Responses of Japanese Cenozoic molluscs to Pacific gateway events

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ABSTRACT

The Cenozoic history of Pacific Ocean gateways can be divided into seven stages, extending from the Eocene onset of the Tasmanian seaway to the Pliocene closure of the Central American seaway. The first stage was the interval before 43 Ma, tentatively named the proto-Tasmanian stage. Development of the Tasmanian seaway (43-29 Ma) occupied the second stage. The third stage (29-23.5 Ma) was the oceanographically and paleoceanographically most open system, because the Pacific was not isolated from other oceans. The 4th stage consists of the closing of the Bering Strait prior to closure of the Indonesian seaway (23.5-17 Ma). The 5th stage was the time during which the Indonesian and Bering Seaways were both closed (17-5 Ma). The 6th stage consisted of a closed Indonesian seaway, and an open Bering Strait and Central American seaway (5-2 Ma). The 7th and final stage is the modern situation, with a closed Central American seaway.

The responses of Japanese Cenozoic molluscan faunas to these Pacific gateway events reflect Pacific-wide patterns. The remarkable faunal changes from the late Eocene to the early Oligocene record the transition from warm-water environments to temperate or cool-water environments. The Oligocene Ashiya and Asagai molluscan faunas evidently developed as a response to oceanic cooling, which may have been related to the onset of both the Drake and Tasmanian Seaways (32-29 Ma to 23.5 Ma). A drastic change in bio-siliceous sedimentation in the early Miocene, recently recognized in Sakhalin may have been related to diatom floral turnover. As with the early Miocene Kunugidaira-Akeyo molluscan fauna that lived from 20 to 16.4 Ma, the diatom turnover may have been related to the stepwise closure of the Indonesian seaway. The Kadonosawa fauna lived during the first Neogene climatic optimum, at about 16 Ma. Formation of the modern north-flowing Kuroshio Current may have resulted from closure of the Indonesian seaway at that time. The widespread occurrence of the bivalve Chlamys cosibensis during the late Miocene and early Pliocene in the North Pacific implies that surface waters were within the temperate realm.

Key words: Cenozoic, Pacific, gateway, event, cooling-event

RESUMEN

La historia Cenozoica relativa al cierre y apertura de intercomunicaciones del océano Pacífico se ha dividido en siete etapas. Esto ocurre desde el Eoceno, con el establecimiento del paso marítimo de Tasmania, hasta el Plioceno, con el cierre del paso marítimo de Centroamérica. La primera etapa es anterior a 43 Ma y tentativamente es denominada como la etapa proto-Tasmania. El desarrollo del paso marítimo de Tasmania (43-29 Ma) corresponde a la segunda etapa. La tercera etapa (29-23.5 Ma) atestiguó el sistema paleoceanográfico más abierto, puesto que el Pacífico no estuvo aislado de otros océanos. La cuarta etapa consiste en el cierre del Estrecho de Bering, antes del cierre del paso marítimo de Indonesia (23.5-17 Ma). La quinta etapa corresponde al tiempo en que se cerraron tanto el Estrecho de Bering como el paso marítimo de Indonesia (17-5 Ma). La sexta etapa *corresponde al cierre "total" del paso marítimo de Indonesia, y apertura del Estrecho de Bering y del paso marítimo de Centroamérica (5-2 Ma). La séptima etapa y final corresponde a la situación moderna, con el paso marítimo de Centroamérica cerrado.*

Las respuesta de la fauna de moluscos del Cenozoico a estos eventos de interconexión reflejan patrones generalizados del Pacífico. Los cambios en dicha fauna desde el Eoceno tardío al Oligoceno temprano registran la transición de ambientes de agua tibia a ambientes de agua fría. La fauna de moluscos Ashiya y Asagai del Oligoceno evidentemente se desarrolló como una respuesta al enfriamiento oceánico, que puede haber estado relacionado con el inicio de los pasos marítimos de Drake y Tasmania (32-29 Ma a 23.5 Ma). Un cambio drástico en la sedimentación biosilícea en el Mioceno temprano, recientemente reconocido en Sakhalin, puede haber estado relacionado con reversión de la flora diatomacea. Tal como sucedió con la fauna de moluscos Kunugidaira-Akeyo del Mioceno temprano que vivió de 20 a 16.4 Ma, la reversión de la flora diatomacea puede haber estado relacionada con el cierre paulatino del paso marítimo de Indonesia. La fauna Kadonosawa vivió durante el primer periodo climático óptimo del Neogeno, a aproximadamente 16 Ma. La formación de la moderna Corriente Kuroshio, que fluye hacia el Norte, puede haber resultado del cierre del paso marítimo de Indonesia en ese tiempo. La amplia presencia del bivalvo Chlamys cosibensis durante el Mioceno tardío y Plioceno temprano en el Pacífico Norte implica que las aguas superficiales se encontraban a temperaturas templadas.

Palabras clave: Cenozoico, Pacífico, pasos marítimos, eventos biogénicos, enfriamiento.

INTRODUCTION

The recent IGCP-355 project on "Neogene evolution of Pacific Ocean gateways," under the leadership of Prof. S. Nishimura of Kyoto University, aimed to elucidate the paleobiogeographic, paleoceanographic and paleoclimatic responses to the openings and closings of Pacific seaways. Core results of this project were published in *Tectonophysics* (1997, vol. 281, nos. 1-2) and in the *Journal of Asian Earth Sciences* (1998, vol. 16, no. 1), and focus on the histories of five major gateways: the Tasmanian seaway, the Drake Passage, the Indonesian seaway, the Bering Strait and the Central American seaway (Isthmus of Panama). Advances were also made in understanding Cenozoic paleoclimatic history as it relates to the development of sea ice in the Antarctic and Arctic (*e.g.*, Kennett and Barker, 1990; Flower and Kennett, 1994; Wolfe, 1994; Ogasawara, 1998). In addition, the Cenozoic geological history of the Japanese Islands has come to be understood as a progression of advances in biostratigraphy and geochronology within the context of tectonic events, igneous activity, sedimentary cycles, paleoclimates, and biological evolution (Kano *et al.*, 1991; Sugiyama, 1992; Shuto, 1993; Ogasawara, 1994; Saito, 1999).

Based on these investigations, I will discuss the responses of Japanese Cenozoic molluscs to Pacific gateway events, as well as suggest future research directions. I infer that paleoenvironmental changes, especially paleoceanography and marine climates, are related to both ocean gateway configurations and sea ice development. Therefore, it is essential to consider paleoclimatic changes and gateway events together.

CENOZOIC PACIFIC OCEAN GATEWAYS

The times of opening and closing of Pacific Ocean gateways with reference to the onset of sea ice in the polar regions are summarized in Figure 1. It is clear that step-wise cooling related the development history of Antarctic ice sheets took place during the Cenozoic. According to Kennett and Barker (1990), the onset of the East Antarctic ice sheet occurred at 36 Ma (late Eocene), whereas the West Antarctic ice sheet began in the late Miocene and has remained stable since 3.5 Ma (middle Pliocene). The development of sea ice was discussed by Miller *et al.* (1987) with reference to the Earth's cryospheric system (Crowley and North, 1991), based mainly on oxygen isotope data.

The development of Pacific Cenozoic gateways can be divided into seven stages, ranging from the Eocene initiation of the Tasmanian seaway to the Pliocene closure of the Central American seaway. The first stage was the interval before 43 Ma, tentatively named the proto-Tasmanian stage. The 2nd stage was the development of the Tasmanian seaway (43-29 Ma). The 3rd stage (29-23.5 Ma) was the oceanographically and paleoceanographically most open Pacific Ocean, before its isolation from other oceans. The 4th stage consisted of the closing of the Bering Strait prior to closure of the Indonesian seaway (23.5- 17 Ma; Figure 2). The 5th stage was the time during which the Indonesian and Bering seaways were both closed (17-5 Ma). The 6th stage consisted of a closed Indonesian seaway, while both the Bering Strait and the Central American seaway were open (5-2 Ma). The 7th and final stage consists of the modern situation, with a closed Central American

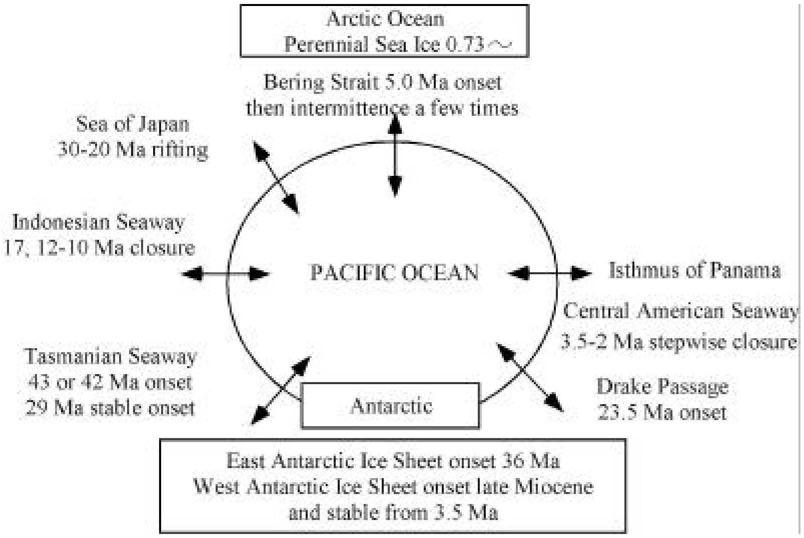

Figure 1. Pacific Ocean Cenozoic gateways, with a short note on sea ice history.

seaway (Figure 3).

Of these seven stages, the closing and opening of the Bering Strait in the Oligocene to early Miocene, and its possible effects on the biota of the Turgai Strait in western Siberia during the Eocene, are still controversial. However, it is clear that the appearance and disappearance of gateways had profound effects on Pacific Ocean environments, and this may be termed the "gateway effect."

CENOZOIC GEOLOGICAL AND PALEONTOLOGICAL EVENTS IN THE PACIFIC

The relationship between geological and paleontological events is clear, although the events may not be precisely understood (*e.g.*, Pomerol and Premoli-Silva, 1986, p. 20, fig. 3). These events involved factors that may have included the cosmic, tectonic, volcanic, sedimentary, geochemical, geomagnetic, biological, oceanographic and climatic. In addition, the role of plate tectonics is a key to understand the interrelationships of events, since seemingly unrelated geological events may ultimately have the same tectonic origin. For instance, eustatic and paleoclimatic fluctuations may have a general relationship to each other, and these may, in turn, be controlled mainly by the production rate of the MORB (*e.g.*, Kaiho, 1994). As a consequence, the knowledge of the velocities and directions of plates is important for adding precision to our understanding of the Earth system (*e.g.*, Shuto, 1993). The overall timing of Japanese Cenozoic tectonic, paleogeographic, climatic, eustatic, sedimentary, volcanic, isotopic and geomagnetic events is well understood (Kano *et al.*, 1991; Ogasawara, 1994). As an example of this, the Cenozoic history of Japan from 57.5 Ma to 2.7 Ma is presented here (Table 1), based on a compilation of current knowledge. Viewed from another aspect, Japanese Cenozoic molluscan faunas can be divided biostratigraphically into four Paleogene and six Neogene assemblages. These assemblages or Molluscan faunas reflect relationships between the eustatic curve, ocean gateways and climatic events (Figure 4). The responses of Japanese Cenozoic molluscan faunas to Pacific gateway events reflect overall Pacific patterns.

Japanese Paleogene molluscan faunas and related events

Paleogene molluscs of southern Japan have been divided into the Okinoshima-Takashima, Funazu, Maze and Ashiya faunas. The marine climates represented by these faunas have been inferred mainly from analogies with living molluscs (Shuto, 1991, 1993; Kano *et al.*, 1991; Honda, 1994;Ogasawara, 1996). For instance, the Okinoshima-Takashima fauna has been assigned to the tropical or subtropical realm, the Funazu and Maze faunas to the subtropical or warm-temperate realm, and the Ashiya fauna to the temperate realm (Figure 4). Paleocene to early Eocene shallow-marine molluscs are unknown in Japan. However, the remarkable faunal transition from the late Eocene to the early Oligocene is well represented by warm-water to temperate or cool-water faunas. The Oligocene Ashiya and Poronai-Asagai molluscan faunas likely reflect oceanic cooling (Shuto, 1991, 1993), which may have been related to the onset of both the Drake and Tasmanian seaways (32-29 Ma to 23.5 Ma). The Okinoshima, Funazu and Maze faunas are coeval with the terminal Eocene climatic transition, which was a long-duration event that transpired from 43 to 33 Ma (Wolfe, 1994). The Poronai-Asagai faunas are

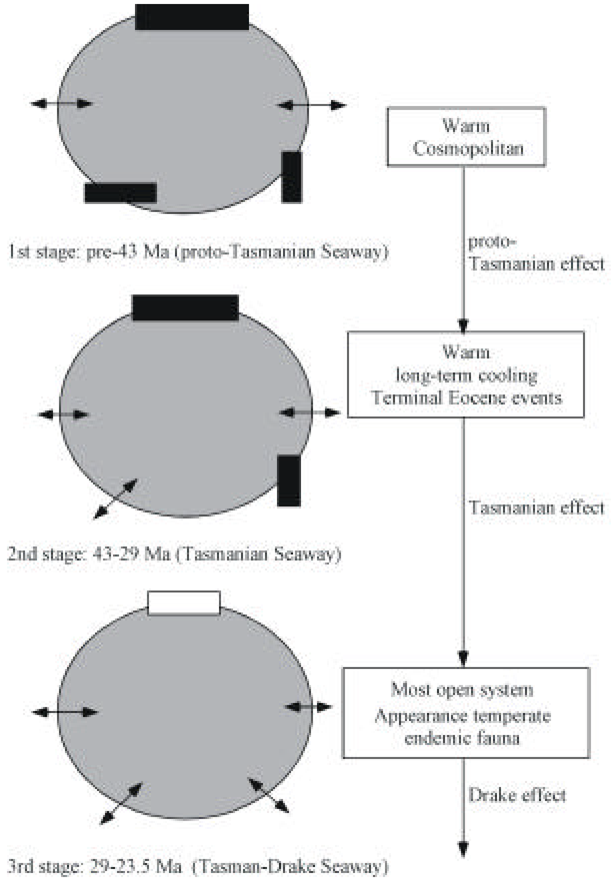

Figure 2. The 1st to 4th stages of Pacific Ocean gateway history, with notes on their inferred effects.

biostratigraphically equivalent to the Ashiya fauna, although they represent a greater paleodepth and a cool-temperate environment (Shuto, 1991; Ogasawara, 1996). The Ashiya fauna is characterized by a number of shallow-marine species that imply a temperate paleoclimate, such as *Dosinia chikuzenensis* Nagao, *Pitar ashiyaensis* (Nagao), *P. matsumotoi* (Nagao) and *Glycymeris cisshuensis* Makiyama (Shuto, 1991). Shallow-marine molluscs representing the Oligocene-Miocene transition are unknown in Japan due to a regional unconformity.

Japanese Neogene molluscan faunas and related events

A profound change in biosiliceous sedimentation in the early Miocene, first recognized in Sakhalin was evidently related to diatom floral turnover (Kawata *et al.*, 2000). Moreover, this early Miocene event may have been more generally related to the first appearance of a silica-rich water-mass generated by opening of the Drake Passage at about 23.5 Ma (Ogasawara *et al.*, 2000). The recognition of early Miocene strata in Japan is still controversial, since most of the relevant strata are of non-marine or very shallow-marine origin, and include a preponderance of altered pyroclastic rocks. However, a paleoenvironmental reconstruction based on early Miocene desmostylid marine mammals is the basis for establishing a new correlation between the Joban, Chichibu and Mizunami basins (Ogasawara, 2000). The Akeyo fauna may be equivalent to the Kunugidaira-Shiode fauna in the Joban district in Northeast Honshu, and its age is thought to be 20 Ma (Yabe *et al.*, 1996; Ogasawara, 2000). The Nenokami fauna of the Chichibu Basin and the Goyasu fauna of the Joban area can be correlated on the basis of the distinctive bivalve *Mytilus tichanovitchi* Makiyama, and tentatively assigned an age of 18.4 Ma, at the base of the *Crusidenticula sawamurae* diatom zone that extends from 18.4 and 16.9 Ma (Gladenkov and Barron,1995). These data suggest that the Nenokami and Goyasu faunas, along with the early to middle Miocene Akeyo and Kadonosawa faunas (which lived at 20 to 16.4 Ma and 15 Ma, respectively), may be artifacts of the stepwise closing of the Indone-

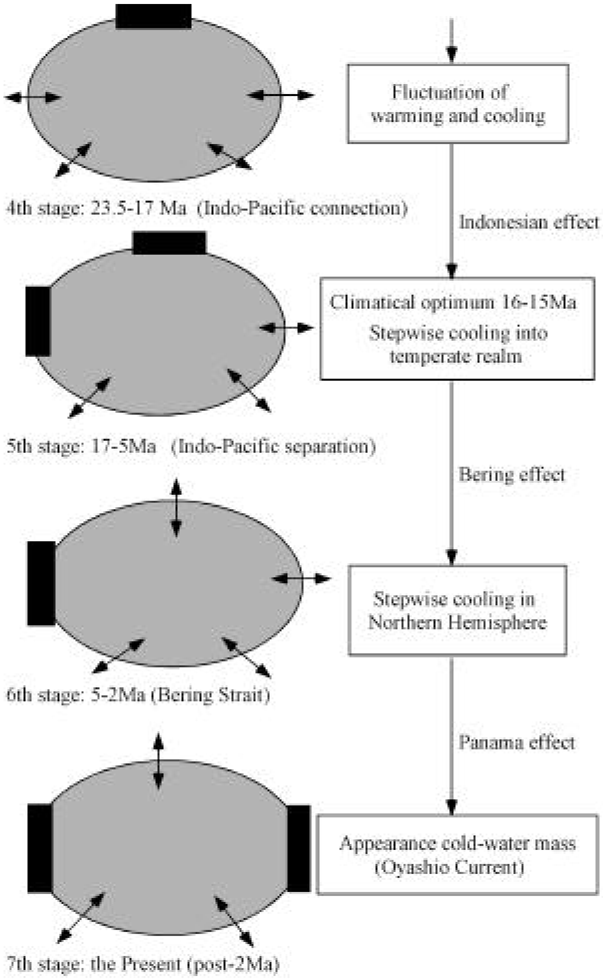

Figure 3. The 4th to 7th stages of Pacific Ocean gateway history, with notes on their inferred effects.

Table 1. Major Cenozoic geological events from 57.5 Ma to 2.4 Ma, showing the stages in Pacific Ocean gateway history.

	1st stage: Proto-Tasmanian Seaway
57.5 Ma:	Extinction of the Velasco-type fauna in the Indian Ocean (Tethys) and appearance of the Midway-type fauna (Nomura, 1990)
49 Ma:	-150 m sea level drop (Haq *et al*., 1987)
47 Ma:	Vicariance of benthic foraminiferal biogeography (Kaiho, 1994)
Early Eocene:	Turgai Strait still connected between Arctic and Tethys Oceans (Tedford, 1974; Marincovich *et al*., 1990)
43-33 Ma:	Terminal Eocene event (long span cooling) (Wolfe, 1994)
43 Ma:	Preliminary onset of the Tasmanian Seaway (Nomura *et al*., 1997): Moving direction of the Pacific Plate changes from NNW to WNW (Clague and Jarrard,1973; Engebretson *et al*., 1985; Sugiyama, 1992)
	2nd stage: Tasmanian Seaway
38 Ma:	Tethys closed between the Mediterranean and Indian Oceans (Nomura *et al*.,1997)
	Cooling Eocene/Oligocene (Koizumi, 1986; Nomura, 1987)
37-30 Ma:	Onset of the Tasmanian Seaway (Beu *et al*., 1997)
36 Ma:	Established of the Eastern Antarctic Ice Sheet (Kennett and Barker, 1990)
35.8 Ma:	Abrupt cooling and appearance of the temperate Ashiya Fauna in Japan (Schakleton, 1986; Shuto, 1993)
30 Ma:	-350 m sea level drop (Haq *et al*., 1987)
	3rd stage: Tasman-Drake Seaways
23.5 Ma:	Onset of the Drake Passage (Beu *et al*., 1997)
	4th stage: Indo-Pacific connection
21-17 Ma:	Up-rifting of the Himalaya (Sr ratio increase) (Nomura *et al*., 1997)
20-18 Ma:	Takachiho Orogeny (Shuto, 1963; Sugiyama, 1992)
18.5-17 Ma:	Appearance of the Daijima Flora (Yamanoi, 1992)
	5th stage: Indo-Pacific separation
17 Ma:	Closing of the Indonesian Seaway (Nishimura and Suparka, 1997)
16 Ma:	Warming of the 1st Neogene climatical optimum (N8b; Tsuchi, 1992)
14.5 Ma:	Cooling (Koizumi, 1986; Nomura, 1987)
14 Ma:	Major expansion of Antarctic Ice Sheet (Kennett and Barker, 1990)
13 Ma:	Floral change in Japan (Yamanoi, 1992)
10-8 Ma:	Benthic foraminiferal speciation, endemism and parallel evolution (Woodfruff, 1985; Nomura, 1987)
9 Ma:	Shoaling of the Isthmus of Panama (Diatom event A; Barron, 1998)
7 Ma:	Appearance of the Mitoku type Flora in Japan (Yamanoi, 1992)
Late Miocene:	Established Western Antarcitc Ice Sheet (Kennett and Barker, 1990)
6.5/6.2/5.5 Ma:	6.5 Ma; diatom accumulatin rate (MARs) increase in California/ 6.2 Ma; increase in High-latitude/ 5.5 Ma; increase in Japan (Diatom event B; Barron, 1998)
6 Ma:	Warming N7b (Tsuchi, 1992)
	6th stage: Bering Strait
5.2-3.9 Ma:	Brake between the Indian and Pacific Oceans (Srinivasan and Sinha, 1998)
5 Ma:	Messinian event (Salinity crisis)
4.5 Ma:	Diatom sediments increase in NW Pacific and decrease in California-Japan (Diatom event C; Barron, 1998) <Interpretation: Warming event>
4 Ma:	Appearance of the Shinjo-type Flora (Yamanoi, 1992)
3.5 Ma:	Major ice sheet of the Arctic Ocean (Kennett and Barker, 1990)
3.5-2 Ma:	Closing of the American Seaway (Isthmus of Panama)
3 Ma:	Warming (N21a) (Tsuchi, 1992); Cooling (Koizumi, 1986)
2.7 Ma:	Step cooling (Diatom event D; Barron, 1998)
2.4 Ma:	Expansion of the Arctic Ice Sheet (Kennett and Barker, 1990)

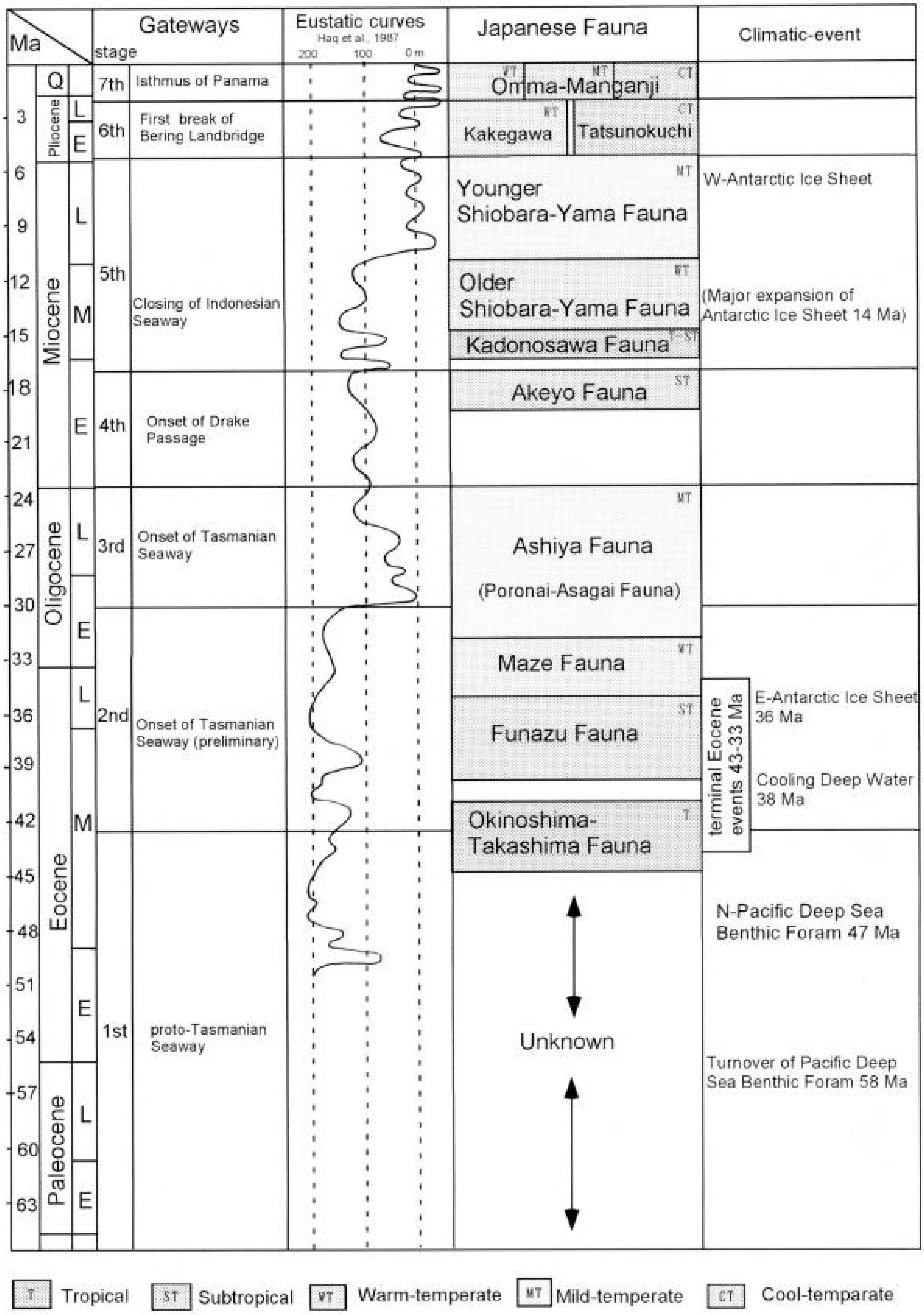

Figure 4. Japanese Cenozoic molluscan faunas, showing their paleoclimatic interpretations and relationship to gateway events, climatic events and the eustatic curve of Haq *et al*. (1987).

sian seaway. The Kadonosawa (or Yatsuo-Kadonosawa) fauna represents the first Neogene climatic optimum at about 16 Ma that has been discussed by many workers (*e.g.*, Tsuchi, 1992; Ogasawara, 1994). Initiation of the modern Kuroshio Current may have resulted from closure of the Indonesian seaway. As for North Pacific Miocene to Pliocene marine climates, the widespread occurrence of the pectinid bivalve *Chlamys cosibensis* implies that surface waters were essentially temperate. The cooling history of the northern Pacific Ocean related to the Bering land bridge has recently been compiled by Ogasawara (1998). These data suggest that the appearance of an Oyashio-type molluscan fauna at 1.0 Ma reflects the appearance of a cold-water, sub-boreal water mass in the Northern Hemisphere. This event may have been related to both the opening of the Bering Strait and the closure of the Central American seaway.

PALEOCEANOGRAPHIC SIGNIFICANCE OF GATEWAY STAGES

Event-to-event correlations have been accomplished by IGCP-246 participants (Tsuchi and Ingle, 1992, p. 254-257) as a way to elucidate global responses to paleoenvironmental changes. Comparative studies such as these have proved invaluable when considering the interplay of events or of the gateway effect.

The first stage in gateway evolution was the interval before 43 Ma, tentatively named the proto-Tasmanian stage (*i.e.*, the initial opening of the Tasmanian seaway). Development of the Tasmanian seaway (43-29 Ma) occupied the 2nd stage. It is estimated that the opening of the Tasmanian seaway may have led to the establishment of the Antarctic circum-polar gyre system, and also led to formation of the East Antarctic ice sheet at 36 Ma (Kennett and Barker, 1990). The time around 43 Ma (or 42 Ma) was also very important in plate tectonic history, because the direction of the Pacific plate changed from NNW to WNW (Clague and Jarrard, 1973), as evidenced by the bending of the Emperor to Hawaiian sea-mount chain, and the beginning of the Aleutian trench (Worrall, 1991) at 43 Ma. This time is also paleoclimatically significant, because 43 Ma was the start of the long span of cooling known as the terminal Eocene event (*e. g.*, Wolfe, 1994). Overall, 43 Ma was a major turning point in Earth history, although we are only now beginning to understand the interrelationship of events at that time.

The Ashiya fauna evidently reflects abrupt cooling around 36 Ma (Shackleton, 1986; Kennett and Barker, 1990; Shuto, 1993). The extent of paleoceanographic changes from the 2nd to the 3rd stages is uncertain, although the 3rd stage was clearly characterized by an oceanographically open system and gradual cooling coupled with open Tasmanian and Drake seaways. It is clear that the Drake Passage contributed to deep water circulation between the Atlantic and Pacific, as evidenced by homogenized oxygen isotope ratios derived from deep-sea benthic foraminifera (Miller *et al.*, 1987; Kaiho, 1994). The final closing of the Turgai Strait, which had long been a connection between the Arctic and Tethys, took place during the 2nd stage (*i.e.*, Marincovich *et al.*, 1990), and then the Tethyan Ocean fragmented into the Mediterranean Sea and the Indian Ocean.

The 3rd stage (29- 23.5 Ma) was oceanographically the most open system, since the Pacific was not isolated from other oceans except by the Bering land bridge, which still has a controversial history. The 4th stage was characterized by the existence of the Bering land bridge (Biske and Baranova, 1986). A significant geological event at that time was an abrupt increase in Sr ratios, which may have reflected an increase in the erosion of older sedimentary rocks, perhaps related to uplift of the Himalayan Range (Nomura *et al.*, 1997).

The Bering land bridge was probably closed during the 4th and 5th stages (Marincovich *et al.*, 1990). The 5th stage consists of the closure of the Indonesian seaway at about 17Ma when an island barrier came into existence, which may have separated tropical water masses between the eastern Indian and western Pacific oceans.

The closing or opening of gateways evidently affected not only the oceanic gyre system, but also the climate and biotas of the Pacific. It is clear that formation of the Kuroshio Current may have resulted from closure of the Indonesian seaway from an oceanographic point of view. Ogasawara and Noda (1996) discussed one result of this event, the invasion of the bivalve *Hataiarca* into Japan. At the end of the 5th stage, the West Antarctic Ice Sheet was stable (Kennett and Barker, 1990) and cooling was taking place in the Northern Hemisphere, as evidenced by abundant glacial dropstones in high-latitude seas (Ogasawara, 1998). Related to this cooling event, Shackleton *et al.* (1995) suggested that the Messinian event, previously referred solely to a salinity crisis, may have been triggered by the development of Northern Hemisphere sea ice. During this interval, the late Miocene and early Pliocene, shallow-marine Molluscan faunas of the North Pacific were of temperate aspect, as seen in the widespread occurrence of the bivalves *Dosinia, Anadara* and *Ostrea*. The temporal and spatial distribution of *Chlamys cosibensis* (Yokoyama) is one key to understand the paleoenvironment of the 5th stage (Masuda, 1986).

The 6th stage corresponded to the first breach of the Bering land bridge at about 5 Ma. The configuration of the Bering Strait during the Oligocene and Miocene is still unclear, although the initial Neogene marine connection between the Arctic and the North Pacific has recently been documented by Marincovich and Gladenkov (1999) based on the migration history of the bivalve *Astarte* (*Tridonta*). The 7th and the final stage is the modern situation, characterized by an open but shallow (less than 50-m-deep) Bering Strait. Other gateways are as follows: onset of the Drake Passage, closure of the Indonesian seaway, and uplift of the Isthmus of Panama.

TOWARDS THE 21 CENTURY

The appearance and disappearance of gateways had profound effects on Pacific Ocean environments, and this may be termed the "gateway effect." It is fundamentally important to understand the properties of each gateway based on more-precise age control. In this context, local geological and paleontological events should be interpreted in a global context. The application of advanced chemical and isotopic analyses is crucial for achieving increased understanding of processes and events. I hope the cooperation among specialists in various geological disciplines will lead to increased understanding of the Earth System, as exemplified here by Cenozoic Pacific gateways.

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