

2. Localities of echinoid fossils from the northern part of Ibaraki Prefecture

Echinoid fossils were collected from the following localities (Loc. nos.1-40, Fig. 2).

Loc. no.01. Streambed of the Yamizogawa River, about 150 m north of the Idogasawa, Shimonomiya, Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.02. Streambed of the Onamasegawa River, about 450 m southeast of the Tsukimachinotaki Fall in Onamase, Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.03. Streambed of the Masenobuzawa, about 750 m northwest of the cross road at Mesnokubo, Onamase, Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.04. Small cliff along the roadside, about 900 m southeast of the cross road at Masenokubo, Onamase, Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.05. Small cliff along the waterway, about 600 m northwest of the Tatsugamibashi Bridge at Tatsugami, Konamase, Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.06. Small cliff along the waterway, about 350 m northwest

of the Tatsugamibashi Bridge at Tatsugami, Konamase,
Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.07. Cliff of field-side, about 150 m west of the
Tatsugami-bashi Braidge at Tatsugami, Konamase, Daigo-machi,
Kuji-gun, Ibaraki Prefecture.

Loc. no.08. Cliff along the left side of the Onogawa River, about
250 m east of the Tatsugamibashi Bridge at Tatsugami, Konamase,
Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.09. Cliff along the left side of the Onogawa River, about
300 m east of the Tatsugamibashi Bridge at Tatsugami,
Konamase, Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.10. Cliff along the left side of the Onogawa River, about
50 m west of the Nawashiroda, Konamase, Daigo-machi, Kuji-gun,
Ibaraki Prefecture.

Loc. no.11. Streambed of the Yazawagawa River, about 500 m south
of the Shimo-Yazawa, Konamase, Daigo-machi, Kuji-gun,
Ibaraki Prefecture.

Loc. no.12. Cliff along the road-side, about 300 m northwest of the
Miyadaira, Takashiba, Daigo-machi, Kuj-gun, Ibaraki
Prefecture.

Loc. no.13. Cliff along the road-side, about 300 m north of the

Takikura at Kami-Ogawa, Daigo-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.14. Streambed along the Terairizawa, about 250 m west of the Terairi at Kegano, Suifu-mura, Kuji-gun, Ibaraki Prefecture.

Loc. no.15. Small cliff along the path-side, about 250 m south of the western exit of Tatsukuroiso-Tunnel at Tatsukuroiso, Suifu-mura, Kuji-gun, Ibaraki Prefecture.

Loc. no.16. Cliff along the waterway, about 200 m south of the western exit of Tatsukuroiso-Tunnel, at Tatsukuroiso, Suifu-mura, Kuji-gun, Ibaraki Prefecture.

Loc. no.17. Cliff of a Farm, about 700 m west of the Koiwai, Omiya-machi, Naka-gun, Ibaraki Prefecture.

Loc. no.18. Cliff of the roadside, about 300 m east of the Kume Elementary School at Kume, Kanasago-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.19. Small cliff along the path-side, about 300 m northeast of the Kume Elementary School at Kume, Kanasago-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.20. Stone pit, about 600 m west of the Yanagisawa at Odaira, Kanasago-machi, Kuji-gun, Ibaraki Prefecture.

Loc. no.21. Satake-Minami-Dai New Town, Tenjin-cho, Hitachiota City, Ibaraki Prefecture.

Loc. no.22. Small cliff of the waterway, about 300 m northwest of the Hitachiota-Kogyo-Danchi, Hitachiota City, Ibaraki Prefecture.

Loc. no.23, Small cliff along the waterway, about 600 m northeast of the Yakitsukiyama Mountain Omori-cho, Hitachiota City, Ibaraki Prefecture.

Loc. no.24, Small cliff of the waterway, about 100 m south of the Nagai at Nukada-Togo, Naka-machi, Naka-gun, Ibaraki Prefecture.

Loc. no. 25, Cliff along the waterway, about 700 m southeast of the Tokai Station, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.26. Cliff along the waterway, about 500 m south of the Muramatsu Elementary School, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.27. Small cliff along the waterway, south of the Hirahara -Nanbu-Kogyo-Danchi, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.28. Streambed along the waterway, about 500 m southeast of the Hirahara-Nanbu-Kogyo-Danchi, Tokai-mura, Naka-gun,

Ibaraki Prefecture.

Loc. no.29. Small cliff, about 500 m southwest of the Tenjin-Yama Mountain, Muramatsu, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.30. Small cliff of the wasteland, about 300 m west of the Tenjinyama Mountain, Muramatsu, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.31. Small cliff of the wasteland, about 250 m south of the Akogigaura Lake, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.32. Small cliff of the wasteland, about 200 m south of the Akogigaura Lake, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.33. Small cliff of the wasteland, about 200 m southwest of the Akogigaura Lake, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.34. Small cliff of the wasteland, about 200 west of the Akogigaura Lake, Tokai-mura, Naka-gun, Ibaraki Prefecture.

Loc. no.35. Small cliff of the wasteland, about 300 m northwest of the Akogigaura Lake, Tokai-mura, Naka-gun, Ibaraki Prefecture

Loc. no.36. Beach of the Ose Coast, about 800m south of the Hitachi Station, Hitachi City, Ibaraki Prefecture.

Loc. nos.36-37. Cliff along the beach side at Turushimisaki Cape,
Hitachi City, Ibaraki Prefecture.

Loc. no.39. Cliff of the Takaiso Beach at Hidaka-cho, Hitachi City,
Ibaraki Prefecture.

Loc. no.40. Small cliff of roadside, about 500 m south of Hnabusa,
Kanasago-machi, Kuji-gun, Ibaraki Prefecture.

3. Distribution of time and space and ecology of echinoid fossils from the northern part of Ibaraki Prefecture

Base on systematic studies of echinoid fossils in the present study, the writer discusses herein the time and space distribution and ecology of each echinoid taxa.

1) Echinothuriidae gen. et sp. indet.

Echinothuriidae contains three subfamily and eleven genera (Fill, 1966), and is known from the Danish Upper Cretaceous (Kier and Lowson, 1978) to the Japanese early middle Miocene (Mizuno, 1992). Although it is imperfect specimens, the occurrence from the early middle Miocene Naeshiroda Formation is the second record in Japan.

2) *Anthocidaris* sp.

Cooke (1957) reported *Anthocidaris* sp. from the Miocene strata of the Saipan Island, and also Kikuchi (2000) reported *Anthocidaris* sp. from the Pleistocene Nakoshi Formation in Okinawa Prefecture. Therefore, this report is the first record from Pliocene in the world. However, Nisiyama (1966) described that of the genus *Anthocidaris* which reported by Cooke (1957) is doubtful one.

It is known that *Anthocidaris crassispina* of living species is inhabiting in waters of littoral zone to 3 m depth (Table 19) from central part of Japan to Taiwan and Hong Kong. Ecological information of this living species can be available to that of the Pliocene Muramatsu Formation (Figs. 72, 76; Tables 19-20).

3) *Temnotrema rubrum* (Döderlein)

Fossil of *Temnotrema rubrum* is only reported from the Pleistocene Tokyo Formation (Nisiyama, 1966) in Kanagawa Prefecture and the Pleistocene Atsumi Group in Aich Prefecture (Fujiyama, 1982). Therefore, the occurrence from the Hatsuzaki Sandstone Member of the Hitachi Formation is the first record in Pliocene (Fig. 49).

Living *Temnotrema rubrum* is only known from shallow-sea of the Tokyo Bay area (Nisiyama, 1968; Shigei, 1974) (Figs. 72, 76; Table

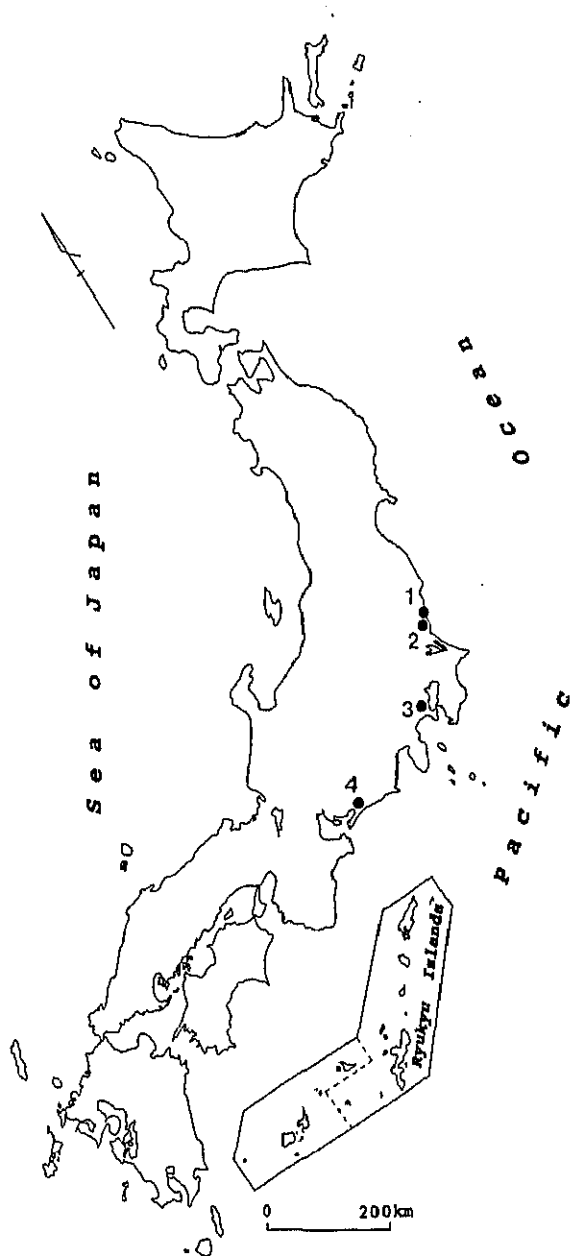


Fig. 57. Distribution of *Temnotrema rubrum* (Döderlein) in Japan.

Pliocene; 1-2. Hatsuzaki Sandstone Member of the Hitachi Formation (Present paper). Pleistocene; 3. Naganuma Fossil Bed (Nisiyama, 1936), 4. Atsumi Group (Fujiyama, 1982).

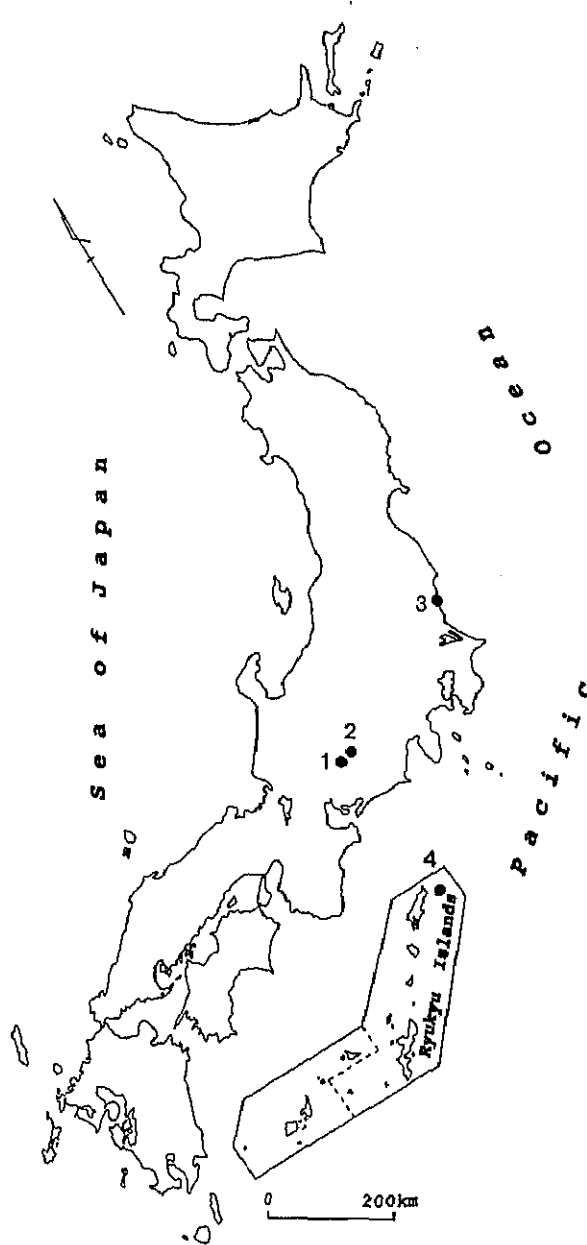


Fig. 58. Distribution of *Echinocyamus crispus* Mazzetti in Japan.

Miocene; 1. Oidawara Tuffaceous Mudstone (Morishita, 1956), 2. Akeyo Formation (Morishita, 1974). Pliocene; 3. Hatsuzaki Sandstone Member of the Hitachi Formation (Present paper). Pleistocene; 4. Ryukyu Limestone (Nisiyama, 1968; Fujiyama, 1982).

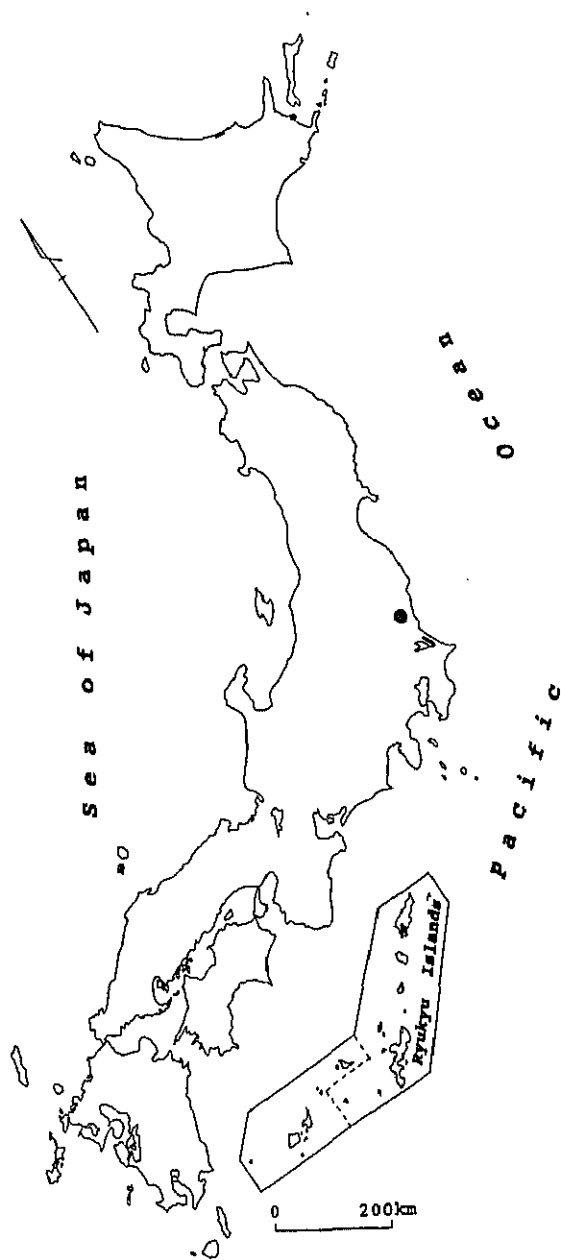


Fig. 59. Distribution of *Pourtalesia kusachii* n. sp. and *Aceste* sp. in Japan. Miocene; Tatsukuroiso Mudstone Member of the Higashikanasayama Formation (Present paper).

19-20).

4) *Echinocyamus crispus* Mazzetti

Fossil of *Echinocyamus crispus* is reported from the Pleistocene Ryukyu Limestone of Kikai Island in Kagoshima Prefecture (Nisiyama, 1968; Fujiyama, 1982). Therefore, the occurrence from the Hatsuzaki Sandstone Member from the Hitachi Formation is the first record in Pliocene.

Living *Echinocyamus crispus* is widely distributed from the Sagami Bay of Japan to Philippines, Indo-west Pacific Ocean to Red Sea and Hawaiian Islands in waters 18 to 192 m depth (Nisiyama, 1968; Shigei, 1974, 1986) (Table 19). Ecology that of the living species (Fig. 76; Table 20) should be useful for fossil records.

5) *Scaphechinus* cf. *mirabilis* A. Agassiz

This fossil *Scaphechinus* cf. *mirabilis* is remained as "cf." in the species level because of ill preservation.

Living genus *Scaphechinus* contains three species and one subspecies (Nisiyama, 1968). It is known from shallow sea in the Japanese waters (Nisiyama, 1968; Shigei, 1974, 1986) (Table 19). Paleoecology of fossil *Scaphechinus* cf. *mirabilis* may be similar to

that of the living allied species (Figs. 72, 76; Tables 19-20).

6) *Pourtalesia kusachii* n. sp.

It is known that species of *Pourtalesia* are living in deep-sea waters and five species and one subspecies of are distributed in the world. Among them, *Pourtalesia laguncula* A. Agasiz lives in the sea area of Japan. Kikuchi and Nikaido (1985) reported *Pourtalesia* sp. from the Tatsukuroiso Mudstone Member of the Higashikanasayama Formation.

In addition to *Pourtalesia* sp. reported by Kikuchi and Nikaido (1985), new species *Pourtalesia kusachii* was collected from the Tatsukuroiso Mudstone Member of the Higashikanasayama Formation by the present study (Fig. 69). Although Smith (1984) described species of Pourtalesiidae are restricted in recent, their stratigraphical range should be down to middle Miocene owing to the present study.

Although, *Pourtalesia kusachii* is the oldest record in Pourtalesiidae, it needs a more detail study concerned the origin of genus *Pourtalesia*. Living *Pourtalesia laguncula*, which very similar to *Pourtalesia kusachii*, is distributed widely from Japan to the sea area of the New Zealand in waters 220 to 1,400 m depth (Nisiyama, 1968; Shigei, 1974, 1986) (Fig.75, Tables 17-18).

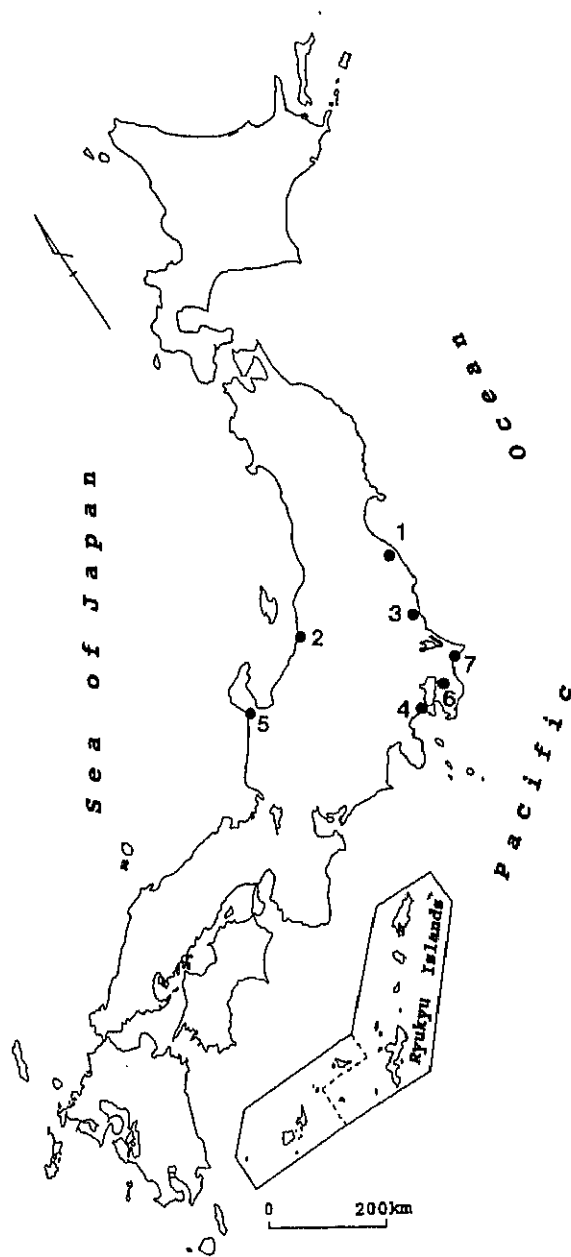


Fig. 60. Distribution of *Palaeopneustes psoidoperiodus* Nishio in Japan.

Pliocene; 1. Nakamura Formation (Nisiyama, 1968), 2. Nadachi Formation (Morishita, 1953a), 3. Muramatsu Formation (Present paper), 4. Kanazawa Formation (Hashimoto and Shibata, 1960), 5. Sakiyama Siltstone Member (Matsuura and Hotsuta, 1986). Pleistocene; 6. Umegase Formation (Nishio, 1961), 7. Byobugaura Formation (Present paper).

7) *Aceste* sp.

It is predicted that genus *Aceste* was derived from family Hemiasteridae (Fisher, 1966). *Aceste* sp. is the first fossil recorded as including both of family and genus from middle Miocene (Fig. 69).

Recent species *Aceste ovata* is known in waters 400 to 4,000 m depth of the Japanese Sagami Bay to the Indian Ocean and Hawaiian Island (Mortensen, 1950a; Nisiyama, 1968; Shigei, 1974) (Table 17).

8) *Palaeopneustes psoidopreiodus* Nishio

Four species of the Japanese *Palaeopneustes* yield from Miocene to Pleistocene; *Palaeopneustes lepidus* and *Palaeopneustes priscus* from Miocene; *Palaeopneustes (Oopneustes) periturus* and *Palaeopneustes psoidoperiodus* from Pliocene (Nisiyama, 1968; Morishita, 1983).

Judged from the time and space distribution of *Palaeopneustes* (Fig. 52), *Palaeopneustes* extends its inhabiting area to the north to Hokkaido corresponding the warming of the Ocean climate in early Middle Miocene. Then, *Palaeopneustes* was migrated to the south in Pliocene, due to cooling of the ocean climate.

Palaeopneustes (Oopneustes) periturus and *Palaeopneustes psoidopreiodus* are now not living in the Japanese sea (Fig. 69, Table

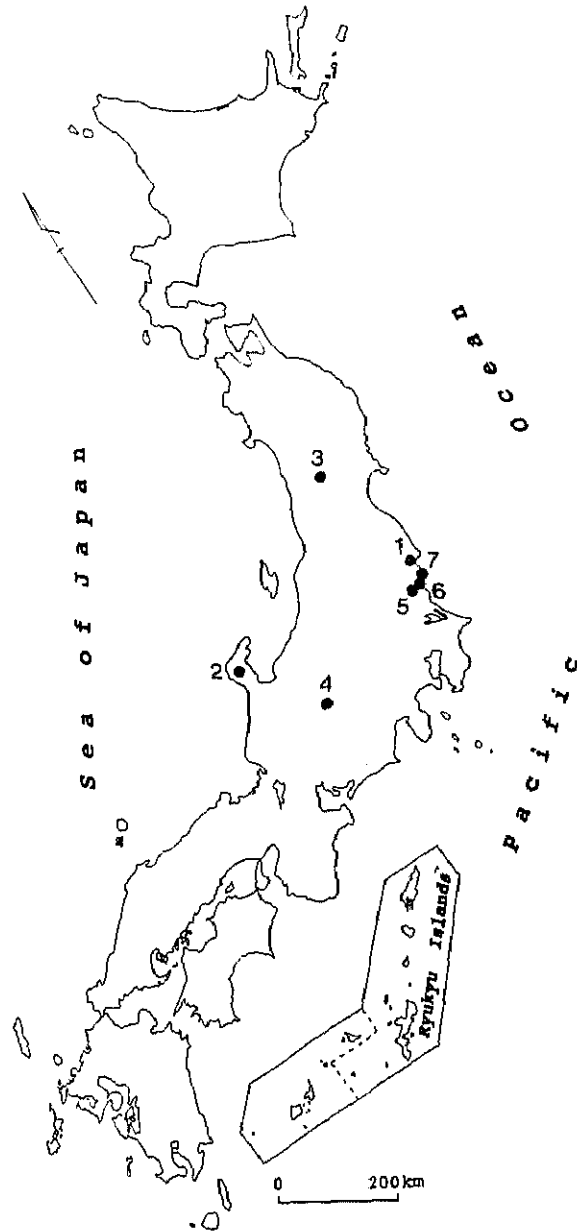


Fig. 61. Distribution of *Linthia nipponica* Yoshiwara in Japan.

Oligocene; 1. Asagai Formation (Tokunaga, 1927).
 Miocene; 2. Wajimazaki Sandstone (Matsura and Hotsuta, 1986).
 Pliocene; 3. Formation name ungiven in Yamagata Prefecture (Fujiyama, 1982), 4. Ogawa Formation (Tokunaga, 1903; Morishita, 1953*; Nisiyama, 1968), 5. Kume Formation (Ishii et al., 1974*; Present paper), 6. Muramatsu Formation (Present paper), 7. Probably Hatsuzaki Sandstone Member of the Hitachi Formation (Tokunaga, 1899, 1903, Otsuki, 1901). *Probably *Linthia tokunagai* Lambert.

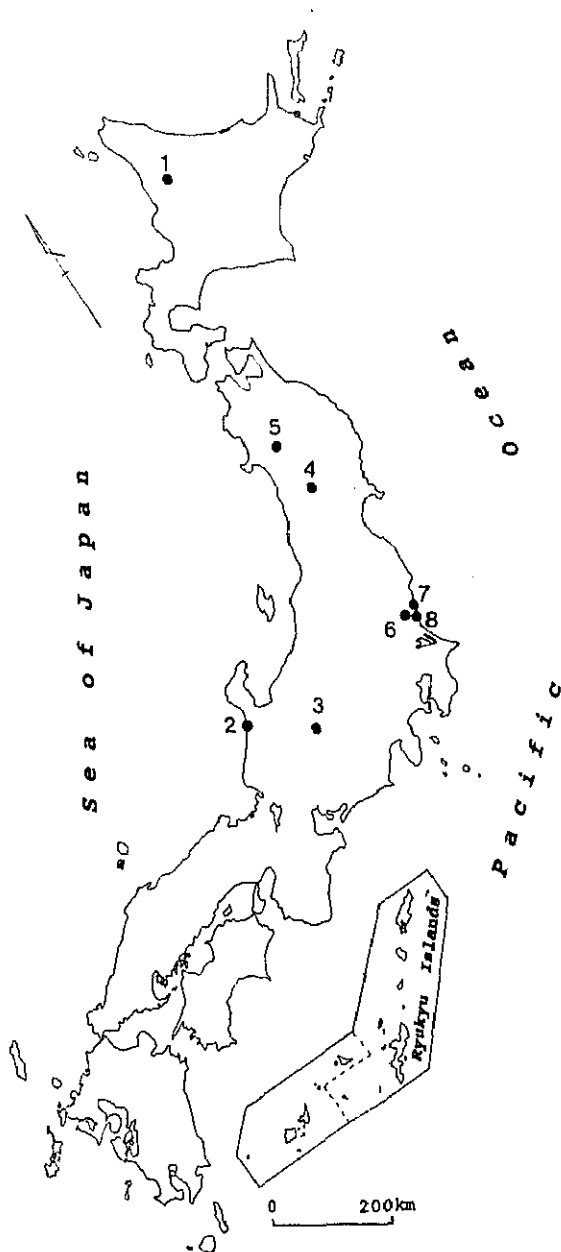


Fig. 62. Distribution of *Linthia tokunagai* Lambert in Japan.

Miocene; 1. Formation name ungiven in Hokkaido (Fujiyama, 1982), 2. Hosozaki Sandstone (Matsuura et al., 1984). Pliocene; 3. Ogawa Formation (Lamberte and Thiéry, 1925; Morishita, 1953a; Nisiyama, 1968), 4. Kazusawa Formation (Nisiyama, 1968), 5. Sasaoka Formatio (Nisiyama, 1968), 6. Kume Formation (Kikuchi and Nikaido, 1987; Present paper), 7. Hatsuzaki Sandstone Member of the Hitachi Formation (Present paper), 8. Muramatsu Formation (present paper).

20). Species of *Palaeopneustes* may flourish in the mild-temperate realm (Ogasawara, 1993, 2001) in Japanese sea, and the Transitional Zone of warm and cold currents in Pacific Ocean (Noda and Amano, 1977) and/or Subtropical area (Ogasawara, 1993, 2001) (Figs.72, 76; Table 19-20).

9) *Linthia nipponica* Yoshiwara and *Linthia tokunagai* Lambert

Linthia nipponica and *Linthia tokunagai* reported from the same Pliocene Ogawa Formation in Nagano Prefecture by Yoshiwara (1899), and Lambert and Thiéry (1925), respectively. Then, both type localities are the same Pliocene Ogawa Formation in Nagano Prefecture.

Morishita (1954, 1967, 1974) examined all species of genus *Linthia* including *Brissopsis daigoensis* n. sp. of the late Miocene to Pliocene materials (Figs.61-62). As a result, it was confirmed that the biogeographical distribution of *Linthia nipponica* and *Linthia tokunagai* have been extended to central Hokkaido. However, Tokunaga (1927) described *Linthia tokunagai* appeared in the Oligocene Asagai Formation, Ibaraki Prefecture. It can be assigned that *Linthia nipponica* and *Linthia tokunagai* are adapted forms living in muddy bottom of continental shelf in a cold current condition (Fig.

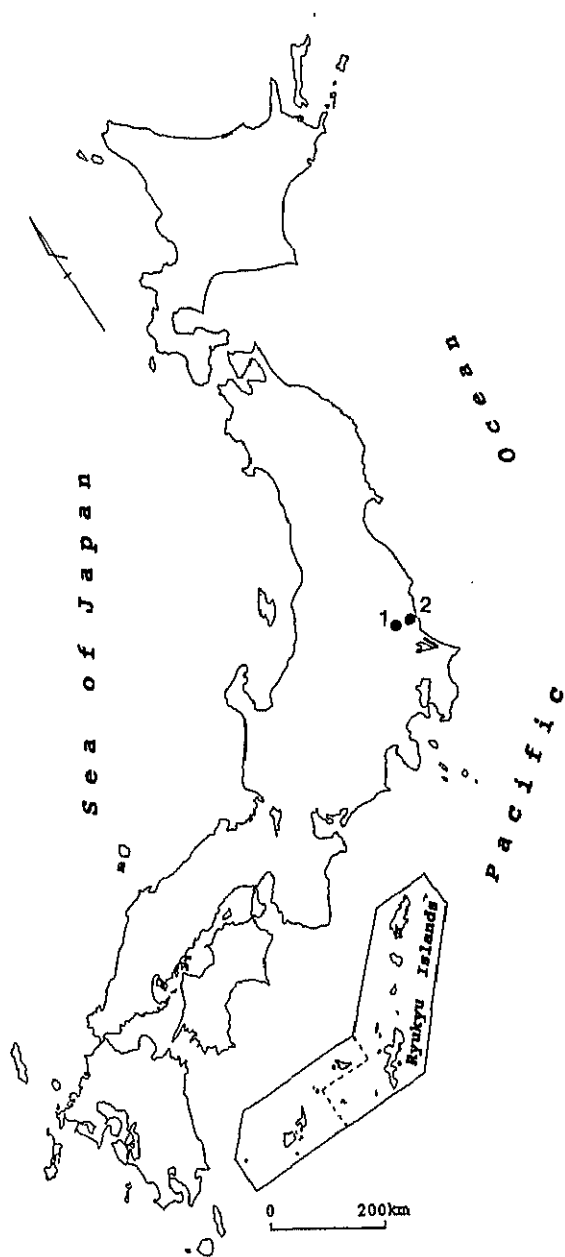


Fig. 63. Distribution of *Lutetiaster ogasawarai* n. sp. in Japan. Pliocene; 1. Kume Formation (Present paper), 2. Muramatsu Formation (Present paper).

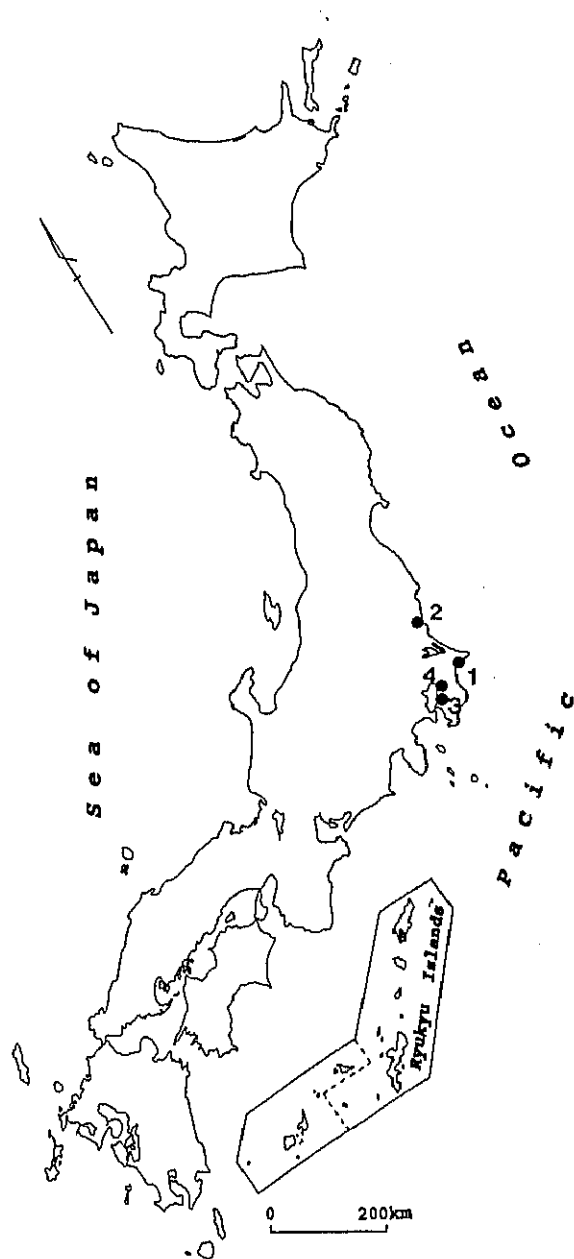


Fig. 64. Distribution of *Brisaster owstoni* Mortensen in Japan.

Pliocene; 1. Iioka Formation (Ozaki, 1951), 2. Muramatsu Formation (Present paper). Pleistocene; 3. Sanuki Formation (Nisiyama, 1968), 4. Kakinokidai Formation (Nisiyama, 1968; Fujiyama, 1982).

76, Table 20).

Species of Japanese *Linthia* are known as follows: *Linthia boreastreia* (Nisiyama, 1968), *Linthia yessoensis* (Minato, 1950), *Linthia paranipponica* (Nagao, 1928) and "*Linthia tokunagai*" from Oligocene. Although Japanese *Linthia* ranges from Oligocene through late Miocene to Pliocene, it is lacking during the early middle Miocene. The reason of this lacking may be due to the paleoclimatic condition of the Japanese Island, that is, this time was influenced the tropical to subtropical realms. Thus, it is noteworthy that *Linthia* species were adapted to a cold current condition.

10) *Lutetiaster ogasawarai* n. sp.

Three fossil species of *Lutetiaster* have been reported as; *Lutetiaster subglobosus* Imber and L. Lamberti Castex from France and *Lutetiaster maccagnoi* Checchia-Rispoli from East Africa. All species were yielded from middle Eocene (Castex, 1930; Kier and Lawson, 1978).

Occurrence of the *Lutetiaster* species from the Pliocene Kume and the Muramatsu Formations (Figs.72, 76) of Japan suggests it migrated to the east during and/or after Eocene. Distribution of the species in time and space is suggesting *Lutetiaster* species is

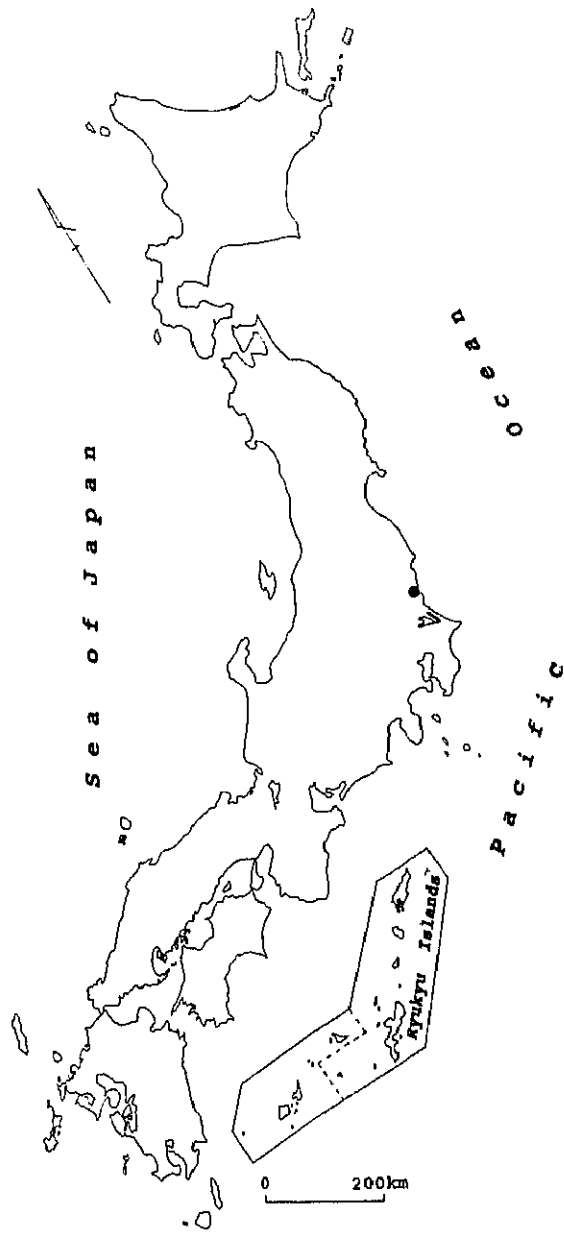


Fig. 65. Distribution of *Nikaidoster tokaiensis* n. gen. et n. sp. in Japan. Pliocene Muramatsu Formation (Present paper).

of the Tethys origin. *Lutetiaster* can be recognized from Neogene strata of the south Asia and Ryukyu Island.

11) *Brisaster owstoni* Mortensen

Living species *Brisaster owstoni* is known only from the Tokyo Bay (Mortensen, 1951a), and fossils have been recognized from the "Pliocene" Iioka Formation, Pleistocene Sanuki and the Kakinokida Formations in Chiba Prefecture by Nisiyama (1968) and Fujiyama (1982) (Fig. 64). These records suggest the species should be an endemic species in Central Japan.

Many specimens of *Brisaster owstoni* yielded from the Pliocene Muramatsu Formation in Ibaraki Prefecture (Fig.72). The northern limit of the geographical distribution of species is located in the Ibaraki Prefecture, and also northern limit of living *Brisaster owstoni* is recorded from off Hitachi (Horikoshi et al., 1983). The species flourished in a transitional zone of warm and cold waters is available to the interpretation of paleoenvironment of Pliocene of the studies area (Figs. 74, 76; Tables 19-20).

12) *Nikaidoster tokaiensis* n. gen. et n. sp.

Nikaidoster tokaiensis. n. gen. et n. sp. (Fig. 70) can be

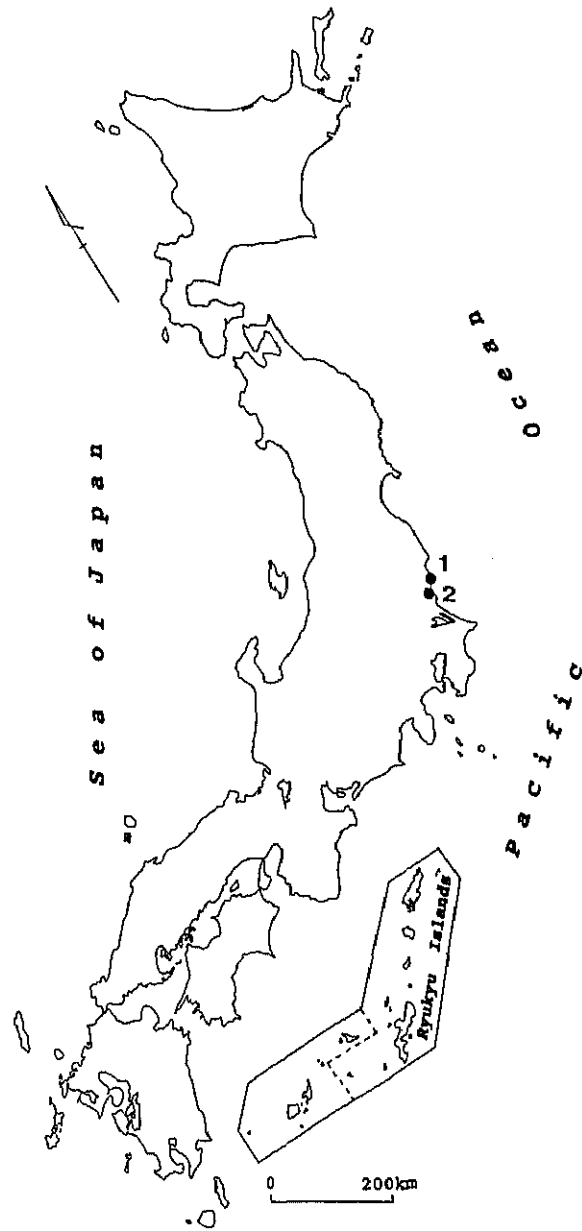


Fig. 66. Distribution of *Nodaster watanabei* n. gen. et n. sp. in Japan. Pliocene; 1. Hatsuzaki Sandstone Member of the Hitachi Formation (Present paper), 2. Muramatsu Formation (Present paper).

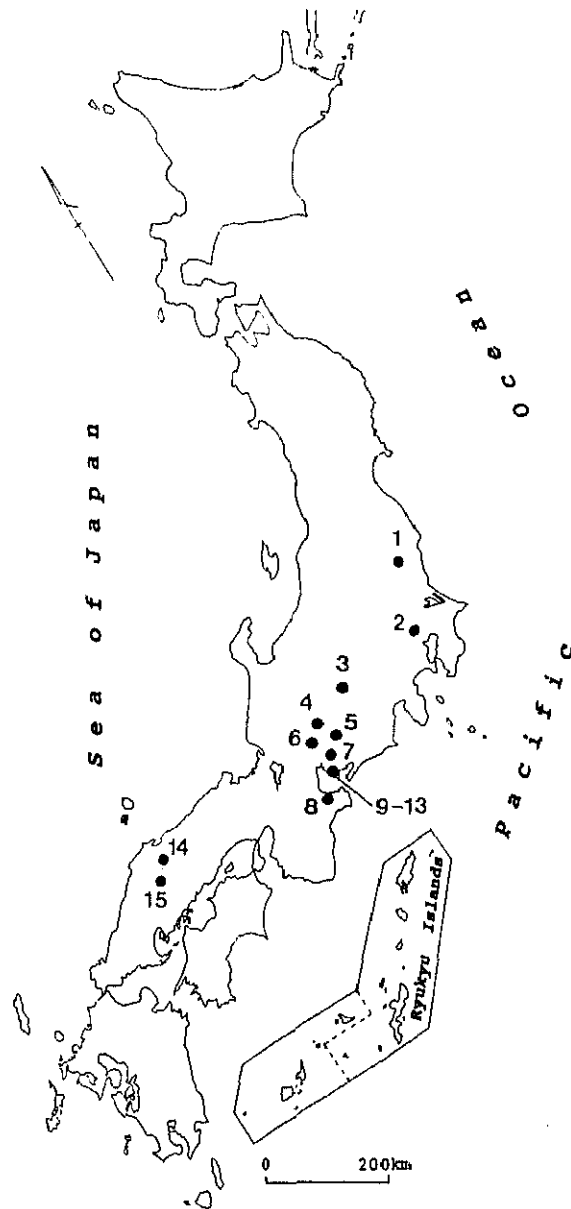


Fig. 67. Distribution of *Brissopsis daigoensis* n. sp. in Japan.

Miocene; 1. Naeshiroda Formation (present paper), 2. Tateya Formation (Present paper), 3. Arakida Formation (Morishita, 1967; *Linthia nipponica**), 4. Oidawara Formation (Morisita, 1974; *Linthia nipponica**), 5. Kadoya Formation (Morishita, 1954; *Linthia nipponica**), 6. Maki Formation (Morishita, 1954; *Linthia nipponica**), 7. Okaza Formation (Hayashi and Miura, 1973; *Shizaster* sp.*), 8. Tajiri Formation (Morishita, 1954; *Linthia nipponica**), 9. Morozaki Formatio (Morishita 1954; *Linthia nipponica**), 10-11. Morozaki Group (Shikama and Kase, 1976; Morishita and Itoigawa, 1986: *Linthia nipponica**), 12-13. Morozaki Group (Mizuno et al., 1993ab; Mizuno, 1989; *Brissopsis* sp.), 14. Tari Formation (Yamana, 1978; *Linthia tokunagai**), 15. Bihoku Group (Okamoto et al., 1990; *Brissopsis makiyamai*).

*Synonym of *Brissopsis daigoensis* n. sp.

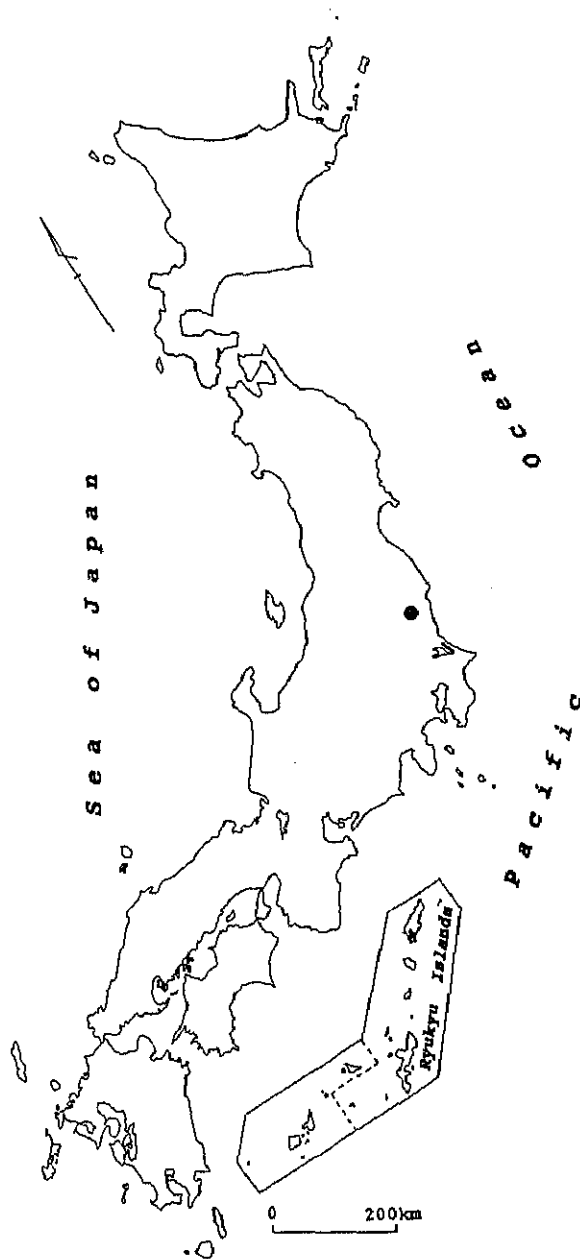


Fig. 68. Distribution of *Brissopsis kajiwarai* n. sp. in Japan. Miocene Naeshiroda Formation (Present paper).

ecologically compared with those of Schizasteridae on the basis of general feature of test and a systematic view. It is estimated that this new species may be flourished on continental slope under a transitional zone of warm and cold waters (Fig.75).

13) *Brissopatagus* sp.

Fossil record of *Brissopatagus* is known from the Eocene of France, Madagascar, North America and Cuba, ranging from Oligocene to Miocene (Kier and Lowson, 1978). It is the first record of the Pliocene species *Brissopatagus* sp. from the Pliocene Muramatsu Formation, Ibaraki Prefecture, although the Pleistocene species known from the Pleistocene Chinen Formation of Okinawa Prefecture (Kikuchi, 2000).

Living species, *Brissopatagus relicutus* Shigei is reported from water of 80 to 117 m depth in the Sagami Bay by Shigei (1975) (Figs.72, 76; Table 19).

14) *Nodaster watanabei* n. gen. et n. sp.

Nodaster watanabei n. gen. et n. sp. is not recognize any living and fossil records from a systematical point of view. The general shape quality of the new taxa suggested it belongs to family

Pericosmidae. However, some features are not examined. Species of the family are characterized by living in the environment of continental slope and under a transitional zone of warm and cold waters (Figs. 72, 76).

15) *Brissopsis daigoensis* n. sp.

Fossil record of the species has been known from the Paleo-Setouchi area in early middle Miocene. Some of the species reported as *Linthia nipponica* Yoshiwara or *Linthia tokunagai* Lambert by Morishita (1954, 1967, 1974), Shikama and Kase (1976) and others are synonymous with *Brissopsis daigoensis* n. sp. (Figs. 67, 69).

Almost specimens of *Brissopsis daigoensis* n. sp. are yielded from dark gray siltstone of the early Middle Miocene in the area between Chugoku and Kanto districts (Fig. 67). The northern limit of distribution of species is assumed around the area of Ibaraki Prefecture, where in the Naeshiroda Formation developed.

A fossil record of *Brissopsis daigoensis* suggests it is of tropical origin, and extends the inhabiting area to the north corresponding to northern extensions of the tropical front in the early Middle Miocene (Ogasawara and Nagasawa, 1992; Ogasawara, 1994).

Therefore, *Brissopsis daigoensis* n. sp. can be assigned as

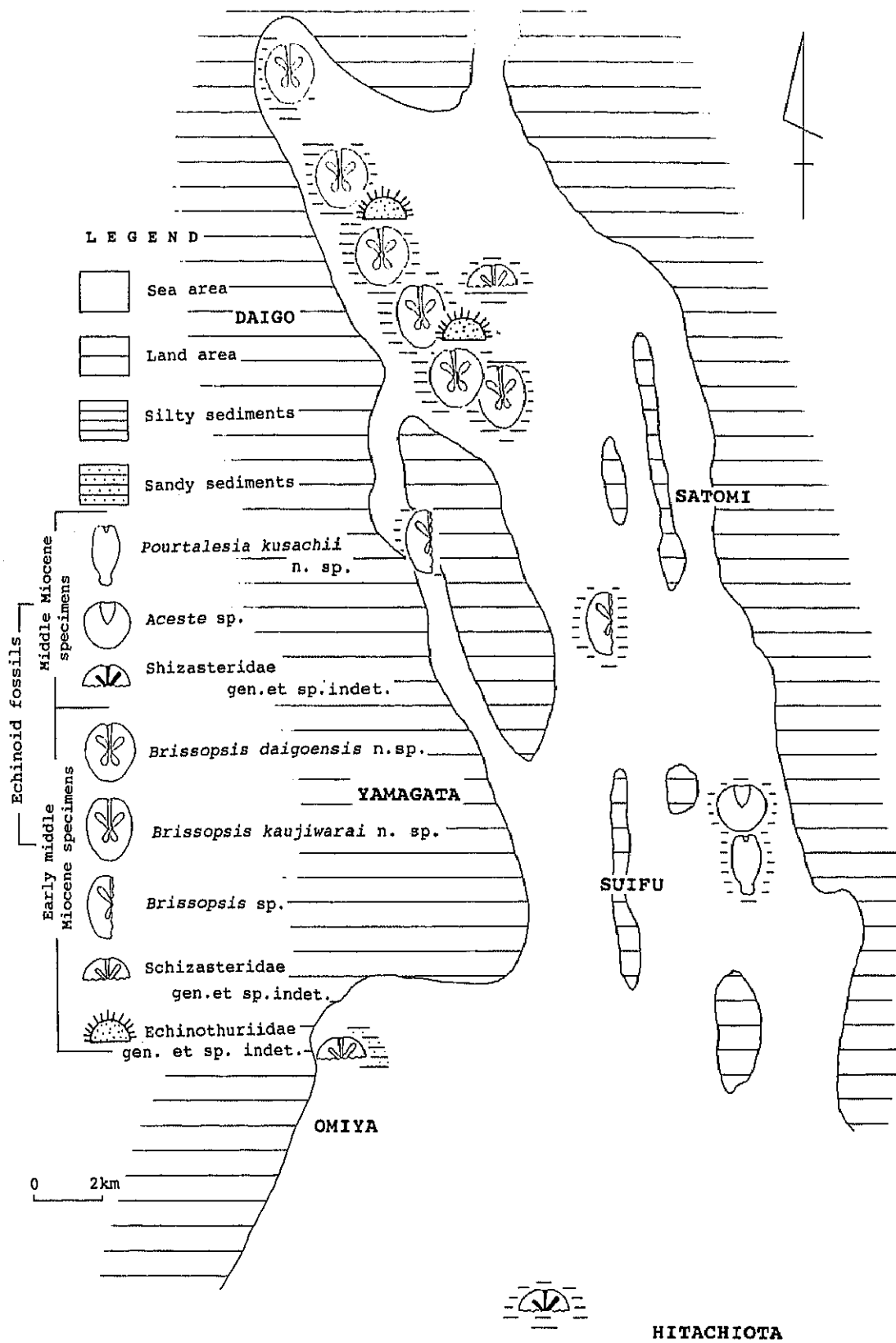


Fig. 69. Paleogeography of the early middle to middle Miocene strata in the northern part of Ibaraki Prefecture indicating paleo-habitats of echinoid fossils.

the index fossil of the early Middle Miocene.

16) *Brissopsis kajiiwarai* n. sp.

Brissopsis kajiiwarai n. sp. usually yields with *Brissopsis daigoensis* (Figs. 68-69). Difference between the two species is inflatness of test, that is, *Brissopsis kajiiwarai* has slender form compared with that of the *Brissopsis daigoensis*. It is defined yet, however *Brissopsis kajiiwarai* and *Brissopsis daigoensis* may be a variety form of sexual dimorphism.

4. Assemblage and paleoenvironment of echinoid fossils from the northern part of Ibaraki Prefecture

The distribution of the echinoid fossils of Miocene and Pliocene yielded from the present study are shown in Figs. 69 and 72. Echinoid fossil assemblages of each stratum are described here in aim to reconstruct the paleoenvironment of the assemblages.

1) Early middle Miocene Tamagawa Formation

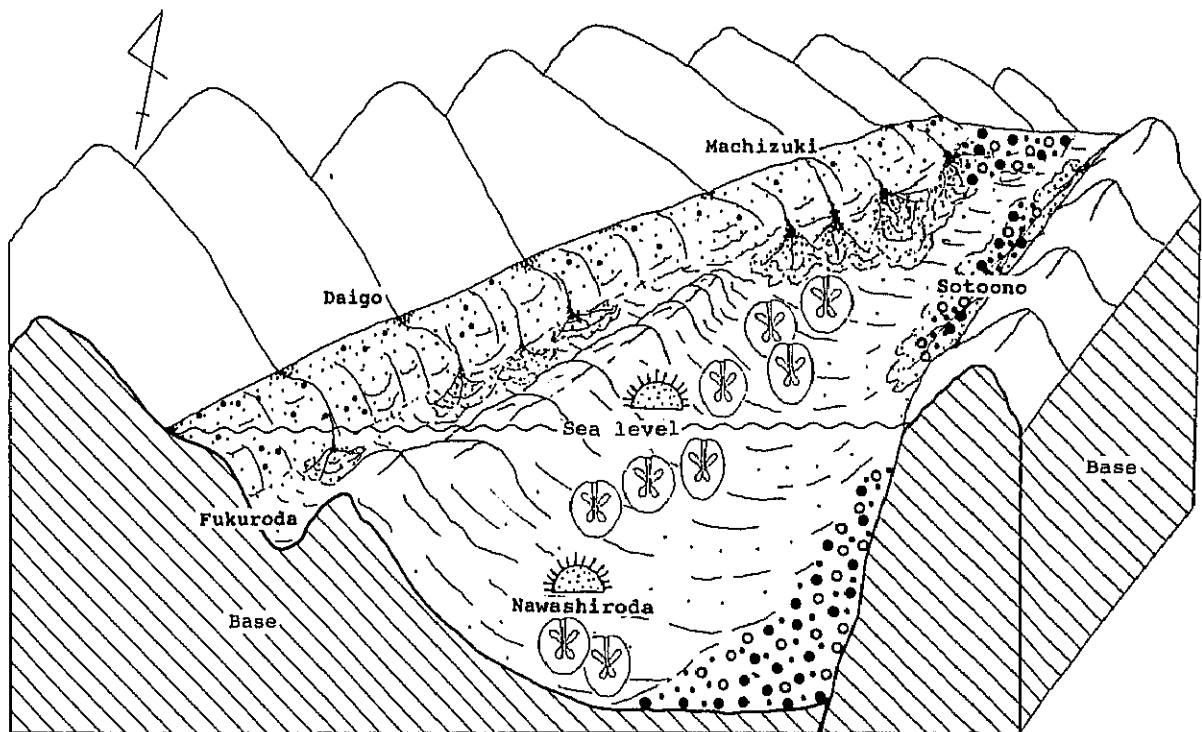
Occurred echinoid fossil from this formation is only the imperfect specimen of Schizasteridae gen. et sp. indet. (Fig. 69).

This species might be the muddy to sandy bottom dweller of shallow-sea under warm waters, associated with *Acila* sp. and *Crassostrea gravitesta* of molluscs. Indeed, a warm-water condition is also suggested by the Arcid-Potamid Fauna molluscan, and also large foraminifera of *Operculina complanata japonica* and *Miogypsina (Miogypsina) kotoi kotoi* that are reported from the Tamagawa Formation (Noda et al., 1994).

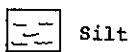
2) Early middle Miocene Daienji Siltstone Member of the Asakawa Formation

Only *Brissopsis* sp. was recognized from this member (Fig. 69). Although discussion of occurrence is not given because of the single and imperfect specimen, it can be assigned that this *Brissopsis* sp. lived deep-water muddy bottom of continental slope on the basis of associated fossils such as crustacean of *Munidia* sp., and mollusca of *Portlandia watasei* (Kanehara).

This *Brissopsis* sp. can ecologically be compared with *Brissopsis daigoensis* n. sp. or *Brissopsis kajiiwarai* n. sp. occurred the upper Naeshiroda Formation. Therefore, sedimentary environment of the Daienji Siltstone Member of the Asakawa Formation is comparable to that of the Naeshiroda Formation.



LEGEND



Silt



Sand



Gravel



Brissopsis kaujiwarai n. sp.



Brissopsis daigoensis n. sp.



Echinothuriidae gen. et sp. indet.

Fig. 70. Paleoenvironment and depositional condition of the early middle Miocene Naeshiroda Formation indicating inhabits of echinoid fossils.

Table 15. Bathymetrical distribution of recent echinoid.

Recent species	Bathymetrical distribution						
	0	500	1000	1500	2000	2500	3000 depth(m)
Family Echinothuriidae							
<i>Phormosoma bursarium</i> A.Agassiz		—	—	—	—	—	
Family Brissidae							
<i>Brissopsis luzonica</i> (Gray)		—					
<i>Brissopsis oldhami</i> Alcock			—	—	—		
<i>Brissopsis bergalensis</i> Mortensen		—	—	—	—	—	

Table 16. Marine condition suggesting by echinoid fossils
of the early middle Miocene in the northern part of
Ibaraki Prefecture.

Warm-water type	Cold-water type	Unclear
Echinothuriidae gen.et sp.indet. <i>Brissopsis daigoensis</i> n.sp. <i>Brissopsis kajiwarae</i> n.sp.		

4) Early middle Miocene Naeshiroda Formation

Three species, Echinothuriidae gen. et sp. indet., *Brissopsis daigoensis* n. sp. and *Brissopsis kajiiwarai* n. sp. are recognized in this formation (Fig. 70). Based on analogy of living species (Table 15), these echinoids are judged the muddy bottom dwellers of continental slope (Figs. 70, 75). This habitat is supported from the co-occurred such fossils as; molluscs of *Phanerolepida expansilabrum*, *Acilana tokunagai*, *Portlandia kakimii* and *Propeamussium tateiwai*; holothurians of *Yipsilothuria bitentaculata* (Kikuchi and Nikaido, 1996); and trace fossil of *Zoophycos* isp. and *Condrites* isp. As noted formerly, larger foraminifera, *Operculina complanata japonica* and *Miogypsina* (*Miogypsina*) *kotoi kotoi* yielded from the Naeshiroda Formation, which indicates a warm-water condition.

5) Early middle Miocene Uchiono Formation

Fossil record has not been recorded from this formation (Fig. 63) except Schizasteriidae gen. et sp. indet. of echinoid fossil which is first occurred by the present study. However, it is judged that depositional environment of the Uchiono Formation is continental slope as suggesting abundant occurrence of sponge

fossil, *Makiyama chitanii* from the formation as like as that of the Naeshiroda Formation. Although rock facies are different to each other, the Naeshiroda, Konamase and the Uchiono Formations are considered to a rather deep-water condition based on fossil records of these strata.

6) Early middle Miocene Oginokubo Siltstone Member of the Nishizome Formation

The echinoids fossil yielded from this member is *Brissopsis* sp. The Oginokubo Siltstone Member of the Nishizome Formation is judged the interfingering one of the Nantaisan Formation that is composed dacitic phyaloclastite. Molluscan fossil from the member are *Acilana tokunagai*, *Portlandia kakimii* and *Propeamssium tateiwai*, that are represented a deep-water condition of muddy bottom.

Therefore, this *Brissopsis* sp.-bearing strata of the Oginokubo Siltstone Member is judged to be deposited at continental slope, as like as the Naeshiroda Formation (Fig. 75).

7) Middle Miocene Tatsukuroiso Mudstone Member of the Higashi-kanasayama Formation

Peculiar deep-sea type echinoid, *Pourtalesia kausachii* n.

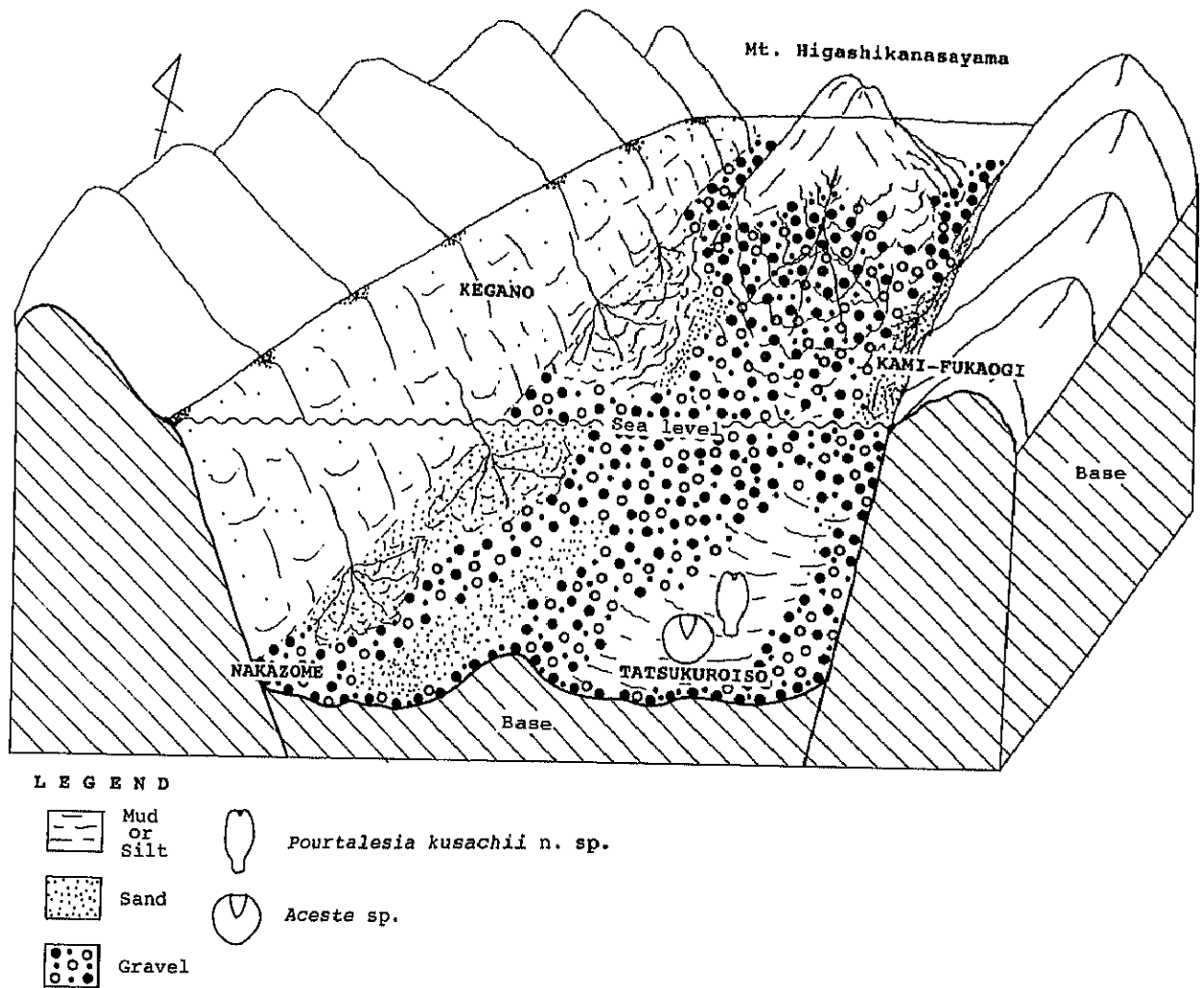


Fig. 71. Paleoenvironment and depositional condition of the middle Miocene Tatsukuroiso Mudstone Member of the Higashikanasayama Formation indicating inhabits of echinoid fossils.

Table 17. Bathymetrical distribution of recent echinoid.



Recent species	Bathymetrical distribution						
	0	500	1000	1500	2000	2500	3000 Depth(m)
Family Pourtalesiidae <i>Pourtalesia laguncula</i> A.Agassiz							
Family Aeropsidae <i>Aceste ovata</i> A.Agassiz and H.L.Clark							

Table 18. Marine condition suggesting by echinoid fossils
of the middle Miocene in the northern part of Ibaraki
Prefecture.

Warm-water type	Cold-water type	Unclear
<i>Pourtalesia kusachii</i> n.sp. Aceste sp.		

sp. and *Aceste* sp. were recognized from this member (Figs.69, 71). *Pourtalesia laguncula* of recent species is ecologically compared to the fossil *Pourtalesia kusachii* n. sp. which is known from the Japanese Sagami Bay to the Indonesia, New Guinea and New Zealand seas in waters of 200 to 1,500 m depth (Nisiyama, 1968; Shigei, 1974, 1986) (Table 17).

Fossil *Aceste* sp. is the first occurrence including family and genus of *Aeropsiidae*. Recent species *Aceste ovata* is reported from water of 400 to 4, 000 m depth of the Japanese Sagami Bay to the Indian Sea and Hawaiian Island seas (Mortensen, 1950a; Nishiyama, 1968; Shigei, 1974) (Table 17).

The inhabiting environment of these species is to be muddy bottom under influenced a warm-water condition of continental slope and/or deeper place.

In addition, *Pourtalesia kusachii* and *Aceste* sp. yielded from the Tatsukuroiso Mudstone Member of the Higashikanasayama Formation are occupied the middle portion of the subsided are along the Tanakura Tectonic Line (Fig. 71). The Tatsukuroiso Mudstone Member shows peculiar depositional facies, which is composed of thick conglomerate of the Higashikanasayama Formation.

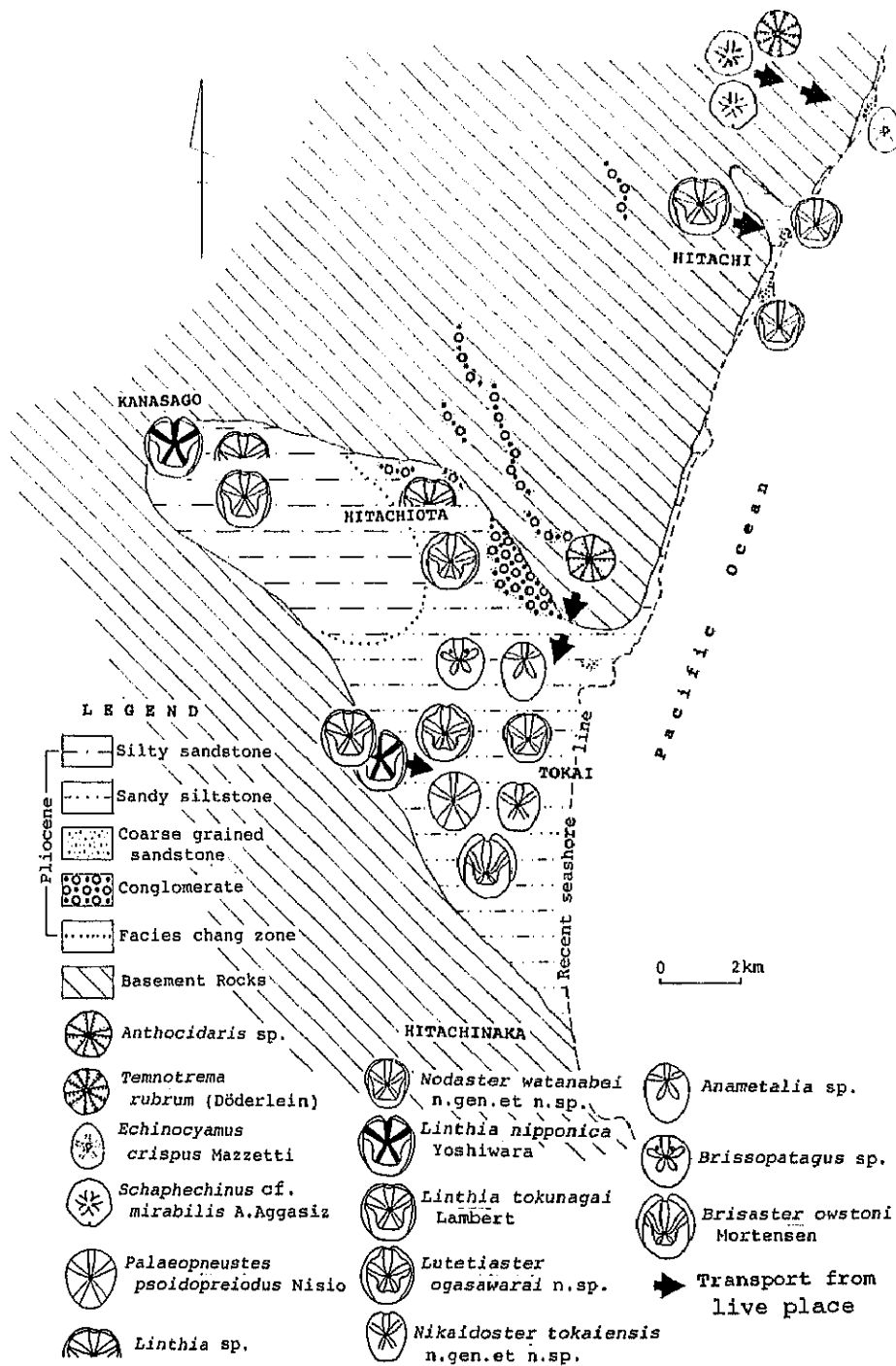
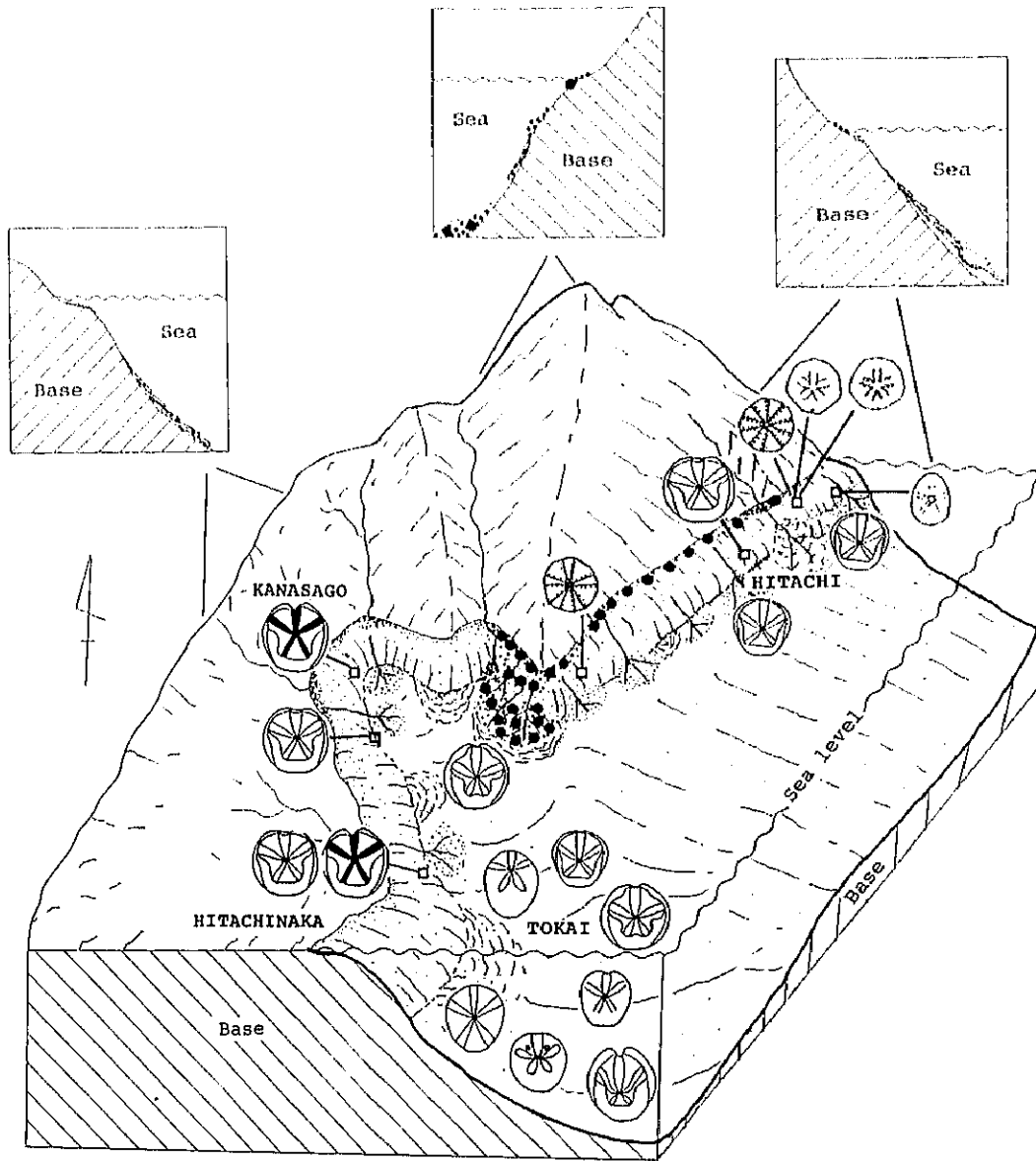


Fig. 72. Paleogeography of the Pliocene strata in the northern part of Ibaraki Prefecture indicating paleo-habitats of echinoid fossils.



LEGEND





 Silt	 <i>Palaeopneustes psoidopreiodus</i> Nisio	 <i>Anametalia</i> sp.
 Sand	 <i>Nodaster watanabei</i> n.gen.et n.sp.	 <i>Brissopatagus</i> sp.
 Gravel	 <i>Linthia nipponica</i> Yoshiwara	 <i>Brisaster owstoni</i> Mortensen
 <i>Anthocidaris</i> sp.	 <i>Linthia tokunagai</i> Lambert	
 <i>Temnotrema rubrum</i> (Döderlein)	 <i>Lutetiaster ogasawarai</i> n.sp.	
 <i>Echinocyamus crispus</i> Mazzetti	 <i>Nikaioster tokaiensis</i> n.gen.et n.sp.	
 <i>Schaphechinus</i> cf. <i>mirabilis</i> A.Aggasiz		

Fig. 73. Paleoenvironment and depositional condition of the Pliocene Kume Formation, Muramatsu Formation and the Hatsuzaki Sandstone Member of the Hitachi Formation as showing inhabitants of echinoid fossils.

8) Middle Miocene Genjigawa Formation

Imperfect specimen of Shizasteriidae gen. et sp. indet. is only recognized from this formation (Fig. 67). Although the details of mode of occurrence is not clear, some deep-sea molluscs such as *Solemya tokunagai*, *Lucinoma* sp. and *Periproma* sp. were co-occurred. Therefore, this echinoids fossil is regarded a deep-sea one rather than continental slope.

9) Pliocene Kume Formation

Echinoid assemblage of the Kume Formation is composed of *Linthia nipponica*, *Linthia tokunagai* and *Lutetiaster ogasawarai* n. sp. (Figs. 72-73). This fauna is ecologically characterized by both of shallow and deep species. Therefore it is considered to flourish on continental self-edge (Figs. 61-62). It is judged shallow species of *Linthia nipponica* and *Linthia tokunagai* might be transported into deep-sea environment. Molluscan fossils from the Kume Formation (Takahashi, 1986; Noda et al., 1993) also suggested that depositional environment of outer-neritic or shelf edge.

Lutetiaster ogasawarai co-occurred with *Portlandia lischkei* and *Ennucula nipponica* of molluscan fossil indicates a rather deep-sea condition. Subsequently, it is regarded *Lutetiaster ogasawarai*

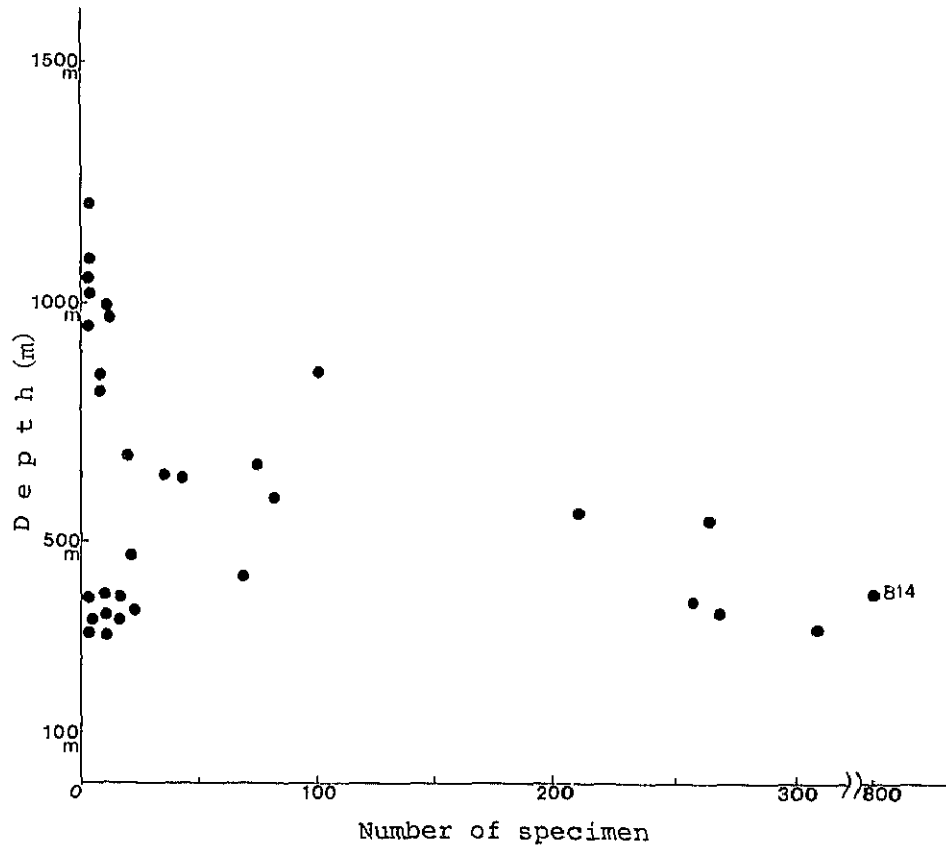


Fig. 74. Bathymetrical distribution of living *Brisaster owstoni* Mortensen in of the Sagami Bay and the Suruga Bay in Japan (data by Horikoshi et al., 1983).

Table 19. Bathymetrical distribution of recent echinoid.

Recent species	Bathymetrical distribution			
	0	500	1000	1500 Depth (m)
Family Echinometeridae <i>Anthocidaris crassispina</i> A.Agassiz	—			
Family Temnopleuridae <i>Temnotrema rubrum</i> (Döderlein) <i>Temnotrema sculptum</i> A.Agassiz	—			
Family Fibulariidae <i>Echinocyamus crispus</i> Mazzetti	—			
Family Scutellidae <i>Scaphechinus mirabilis</i> A.Agassiz <i>Scaphechinus brevis</i> (Ikeda)	—			
Family Palaeopneustidae <i>Linopneustes murrayi</i> (A.Agassiz) <i>Linopneustes fragilis</i> (Meijere)	— (1,695m)			
Family Shizasteridae <i>Brisaster owstoni</i> Mortensen	—			
Family Brissidae <i>Brissopatagus relictus</i> Shigei <i>Anamatalia sternaloids</i> (Bolau) <i>Anamatalia regularis</i> (H.L.Clark)	—			

Table 20. Marine condition suggesting by echinoid fossils
of the Pliocene in the northern part of Ibaraki
Prefecture.

Warm-water type	Cold-water type	Unclear
<i>Anthocidaris</i> sp. <i>Echinocyamus crispus</i> Mazzetti <i>Temnotrema rubrum</i> (Döderlein) <i>Schapechinus</i> cf. <i>mirabilis</i> A. Agassiz <i>Palaeopneustes psoidoperidus</i> Nisho <i>Brisaster owstoni</i> Mortensen <i>Brissopatagus</i> sp. <i>Anametalia</i> sp.	<i>Linthia nipponica</i> Yoshiwara <i>Linthia tokunagai</i> Lambert	<i>Lutetiaster ogasawarai</i> n.sp. <i>Nikaidoster tokaiensis</i> n.gen.et n.sp. <i>Nodaster watanabei</i> n.gen.et n.sp.

represents continental slope condition. Shallow species *Linthia nipponica* and *Linthia tokunagai* might be transported into the habitat of *Lutetiaster ogasawarai* by turbidity current.

10) Pliocene Muramatsu Formation

This formation occurs many echinoid species such as *Anthocidaris* sp., *Palaeopneustes psoidoperiodus*, *Linthia nipponica*, *Linthia tokunagai*, *Lutetiaster ogasawarai* n. sp., *Brisaster owstoni*, *Brissopatagus* sp., *Nikaidoster tokaiensis* n. gen. et n. sp., *Nodaster watanabei* n. gen. et n. sp. and *Anametalia* sp. (Figs. 72-73). Based on ecological data of the living counterpart of the species (Tables 19-20), these echinoid can be divided into following three categories; *Anthocidaris* sp. is inhabited shallow sea; *Linthia nipponica*, *Linthia tokunagai*, *Linthia* sp. and *Brissopatagus* sp. are inhabited shallow to offshore; and other remains such as *Palaeopneustes psoidoperiodus*, *Lutetiaster ogasawarai*, *Brisaster Owstoni*, *Nikaidoster tokaiensis* and *Anametalia* sp. are inhabited continental slope or more deep place.

Therefore, echinoid assemblage of the Muramatsu Formation is composed of some kinds of species ranges from shallow-sea and continental slope or deeper place (Fig. 76). These shallow elements

might be transported into deep sea by turbidity current and/or sub-marine gravity flow. Depositional environment of the Muramatsu and Kume Formations are reconstructed, as showing habitats of each echinoid species in Fig. 76.

11) Pliocene Hatsuzaki Sandstone Member of the Hitachi Formation

The assemblage of the member is composed of *Temnotrema rubrum* (Döderlein), *Echinocyamus crispus* Mazzetti, *Scaphechinus* cf. *mirabilis* A. Agassiz, *Linthia tokunagai* Lambert and *Nodaster watanabei* n. gen. et n. sp. (Figs. 72-73).

Owing to ecology of the living counterparts of species (Table 16), these echinoid species can be divided into the followings; *Temnotrema rubrum* and *Scaphechinus* cf. *mirabilis* A. Agassiz are inhabited shallow-sea; *Echinocyamus crispus* and *Linthia tokunagai* are inhabited shallow to offshore one; and *Nodaster watanabei* is inhabited in continental slope of deeper place. Therefore, assemblage of Hatsuzaki Sandstone Member of the Hitachi Formation regarded to a mixture one in origin of shallow-sea and continental slope or deeper place. This mixture assemblage should be a result of transportation by turbidity current and/or debris flow. Allochthonous fossil assemblages are also recognized in molluscan

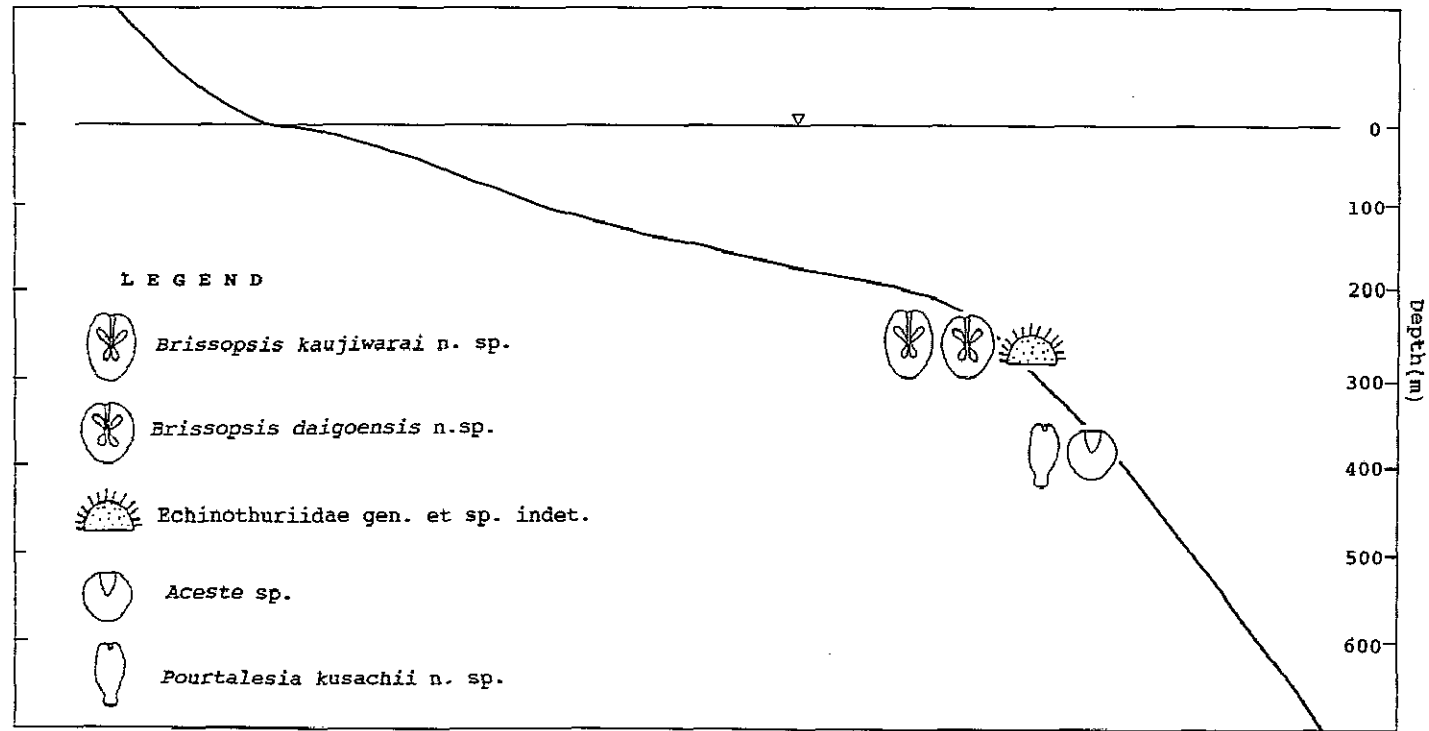


Fig. 75. Bathymetrical distribution of echinoid fossils from the early middle to middle Miocene in the northern part of Ibaraki Prefecture.

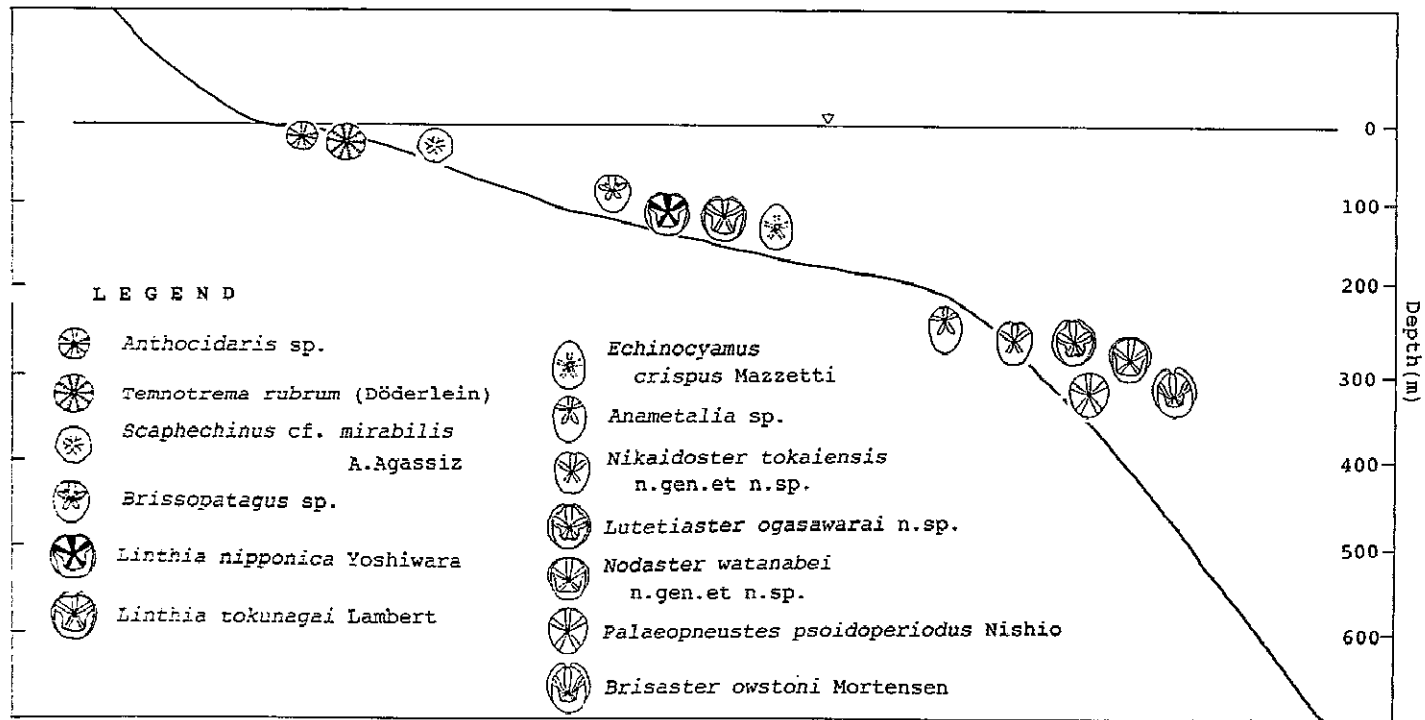


Fig. 76. Bathymetrical distribution of echinoid fossils from the Pliocene in the northern part of Ibaraki Prefecture.

fossils (Noda et al., 1995). However, the Hatsuzaki Sandstone Member is regarded to be a shallow-sea compared with that of the Muramatsu Formation on the basis of feature of the accumulating sediments.

As the result, paleoenvironment of the Pliocene echinoid recognized in all strata can be shown in schematic figures (Figs. 72-73, 76).

As shown in the figure, *Anthocidaris* sp., *Temnotrema rubrum* and *Scaphechinus* cf. *mirabilis* regarded shallow-sea element, *Echinocyamus crispus*, *Linthia nipponica*, *Linthia tokunagai*, *Linthia* sp. and *Brissopatagus* sp. regarded shallow-sea to offshore one, and *Palaeopneustes psoidoperiodus*, *Lutetiaster ogasawarai*, *Brisaster owstoni*, *Nikaidoster tokaiensis* and *Anametalia* sp. are inhabited waters in deep-sea condition.

Boring shell-bearing conglomerate that originally formed in surf zone or intertidal rocky shore abundantly occurred in the deep-sea sediments of the Kume Formation (Kikuchi et al., 1991). It is also reported that shallow-water mollusca fossil of *Anadara* (*Anadara*) cf. *amicula elongata* occurred from Hatsuzaki Sandstone Member which is regarded as accumulated in deep-sea condition (Noda et al., 1995).

The Momiya Conglomerate Member of the Kume Formation, that

is now named this study, is regarded as submarine slope deposits or sub-marine deltaic one as well developed only in Hitachiota to Hitachi area. It is noteworthy that the boring shell-bearing conglomerates are obviously origin of surf zone or intertidal rocky zone.

Although nobody discussed on the tectonic movement of the Abukuma Mountains at Hitachiota to Hitachi area during the Pliocene except for Tokunaga (1927), this study first offer the significant evidences of movement, from paleontological and/or stratigraphical point of views. Submarine canyon that mainly filled by Momiya Conglomerate Member may be caused by abrupt subsidence, which may took place corresponding some movement of the Tanakura Tectonic Line.

5. Faunal change of echinoid fossils from the northern part of Ibaraki Prefecture

As a result of systematic studies of echinoid fossils in the study area, the echinoid faunal change in time-space discuss below.

1) Faunal change of the early middle Miocene

Brissopsis daigoensis n. sp. and *Brissopsis kajiiwarai* n. sp.

Table 21. Stratigraphical ranges of echinoids occurred from the northern part of Ibaraki Prefecture.

Species	Age	Cretaceous		Palaeocene	Eocene	Oligocene	Miocene	Pliocene	Pleistocene	Recent
		Lower	Upper							
Echinothuriidae (Family)				Europe			Japan			
<i>Anthocidaris</i>							Saipan Island	Japan*		
<i>Temnotrema</i>							Java Island			
<i>T. rubrum</i>								Japan		
<i>Echinocyamus</i>				India						
<i>E. crispus</i>								Japan*		
<i>Scaphechinus</i>							Japan			
<i>Pourtalesia</i>							Japan*			
<i>P. kusachii</i>							Japan*			
<i>Palaeopneustes</i>						Central America				
<i>P. psoidoperiodus</i>							Japan			
<i>Aceste</i>							Japan*			
<i>Linthia</i>				Central America						
<i>L. nipponica</i>						Japan? . . .		Japan		
<i>L. tokunagai</i>							Japan			
<i>Lutetiaster</i>					Europe					
<i>L. ogasawarai</i>								Japan*		
<i>Brisaster</i>						North America				
<i>B. owstoni</i>								Japan*		
<i>Nikaidoster</i>								Japan*		
<i>N. tokaiensis</i>								Japan*		
Pericosmidae (Family)					East Africa					
<i>Nodasater</i>								Japan*		
<i>N. watanabei</i>								Japan*		
<i>Brissopsis</i>					North America					
<i>B. kajiwari</i>								Japan*		
<i>B. daigoensis</i>								Japan*		
<i>Brissopatagus</i>					North America			Japan*		
<i>Anametalia</i>								Japan*		

(Japan*; first record by the present study)

were first appeared in this area under the tropical to subtropical marine climate, due to expands of the tropical front to the north in early middle Miocene (Ogasawara and Nagasawa, 1992; Ogasawara, 1993). This assemblage, some time forms colony, may be inhabited deep-sea condition rather than continental slope. This fauna is extinct from this Daigo area in middle Miocene, as it may be caused by thermal deterioration of the marine climate.

2) Faunal change of the middle Miocene

In the middle Miocene, *Pourtalesia kusachii* n. sp. and *Aceste* sp. both of typical deep-sea type and of form colony echinoids migrated from the south into the studied area where deep sedimentary basin first formed tectonically related to some movement of the Tanakura Tectonic Line. During the middle Miocene, *Pourtalesia laguncula* and *Aceste ovata* were also flourished in the sea off the Japanese Island. These living species around Japan may appear after the Pliocene because there are no fossil records of these species in the Japanese Miocene and Pliocene strata.

3) Faunal change of the Pliocene

The drastic change of echinoid fauna occurs in Pliocene.

Linthia nipponica and *Linthia tokunagai* represent a cold-water type migrated from the northern area, while such warm-water type also migrated from the southern area as *Anthocidaris* sp., *Temnotrema rubrum*, *Echinocyamus crispus*, *Scaphechinus* cf. *mirabilis*, *Palaeopneustes psoidoperiodus* and *Anametalia* sp. Among the echinoid species occurred from the studies area, such species are abundantly occurred as *Lutetiaster ogasawarai*, *Brisaster owstoni*, *Brissopatagus* sp., *Nikaidoster tokaiensis* and *Nodaster watanabei*. Occurrence of these two different type species from the area, suggests there was occupied a transitional zone between the warm-water and cold-water biogeographic provinces.

In the late Pliocene to early Pleistocene, following six species disappeared from the area such as *Linthia nipponica*, *Linthia tokunagai*, *Palaeopneustes psoidoperiodus*, *Lutetiaster ogasawarai*, *Nikaidoster tokaiensis* and *Nodaster watanabei*. Then after, echinoid fauna changes to *Anthocidaris* sp., *Temnotrema rubrum*, *Echinocyamus crispus*, *Scaphechinus* cf. *mirabilis*, *Brisaster owstoni*, *Brissopatagus* sp. and *Anametalia* sp. all are living species in the area of the Pacific sea of the Japanese Islands. In other words, it suggested that the of echinoid species now inhabiting the sea area of the Japanese Pacific side are first appeared in late Pliocene to

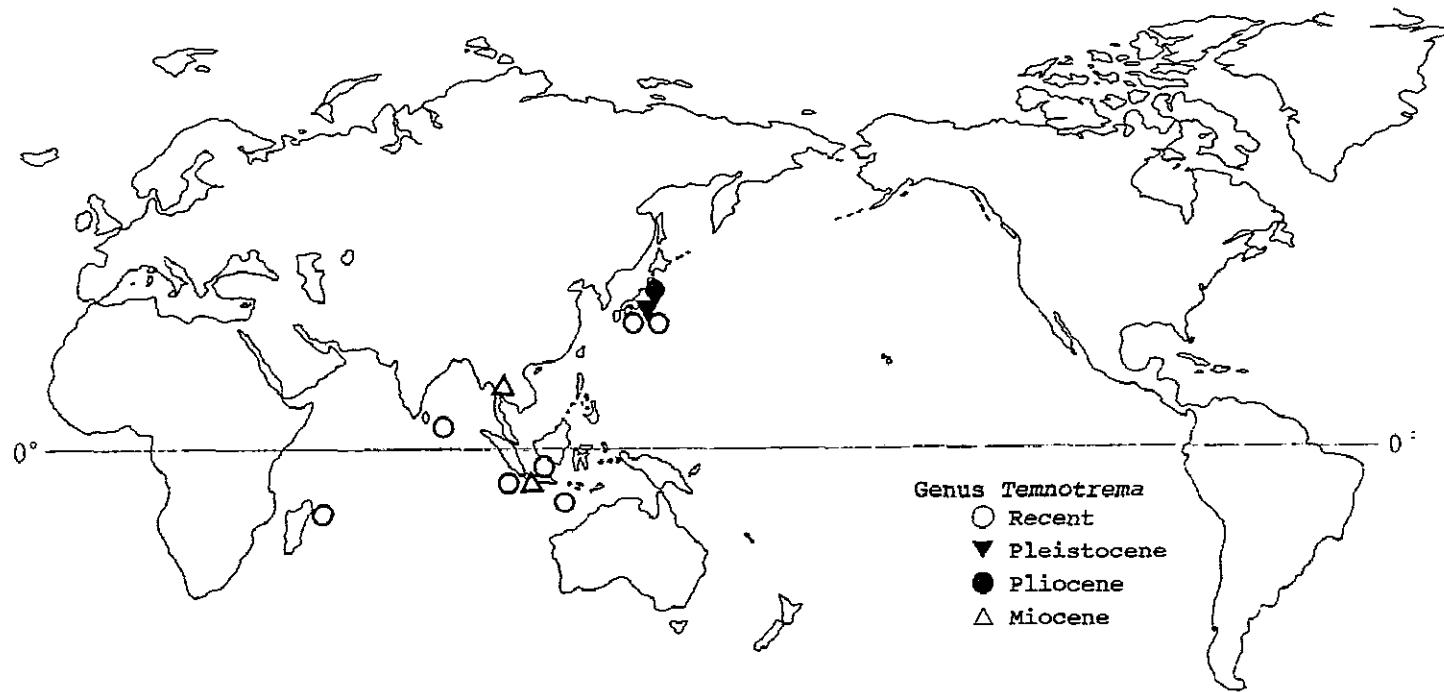


Fig. 77. Geological and geographical distribution of *Temnotrema* species.

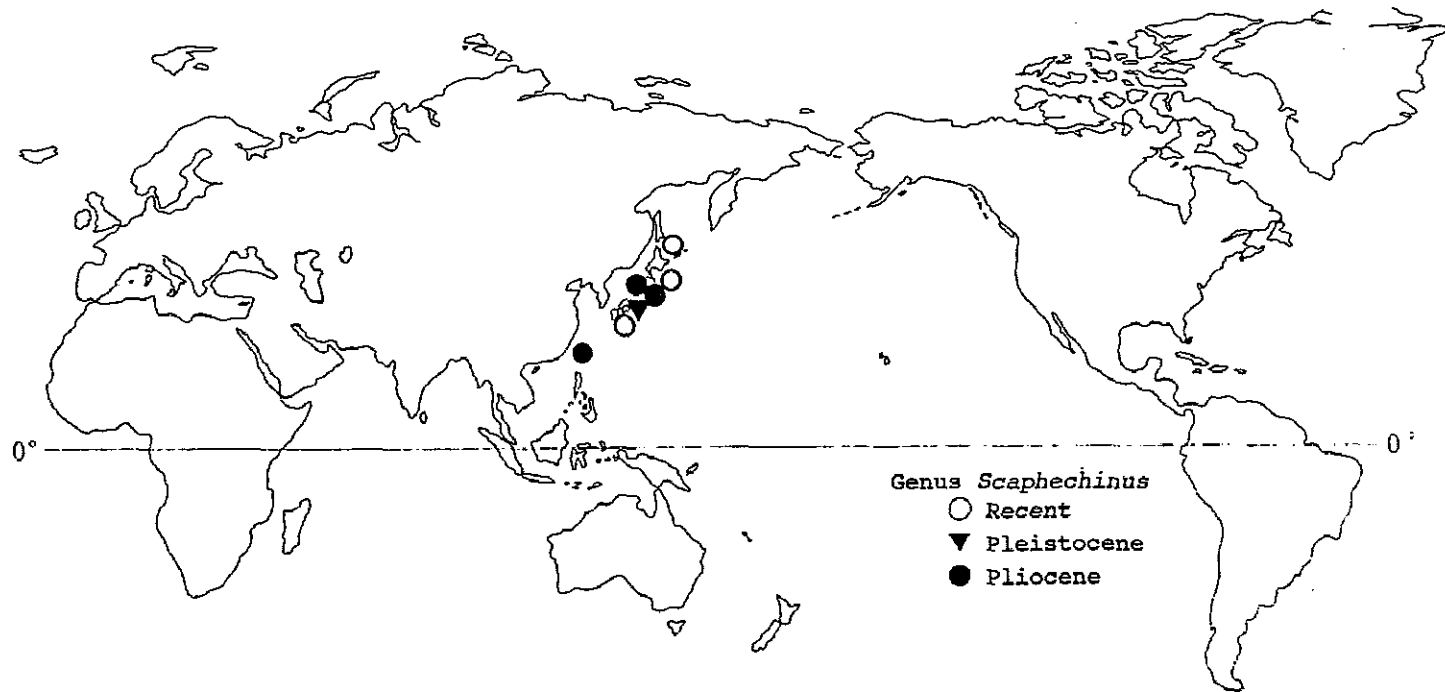


Fig. 78. Geological and geographical distribution of *Scaphechinus* species.

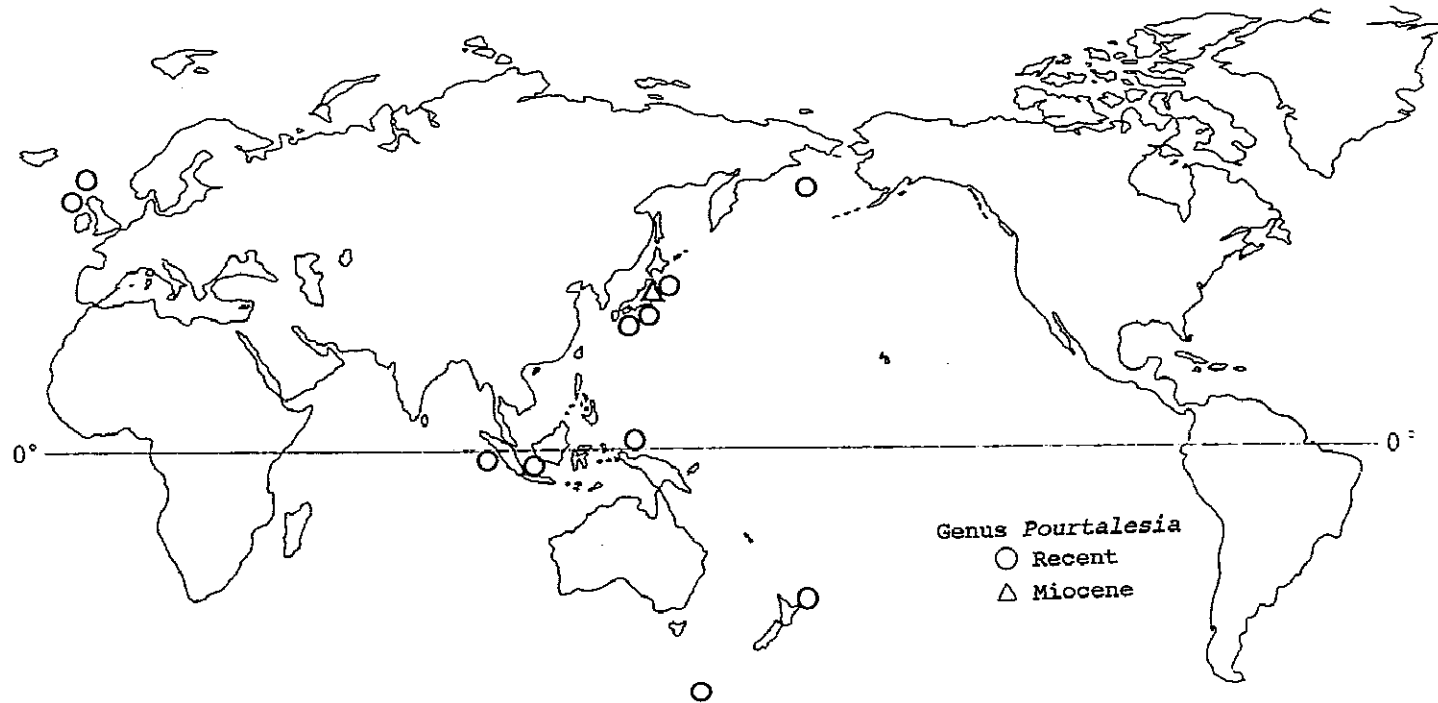


Fig. 79. Geological and geographical distribution of *Pourtalesia* species.

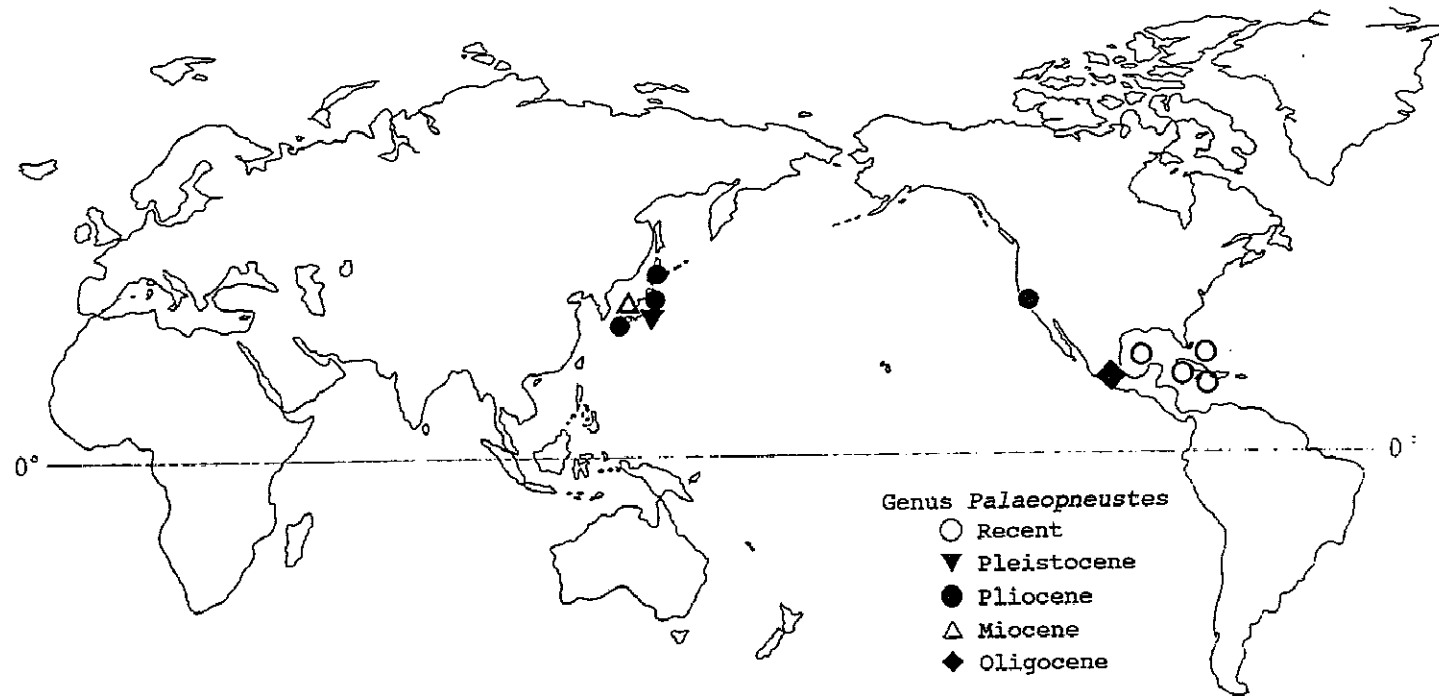


Fig. 80. Geological and geographical distribution of *Palaeopneustes* species.

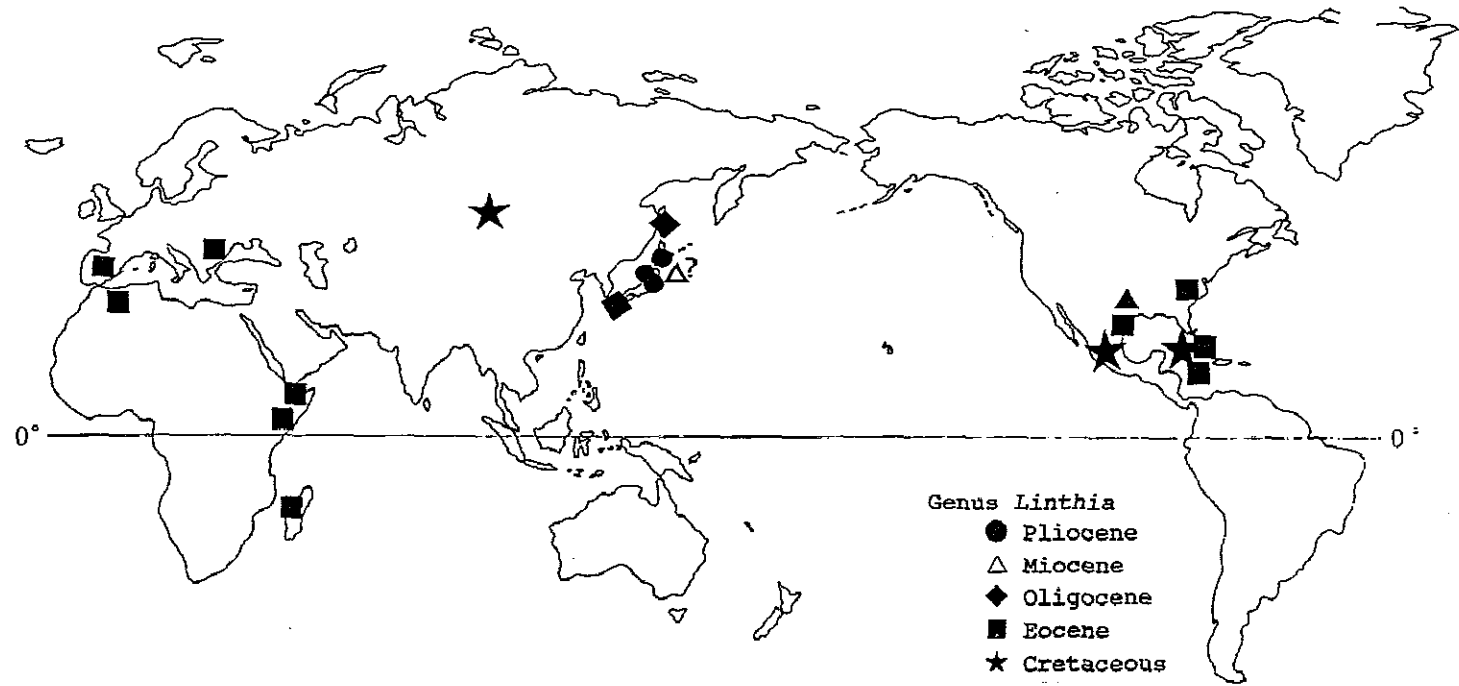


Fig. 81. Geological and geographical distribution of *Linthia* species.

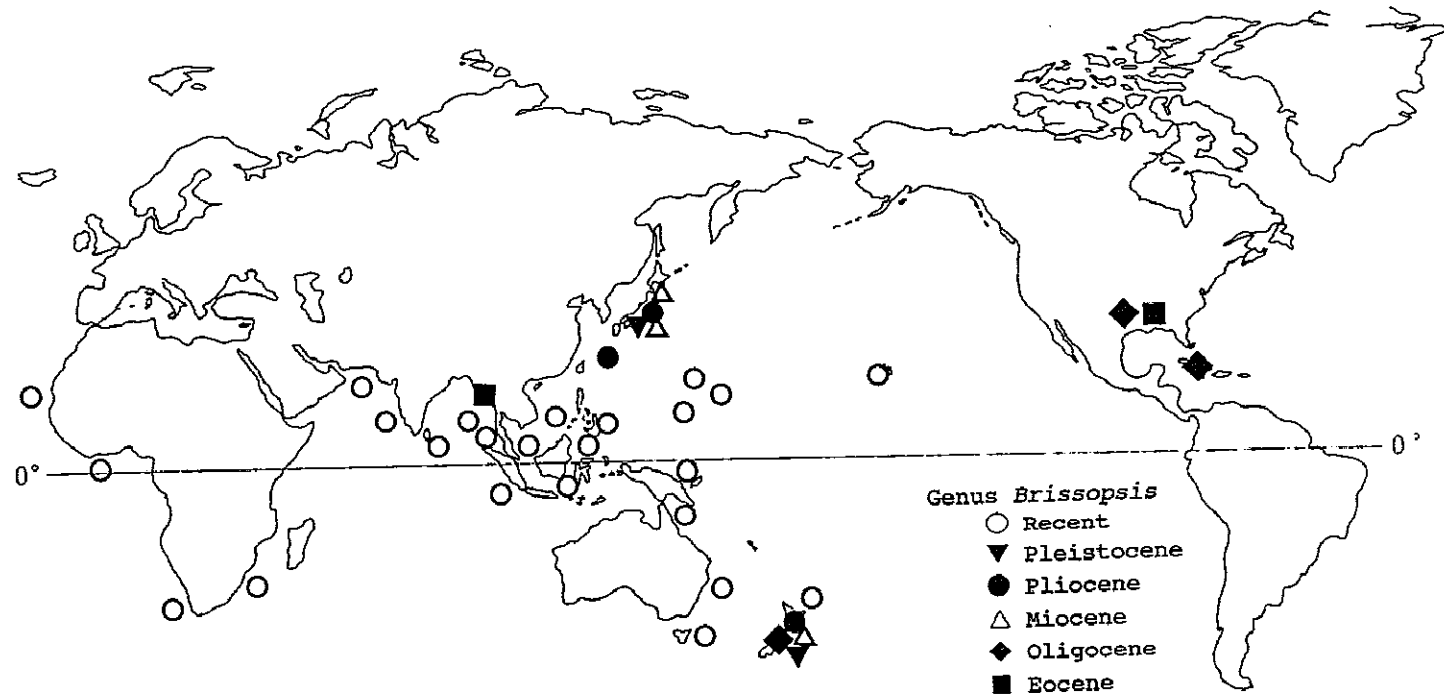


Fig. 82. Geological and geographical distribution of *Brissopsis* species.

early Pliocene.

6. Origin and migration of the Neogene echinoid fossils from the northern part of Ibaraki Prefecture

The origin and migration of echinoid fossils of 11 families, 15 genera, and 39 species yielded from the early middle Miocene to Pliocene in the northern part of Ibaraki Prefecture was examined mainly based on the Smith (1984), Hoffman (1989) and David (1993).

1) *Temnotrema*

Temnotrema was originated in Miocene strata of the Java Island, and it might be migrated to the Japanese area during Miocene. Then, *Temnotrema rubrum* was first appeared in the studied area. (Table 21, Fig. 77).

2) *Scaphechinus*

Scaphechinus is the Japanese endemic genus that has been diversified after Miocene (Table 21, Fig. 78).

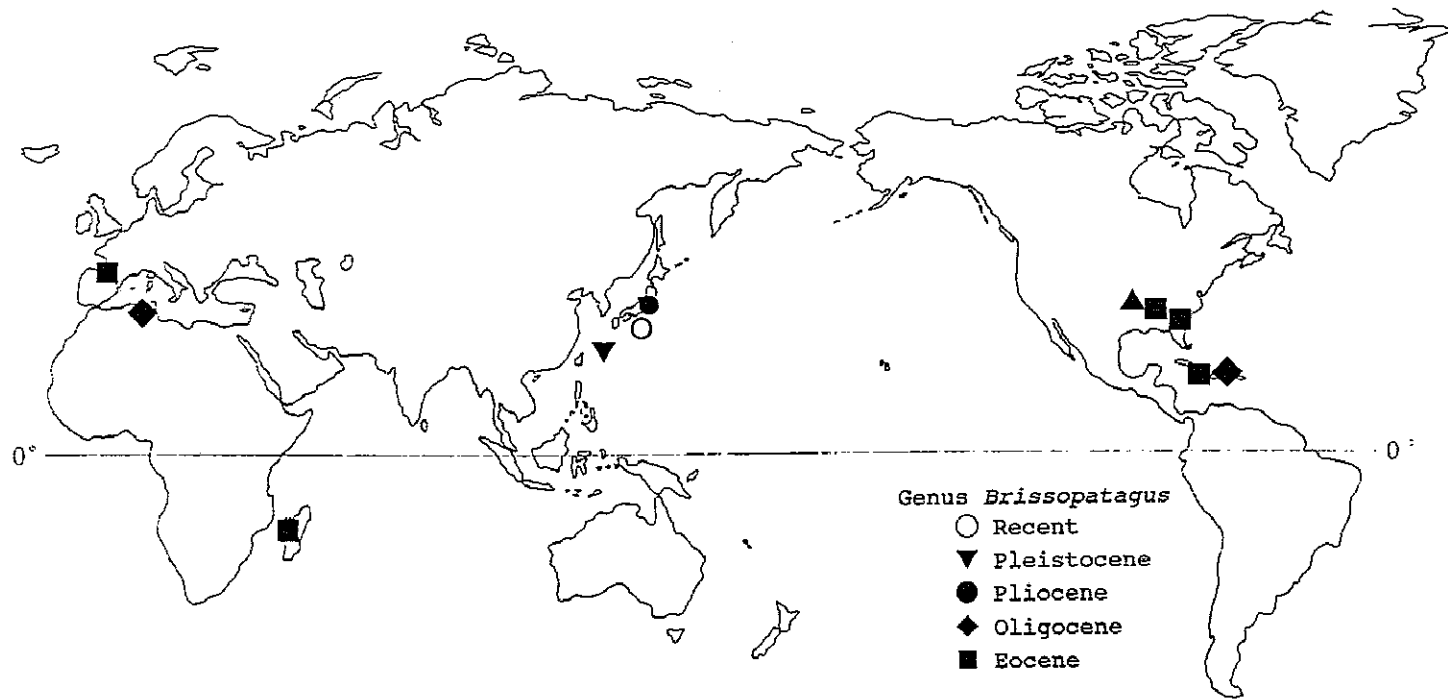


Fig. 83. Geological and Geographical distribution of *Brissopatagus* species.

3) *Pourtalesia*

Fossil *Pourtalesia* only known from the northern part of Ibaraki Prefecture (Table 21, Fig. 79).

4) *Palaeopneustes*

Origin of *Palaeopneustes* is assigned the Caribbean Sea area in Oligocene (Henderson, 1975; Kier and Lawson). (Table 21, Fig. 80).

5) *Linthia*

The oldest record of *Linthia* species is Late Cretaceous of Mongolia and Cuba (Kier and Lawson, 1978). However, the fossil distribution suggested the origin of the genus is Europe (Table 21, Fig.80).

6) *Nodaster*

Nodaster watanabei n. gen. et n. sp. proposed by this study is the genus included in Family Pericosmidae that is originated in the Japan in Pliocene. The oldest fossil record of the Pericosmidae included *Nodaster* is Eocene of Mediterranean Sea area (Table 21).

7) *Brissopsis*

Brissopsis kajiwarai and *Brissopsis daigoensis* are recognized in early middle Miocene in the studied area. The oldest fossil record of *Brissopsis* is Eocene of Southeast Asia and southern part of North America (Kier and Lawson, 1978). It should be migrated from the East Africa through the Indian Ocean, the Southeast Asia, and reached to the Japanese area (Table 21, Fig. 82).

8) *Brissopatagus*

Fossil *Brissopatagus* species of the study area is the second record in the Pacific Ocean area. This genus can be assigned originated in Eocene of the Mediterranean and European areas (Kier and Lawson, 1978). It is migrated from the East Africa through the Indian Ocean, Southeast Asia, and to the Japanese area (Table 21, Fig. 83).