geological age of the so-called "Green tuff", which is mainly composed of a huge amount of volcaniclastic rocks distributed along the Japan Sea side of Japan (back-arc basin of the Honshu arc), have been investigated by many workers (e.g., Kitamura, 1989, ed.; Kano *et al.*, 1991, eds.). Kano *et al.* (2006) proposed new data on the geological age of the pyroclastic rocks related to the tectonic history of the Japan Sea. In addition, Sato *et al.* (2005) and Kano *et al.* (2007) redefined the geological age of the Cenozoic strata of pre-Miocene Nishikurosawa stages of the Oga Peninsula with some new magnetostratigraphic data.

As pointed out above, Sr stratigraphy using Neogene foraminifers is considered to be a good tool for age assignment (Kato and Nakano, 1999). However, it is also a good tool using molluscan shells. Recent results of Sr stratigraphy of Early Miocene molluscan shells are as follows: *Mytilus tichanovitchi* from the Shimonita Formation of the Shimonita Basin, Kanto area, has an age of 20.14 Ma; *Glycymeris* ? sp. from the Nenokami Formation and *Lucinoma acutilineata* from the Shirasu Formation of the Chichibu Basin yielded ages of 20.87 Ma and 18.99 Ma, respectively; *Nipponomarcia nakamurai* from the Yostuyaku Formation of the Kadonosawa area gave ages of 18.64 Ma, 19.20 Ma, 18.99 Ma and 18.57 Ma; a topotype specimen of *Mizuhopecten kobiyamai* from the Joban coal-field yielded 17.79 Ma, and so on (Table 1).

Table 1 Age assignment based on Sr stratigraphy.

Samples	Age (Ma)	Measurements (87 Sr/86 Sr)			Average
No. 1	17.79	0.7086085	0.7086188	0.7086284	0.7086186
No. 2	17.80	0.7086126	0.7086203	0.7086223	0.7086184
No. 3	18.65	0.7085788	0.7085681	0.7085617	0.7085695
No. 4	20.37	0.7084721	0.7084704	0.7084693	0.7084706
No. 5	20.32	0.7084666	0.7084606	0.7084929	0.7084734

Nos. 1-3: *Mizuhopecten kobiyamai* (Kamada), shell fragments of paratype; nos. 2 and 3: shell fragment of topotype specimens; no. 4: *Mytilus tichanovitchi* Makiyama, shell fragment from the Shimonita Formation; No. 5: *Mytilus* sp from the Kakerto Formation, Kamchatka.

In addition to these, the sedimentation rate curve is a very good tool, not only to determine the geological age using invasion methods, but also to consider geological events and geological correlation between neighboring sedimentary basins (Yanagisawa, 1999a, b, 2002; Yanagisawa and Hayashi, 2003; Yanagisawa *et al.*, 2003).

5. Geological and paleontological events

Ogasawara (2001) compiled the geological and paleontological events related to the 7 Cenozoic evolutional stages of the Pacific. In addition to these events, paleoceanographic events indicated by diatoms (Suto, 2004a, b) are interesting from a paleoceanographic point of view.

5.1 Paleogene events and paleoclimate

The most obvious geological event during the Paleogene in the Pacific is the change of Pacific plate motion at 43 Ma, as shown by the NNW-oriented Emperor seamount chain (Tenno-kiazan) and the NW-oriented Hawaiian chain (Shuto, 1993). This event is coeval with the first step of collision of the Indian micro-continent with the Eurasia plate at 43 Ma. After these events, a long-term cooling event (43-33 Ma), the so-called "Terminal Eocene event" (Wolfe, 1978), took place. During this cooling period, a remarkable cooling occurred at 33 Ma, mainly based on isotopic analysis (Zachos *et al.*, 1997, 2001). In relation to this cooling, Shiina *et al.* (2006) recognized a distinct siliceous biomarker event at the Eocene/Oligocene boundary in the Irupinsky section in Kamchatka. This event can be recognized as an upwelling of siliceous-rich bottom and/or middle layers, related to cooling in the Antarctic area. During the cooling at 33 Ma, Suto *et al.* (2005) recognized distinct changes in pollen assemblages (Sato, 1989) within the Iwaki Formation of the Joban coal field. However, not only plant groups, but also many
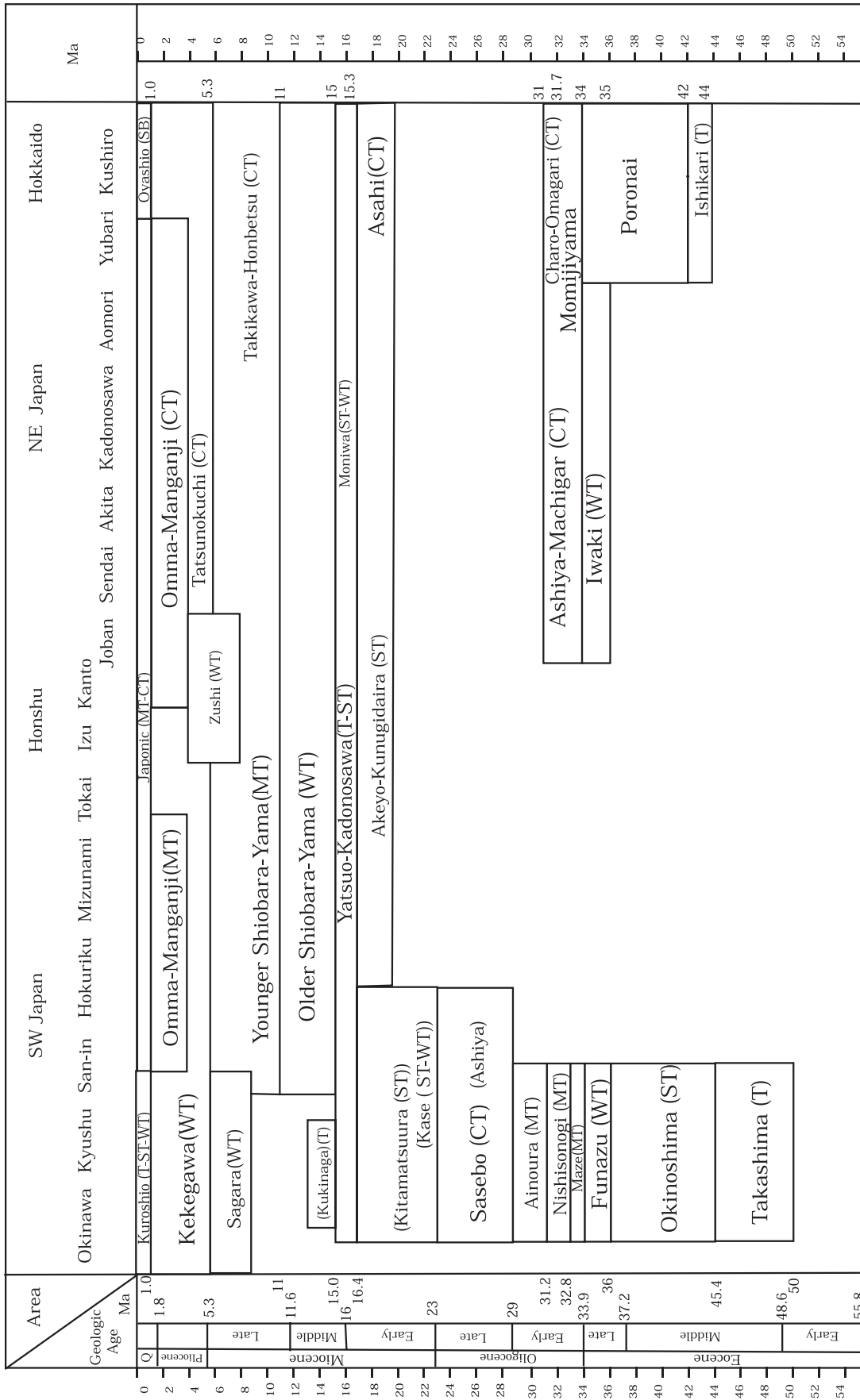
animals such as molluscs, foraminifers, ostracodes, and so on, might have changed during this long-term cooling event (e.g., Ogasawara, 2001; Amano, 2005).

5.2 Miocene events and paleoclimate

Related to the onset of Drake Passage at 23 Ma (earliest Miocene), which suggests the beginning of deep-sea interaction between the Atlantic and Pacific Oceans (Beu *et al.*, 1997), Kawata *et al.* (2000) pointed out a distinct change of siliceous biomarkers at the Oligocene/Miocene boundary in northern Sakhalin.

The Neogene can be understood as a cooling era from early to late stages, as exemplified by the Japanese Cenozoic molluscan faunas (Ogasawara, 1994). However, short-term climatic fluctuations during 20-16 Ma (Ogasawara *et al.*, 2003a) seem to be an exceptional case. They may be related to some gateway events. However, this is a future target for its mechanism to be understood from the viewpoint of the Earth system.

The first Neogene climatic optimum at around 16 Ma has been well understood as a world-wide phenomenon, which may have been caused by the greenhouse effect. The Yatsuo-Kadonosawa fauna of the Japanese Islands is considered to correspond to this optimum horizon. However, the fauna should be subdivided into the Akeyo-Kunugidaira fauna, the Yatsuo-Kadonosawa fauna (s. s.) and the Moniwa fauna, because of the recent microfossil biochronology. The former two faunas are characterized by the arcid-potamidid fauna (i.e., *Anadara* (s. l.) and *Vicarya-Vicaryella* species). However, the *Vicaryella* and *Dosinia* species are different from each other. For instance, *Dosinia kawagensis* and *Vicaryella incica* are characteristic of the Akeyo-Kunugidaira fauna, while *D. nomurai*, *Vicaryella notoensis* and *V. ishiiana* are characteristic of the Yatsuo-Kadonosawa fauna. In addition to these species, the *Mizuhopecten kimurai* group is also a good marker to discriminate between these two and the Moniwa fauna. That is, *Mizuhopecten kobiyamai* is a

Fig. 1 Zonation of the Japanese Cenozoic molluscan faunas with interpretations of paleoclimate.

Japanese Cenozoic molluscan zonation [modified after Mizuno (1964), Chinzei (1986), Ozawa and Tomida (1992), Shuto (1993) and Ogasawara (1994, 2001)]. T: Tropical ST: Subtropical WT: Warm-temperate MT: Mild-temperate CT: Cool-temperate, SB: Subboreal

characteristic species of the Akeyo-Kunugidaira fauna, while *M. kimurai* is characteristics of the Kadonosawa and Moniwa faunas.

As a result, the molluscan fauna of the Early Miocene to early Middle Miocene (20-15 Ma) can be divided as the Akeyo-Kunugidaira fauna, the Yatsuo-Kadonosawa fauna (s. s.) and the Moniwa fauna, which have dates of 20-17 Ma, 16.4-15.5 Ma, and 15. 3-15 Ma respectively (Kurihara and Yanagisawa, 2002). Among these, the invasion event of *Hataiarca kakehataensis*, which is a representative species of the Yatsuo-Kadonosawa fauna, can be related to the closure of the Indonesian seaway (Ogasawara and Noda, 1996), as noted above. In the Akeyo-Kunugidaira biozone, *Mytilus tichanovichi*, which is a typical northern element as represented in the Asahi Fauna in Hokkaido, occurs from the Goyasu-Shimonita-Aokiyama Formations in the Kato region (Kurihara *et al.* 2005). This *Mytilus*-bearing horizon can be considered a cooling invasion event from the north (Ogasawara *et al.*, 2003a), and should be discriminated from the Akeyo-Kunugidaira fauna in future.

Miocene sea-water cooling is recognized remarkably at 14. 5 Ma or 14 Ma, as pointed out by Ogasawara (2002). In relation to this cooling, extinctions of the marine mammal *Paleoparadoxia* and *Desmostylus* species are the most interesting maritime changes during the Miocene. The range of *Paleoparadoxia* species is 19 to 14 Ma and that of *Desmostylus* species is 18.5-11 Ma (Ogasawara, 2000). These ranges are coeval with the molluscan faunal changes of the Older and Younger Shiobara-Yama faunas (15-11 and 11-5.3 Ma). These are attributed to warm-temperate and mild-temperate faunas, respectively, corresponding to cooling within a few degrees of the present annual average temperature. *Nanaochlamys notoensis otutumiensis*, *Miyagipecten matsumoriensis*, *Dosinia kaneharai*, and *Anadara hataii* are characteristic of these faunas.

During the Late Miocene cooling period, the West Antarctic Ice sheet was established (Kennett and Barker, 1990). However, a warming event at 6 Ma is recognized by Tsuchi (1992) in the Japanese Islands. This zone may correlate with the Zushi fauna (Shikama, 1973), which is recognized mainly on the Pacific side of central Japan between the Izu Peninsula and the Joban coal field. This fauna is characterized by *Mizuhopecten planicostulatus*, *Amusiiopecten akiyamae* and some *Mikadotrochus* species. This fauna is considered to be of mid-Pacific origin by Masuda (1986) and Ozawa and Tomida (1992), based on a systematic study of pectinids. However, its geological age and zoogeographical significance are future targets to be clarified.

A cold-water province, comparable to the modern Arctic-subarctic provinces, was not established in the North Pacific during Late Miocene time, from the evidence of paleo-zoogeography. These data suggest that a temperate realm (cool-temperate and/or mild-temperate)

was widely distributed on both side of the North Pacific, as exemplified by the distribution of *Chlamys cosibensis* (Masuda, 1986).

5.3 Pliocene events and paleoclimate

The Pliocene corresponds to the time following the Messinian event of the latest Miocene, which is thought to be the trigger of the development of sea-ice in the Northern Hemisphere, because it caused a salinity decrease of the world ocean (Shackleton *et al.*, 1995).

The Pliocene is the period when climatic deterioration was remarkable, corresponding to the sixth stage of Pacific evolution of Ogasawara (2002). However, its cooling tends to be most obvious at 2.7-2.5 Ma (Barron, 1992, 1998; Lagoe *et al.*, 1993), related to the development of both North Pacific coastal glaciers and the Antarctic ice sheets. The Pliocene, in the Japanese islands, is the period when the marine biogeographical convergence became obvious between the warm Kakegawa, the temperate Omma-Manganji and the cool-temperate Tatsunokuchi faunas.

In the Southern Hemisphere, the major ice sheet of the Antarctic was established at 3.5 Ma and expanded at 2.4 Ma (Kennett and Barker, 1990). In Alaska, a remarkable cooling is recognized at 3.4 Ma after the warm interval of 4.2-3.5-3.0 Ma (Lagoe *et al.*, 1993). Jointly with such cooling events, stepwise closure of the Isthmus of Panama during 3.5-2 Ma may have influenced not only the marine fauna between the Caribbean and the Eastern Pacific, but also the climatic condition of the Arctic region, because the closure caused changes in the current systems of the Pacific and Atlantic Oceans.

The first opening of the Bering Strait recently has been determined to have taken place at 5.5-5.4 Ma (Marincovich and Gladenkov, 1999; Marincovich *et al.*, 2002; Gladenkov, A. *et al.*, 2002; Gladenkov and Gladenkov, 2004). Afterwards, Pacific and Atlantic interchanges via the Bering Strait are recognized at 3.6 Ma and at 1.2-1.9 Ma (Marincovich, 2000; Marincovich *et al.*, 2002).

The extinction of *Fortipecten takahashii*, a characteristic species of the Tatsunokuchi fauna, took place at around 1.2 Ma, corresponding to the establishment of the modern subarctic water-mass (Nakashima, 2002). These data suggested that the present thermal gradient in mid- to high-latitudes was established during late Pliocene to early Pleistocene time.

6. Discussion

Parallel molluscan communities (Chinzei, 1984), which are composed of different species even though they consist of the same or allied genera, are recognized in temporal, spatial and ecological aspects among Neogene shallow marine molluscan faunas, such as the

Yatsuo-Kadonosawa, Shiobara-Yama, Tatsunokuchi and Omma-Manganji faunas. However, this parallelism is not recognized between the modern subarctic and temperate faunas, or between Paleogene and Neogene faunas in the Japanese Islands. The faunal breaks between the Paleogene/Neogene and Arctic/temperate faunas indicate that the parallel communities are composed of easily adapting forms resulting from gradual environmental changes. The modern biogeographic realms indicate that gradual changes are recognized within a few degrees in the annual mean temperature, as discussed by Ogasawara (2001). That is, changes over 4 degrees in the annual temperature lead to the extinction of species of warm-water origin, in general. The faunal break between the cool-temperate and sub-boreal realms suggests that the origin of sub-boreal genera/species is quite different from temperate ones. It is interesting that the maximum of the annual range of surface-water temperature of 18 °C exists between the sub-boreal and cool-temperate biogeographic realms, situated off Erimo Peninsula, Hokkaido, in the modern Japanese Islands（Ogasawara，2001）.

Warming and cooling are not mean changes of a fixed number of degrees. However, isotopic curves and their events (Miller *et al.*, 1987; Williams, 1988; Zachos *et al.*1997, 2001) are very useful to consider the Cenozoic history of paleoclimate changes from a quantitative aspect. The terminal Eocene event (Wolfe, 1978), characterized by long-term obvious cooling in high-latitude areas is, for instance, a good example considered from aspects of both paleontology and stable isotopes.

The driving force of the cooling and warming are considered fundamentally to be the ice-house and greenhouse effects. Jointly with this mechanism, ocean gateways may have influenced world-wide climate changes. The first opening of the Bering land-bridge, for instance, was possibly caused by eustatic changes mainly controlled by glacial influences and submarine crustal deformation. This is because the depth of the Bering Strait is less than 50 m (Ogasawara, 1998) and the early Pliocene sea-level change is estimated to have attained about 150-100 m (Haq *et al.*, 1987; Miller *et al.*, 2005).

Models and assumptions are very important for understanding the Earth system and/or property of the Earth, such as the last 0.72 Ma glacial cycle, which was caused by the astronomical effects of the Earth ⌐s orbit (Zachos *et al.*, 2001).

7. Summary

Japanese Cenozoic molluscan faunas are newly divided from a chronological aspect (Fig. 1) and also are interpreted from a paleoclimatic point of view. Among the 7 stages of Pacific gateway evolution (Ogasawara, 2002), the most open systems from the marine biogeographical aspect were the 3rd and 4th stages, during 29-23

and 23-17 Ma.

Japanese Cenozoic molluscan faunal and climatic changes were caused by global event such as sea-level changes, and the onset/closure of the Pacific gateways. In addition, these events may have been caused partly by plate motion (Shuto, 1993).

Recognition of every kind of geological event in local and regional stratigraphy, and the spatial and temporal distribution of events, are basic data to clarify the cause and effect of the events from the view point of the Earth system, jointly with precise age determination.

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太平洋と他の海洋の開閉事件に関連した北太平洋地域新生代の貝類化石群集と古気候変動：
レビューと今後の展望

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要　旨

　IGCP-355 の研究で，ドレーク海峡やインドネシア海路などの開閉の年代が明確になった．この成果を踏まえると，これまで地域的な地質・古生物学的事件と考えられていた事象が，この開閉事件に関連していることが示唆されるようになった．例えば，サハリンでの漸新世と中新世の境界で認められたシリカのバイオマーカーの変化は，珪藻群集の組成変化であるが，これは北半球高緯度での冷水塊の出現に対応したもので，さらにその出現がドレーク海峡の成立と南極循環流を反映したものであると考えられるからである．また，わが国の八尾－門ノ沢動物群の二枚貝 *Hataiarca* の本邦への侵入事件は，17 Ma のインドネシア海路が赤道地域で閉鎖された結果，黒潮が形成され幼生が海流に依存してわが国に伝播した可能性が高い．

　本論では日本列島の新生代貝類化石群をあらたな統合微化石層序に基づいて再編し，それらの古環境を再解釈した．特に新第三紀の貝類化石群は明世－椚平動物群（20-16.6 Ma）と八尾－門ノ沢（16.4-15.3 Ma），茂庭動物群（15.3-15 Ma），古期と新期の塩原－耶麻動物群などに区分され，これらは基本的に熱帯から亜熱帯・暖温帯・中間温帯・冷温帯へと数百万年単位で，徐々に冷温化した海洋環境を反映したものと解釈される．さらに最新の珪藻化石層序に基づいたベーリング海峡の断続的開閉の年代的変遷の詳細が明確になり，これに伴う本邦の貝類化石群集の変化なども論じた．

　今後の新生代研究の重要課題として，精度の高い年代決定に基づいた地域的な地質学的事件と地球規模の事件を対比すること，さらに，事件と事件の時空分布を検討し，事件が生じた原因を多角的に追究する必要がある．