Conclusion

Results of the paleontological and stratigraphical studies of echinoid fossils of the Neogene strata distributed in the northern part of Ibaraki Prefecture area can be summarized as follows with some discussion.

1. Results on paleontological study of echinoid fossils.

From the early middle Miocene to Pliocene of the northern part of Ibaraki Prefecture, 39 species of echinoid fossils were newly recognized, among which 11 families, 15 genera and 13 species are described including 2 new genera and 4 new species.

1) Echinoid fossils yielded from the early middle Miocene strata of the studied area are Echinothuriidae gen. et sp. indet, *Brissopsis daigoensis* n. sp., *Brissopsis kajiwarai* n. sp., *Brissopsis* sp. and Schizasteridae gen. et sp. indet.

2) Echinoid fossils yielded from the middle Miocene strata are also *Pourtalesia kusachii* n. sp., *Aceste* sp. and Schizsteridae gen. et sp. indet.

3) Echinoid fossils yielded from the Pliocene strata are *Anthocidaris* sp., *Temnotrema rubrum* (Döderlein), *Echinocyamus*

crispus Mazzetti, *Scaphechinus* cf. *mirabilis* A. Agassiz, *Palaeopneustes psoidoperiodus* Nishio, *Linthia nipponica* Yoshiwara, *Linthia tokunagai* Lambert, *Linthia* sp., *Lutetiaster ogasawarai* n. sp., *Brisaster owstoni* Mortensen, *Nikaidoster tokaiensis* n. gen. et n. sp., Schizasteridae gen. et sp. indet., *Nodaster watanabei* n. gen. et n. sp., *Anametaria* sp. and *Brissopatagus* sp.

4) The echinoid fossils (11 families, 15 genera, and 39 species) yielded from northern part of Ibaraki Prefecture are ecologically compared with such living taxa as 37 families, 105 genera, and 152 species in and around the Japanese water. As a result, 3 species are recognized as living one, and also both of the fossil and living species extend to 11 families and 10 genera are also recognized.

Stratigraphical ranges of fossil echinoids yielded from the northern part of Ibaraki Prefecture are shown in Tables 21-22. This data indicate that the specific diversification of Japanese echinoids took place at after early middle to middle middle Miocene.

This phenomenon well agreed with the opinion of Nishimura (1974, 1981) that marine organisms were diversified in the northern Pacific Ocean area after middle Miocene.

5) Owing to the biogeographical study of echinoids by Smith

(1984), the echinoid fossils from the northern part of Ibaraki Prefecture can be divided into the following six categories; the Gulf and Caribbean origin, Circum-Mediterranean, North European origin, Indo-Madagascar origin, Japanese origin and probably the Indo-West Pacific Ocean origins.

6) The following three migration routes can be estimated. a) The route which passed through the Southeast Asia from the Indian Ocean, and migrated to Japanese area, b) The route passed through the Central America and also the Central Pacific Ocean and migrated to Japanese area, c) The route which passed through the Central America from the Caribbean Sea area, through the West Coast of America, the North Pacific Ocean and migrated to Japanese area.

7) *Pourtalesia* and *Aceste* species that are representatives of deep-sea echinoid genera were first discovered from the middle Miocene Tatsukuroiso Mudstone Member of the Higashikanasayama Formation in the northern part of Ibaraki Prefecture. Mironov (1980) described that the new type deep-sea echinoid fauna was originated at Miocene in the Indo-West Pacific Ocean and Antarctic Sea area. Hence, this discovery supports the opinion of Mironov (1980).

8) Most species reported as *Linthia nipponica* Yoshiwara and *Linthia tokunagai* Lambert from the early middle Miocene in the

Paleo-Seto area were considered to belong *Brissopsis* species by the present study. Then, the new names, *Brissopsis daigoensis* or *Brissopsis kajiwarai* were given to them based on species yielded from the Naeshiroda Formation. These two species of *Brissopsis* fossils regarded indicating the warm-water realm and also a deep-sea condition by comparison with the modern species of the Pacific.

9) The echinoid assemblage of the middle Miocene Tatsukuroiso Mudstone Member of the Higashikanasayama Formation is composed of very peculiar species such as *Pourtalesia kusachii* n. sp. and *Aceste* sp. These two species were first recognized in the middle Miocene in the world. Species of *Pourtalesia* and *Aceste* were judged inhabited a deep-sea condition such as an archibenthal one by comparison with the ecology of modern counterpart species.

10) The Pliocene Hatsuzaki Sandstone Member of the Hitachi Formation, Muramatsu Formation and the Kume Formation are correlatives to each other, and also are yielded the same echinoid assemblages.

Subsequently, these echinoid assemblages can be sub-divided into following three categories on the basis of modern analogy of allied species: a) Shallow-sea element: *Anthocidaris* sp., *Temnotrema rubrum* and *Scaphechinus* cf. *mirabilis* ; b) Shallow-sea to offshore one: *Echinocyamus crispus*, *Linthia nipponica*, *Linthia tokunagai*, and *Brissopatagus* sp.; c) deep-sea element: *Palaeopneustes psoidoperiodus*, *Lutetiaster ogasawarai* n. sp., *Nikaidoster tokaiensis* n. gen. et n. sp., *Brisaster owstoni*, *Nodaster watanabei* n. gen. et n. sp., and *Anametalia* sp.

From a paleoclimatical point of view, echinoids can be divided into the two realms as the cool-temperate and warm-temperate realms as the former represented by genus *Linthia* and the latter represented by *Anthocidaris* sp., *Temnotrema rubrum*, *Scaphechinus* cf. *mirabilis*, *Palaeopneustes psoidoperiodus*, *Brisaster owstoni*, *Brissopatagus* sp. and *Anametaria* sp. In addition, *Lutetiaster ogasawarai*, *Nikaidoster tokaiensis* and *Nodaster watanabei* may be regarded a warm-water one. Co-occurrence of two different type echinoids suggests that the studied area at the Pliocene time lay a transitional zone of these warm and cold-water conditions.

Although fossil species of genus *Lutetiaster* has been known from only Europe and East Africa in Eocene age, it is a new discovery of the Pliocene in Japan.

11) Echinoid faunal changes from the early middle Miocene to Pliocene of the northern part of Ibaraki Prefecture can be summarized as follows by comparison with the living counterpart

species of echinoids: Echinothuriidae gen. et sp. indet., *Brissopsis daigoensis* n. sp. and *Brissopsis kajiwarai* n. sp. are migrated to Japan from the Indian Ocean area at the early middle Miocene; *Pourtalesia kusachii* n. sp. and *Aceste* sp. migrated to this area at the middle Miocene. During the Pliocene, such species are migrated this area as *Anthocidaris* sp., *Temnotrema rubrum*, *Echinocyamus crispus*, *Scaphechinus* cf. *mirabilis*, *Palaeopneustes psoidoperiodus*, *Linthia nipponica*, *Linthia tokunagai*, *Linthia* sp., *Lutetiaster ogasawarai* n. sp., *Nikaidoster tokaiensis* n. gen. et n. sp. *Brisaster owstoni*, Schizasteridae gen. et sp. indet., *Nodaster watanabei* n. gen. et n. sp., *Brissopatagus* sp. and *Anametaria* sp. are first appeared at Pliocene in the studied area.

Subsequently, all species of genus *Palaeopneustes*, *Linthia*, *Nikaidoster* and *Nodaster* are extinct in Pleistocene, and *Pourtalesia kusachii* n. sp., *Brissopsis daigoensis* n. sp. and *Brissopsis kajiwarai* n. sp. are extinct in Miocene. However, such species of genus *Anthocidaris*, *Temnotrema*, *Echinocyamus*, *Scaphechinus*, *Pourtalesia*, *Aceste*, *Brisaster*, *Brissopsis*, *Brisopatagus* and *Anametaria* are now flourished around the Japanese Island. These species are *Temnotrema rubrum*, *Echinocyamus crispus*, *Scaphechinus* cf. *mirabilis* and *Brisaster owstoni*. In other words, echinoid assemblages inhabiting the present sea are basically appeared in early middle Miocene and have been flourished and diversified into some species in Pliocene around the Japanese Island.

Consequently, echinoid fossil records in the Neogene strata of the northern part of Ibaraki Prefecture presented significant data on stratigraphic range and also paleobiographic distribution of many species (Table 21, Figs. 77-83).

2. Results on stratigraphcal study.

1) Conglomerates distributed southwest side of the Abukuma Mountains in the three studied areas are assigned to the basal conglomerate of the Pliocene Kume Formation. These conglomerate newly described as the Momiya Conglomerate Member. However this member varies in thickness, it is widely distributed piedmont of the Abukuma Mountains such as from near summit of the mountain range to slope area. This distribution pattern suggests that the Abukuma Mountains of the Hitachiota area to Hitachi area should be under the sea surface in Pliocene. Although it has been regarded that there is no tectonic evidence on the activities of the study area except for Tokunaga (1927), the writer first offered new evidence on the tectonic activities of the southern part of Abukuma Mountains. This

Momiya Conglomerate Member is correlative with the Mayumi Gravel which was reported by Omori and Owada (1985).

2) *Condrites* isp. and *Zoophycos* isp. of trace fossils represent deep-sea condition were recognized from four places of the following late middle Miocene Hase Formation; one is southwest slope of the Abukuma Mountains in Hitachiota area (present altitude is about 200 m), the second is about 400 m southeast of the Hatsuzawa in Machiya-cho (present altitude is about 130 m), the third is about 300 m east of the Okanouchi in Takanuki-cho (present altitude is about 130 m), the forth is about 500 m northeast of Chinone-cho (present altitude is about 100 m). Stratigraphic position of these fossils localities occupied the basal part of the strata.

4) The following thirteen new stratigraphic boundaries are discovered in the present study: unconformity between the late middle Miocene Hase Formation and the Pliocene Kume Formation at Hatasome (Pl. 18, fig. 4), Nodono (Pl. 20, fig. 1), and at Benten (Pl. 20, figs. 2, 4) in the eastern part of Hitachiota area, and at Nukada-Togo in Naka area (Pl. 19, figs. 1-2); unconformity between the late middle Miocene Kawarago Formation and the Pliocene Hanareyama Tuff Member of the Kume Formation at Hanareyama in Hitachi area (Pl. 23, fig. 2); unconformity between the late middle Miocene Kawarago Formation

and the Pliocene Hitachi Formation at Kuji in Hitachi area (Pl. 23, fig. 2); unconformity between the late middle Miocene Shinkawa Formation and the Pliocene Muramatsu Formation at Kawane in Tokai area (Pl. 24, figs. 2-4); unconformity between the early middle Miocene Zuiryu Formation and the middle Miocene Genjigawa Formation at Hanabusa in Kanasago area (Pl. 18, fig. 1); unconformity between the basement rocks of the Abukuma Mountains and the late middle Miocene Hase Formation at Shiraha in eastern part of the Hitachiota area (Pl.20, fig. 3); unconformity between basement rocks of the Abukuma Mountains and the late middle Miocene Kawarago Formation at Kuji in Hitachi area (Pl.23, figs. 3-4); unconformity between the basement rocks of Abukuma Mountains and the Pliocene Momiya Conglomerate Member of the Kume Formation at near summit of the Abukuma Mountains in Kamezaku, eastern part of the Hitachiota area (Pl. 21, figs. 1-3), and at Ishinazaka in Hitachi area (Pl. 22, fig. 3).

5) It is assigned that interfingering the late middle Miocene Isozaki Formation (Saito and Ozaki, 1956; Maruyama, 1984; Yanagisawa *et al.*, 1989; Yoshioka *et al.*, 2001) and the Pliocene Hetano Formation (Maruyama, 1984) based on stratigraphical examination of the strata in this study (Pl. 25, figs. 3-4).

6) The fault and sheared structure made by the same tectonic sense were discovered in the late middle Miocene Urizura Formation and also in the Pliocene Kume Formation at Nukada-Togo in Naka area (Pl. 25, figs. 1-4). Hence, the writer judged that this fault and sheared structure are some of southern elongation of the Tanakura Tectonic Line. Therefore, it is regarded that tectonic movement of the Tanakura Tectonic Line should be continued to not only during Miocene but also during Pliocene.