A new species of *Arca* (Bivalvia: Arcidae) from the lower Miocene Asahi Formation on the Japan Sea side of central Honshu, with remarks on the westward faunal migration from the eastern Pacific

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ABSTRACT

The arcid bivalve, ***Arca* (*Arca*) *budoensis* new species**, is described from the Budo Mudstone Member of the Asahi Formation in northern Niigata Prefecture, central Honshu. The age of the member has been assigned to 16.6–15.9 Ma (late early Miocene) on the basis of dinoflagellate cysts. Judging from the arcid, dinoflagellate cysts and sedimentary facies, the paleoenvironment of the member was a shallow embayment influenced by a warm-water current. The reason that the molluscan fauna of the Budo Member contains no characteristic species of the subtropical to tropical Arcid-Potamid fauna (17.0–16.7 Ma) is that the Budo fauna is slightly later than that Arcid-Potamid fauna. Because the new species resembles fossil and Recent species of the eastern Pacific, *A. budoensis* is accepted as derived from an ancestor that migrated westward to Asia. **The senior author, Kazutaka Amano, is the single author of the new species.**

Additional Keywords: Marine, fossil, shallow sea, warm-current

INTRODUCTION

The Japan Sea was formed in the latest Oligocene (ca. 25 Ma) by separation of the Japanese Islands from the Eurasian continent (Yanai et al., 2010). The oldest "marine" trace fossils from the Japan Sea side were recovered from the Shiose-no-Misaki sediments which were intruded by a dolerite dated at 20 Ma (Ohguchi et al., 2005). However, Sato et al. (2009) argued that these fossils were non-marine. According to Sato et al. (1991, 2009), the oldest marine fossils including the nannofossil, *Sphenolithus heteromorphus* were from the lower part of the NN4 zone (Martini, 1971), later than 17.75 Ma according to Backman et al. (2012).

In the northern part of Niigata Prefecture, the marine sediments occur in the Miocene Asahi Formation (Nishida, 1958; Takahama et al., 1976), which unconformably overlies the Tenjosan Formation and is overlain by the Osudo Shale containing the Osudo flora (Kamoi et al., 1978). This flora corresponds with the late early to early Middle Miocene Daijima-type flora (Takahama et al., 1976; Kamoi et al., 1978). The Asahi Formation consists of the Budo Mudstone, Nagasakatoge Rhyolite and Arasawa Sandstone and Conglomerate Members in ascending order (Takahama et al., 1976). The large foraminifer *Operculina complanata japonica* Hanzawa, from the Arasawa Member indicates a late early to early late Miocene age (Kamoi et al., 1978).

The following mollusks and brachiopods (including *Terebratulina* spp.) were recorded from the Budo Member by Nishida (1958), Tsuda (1965) and Takahama et al. (1976): *Chlamys iwasakiensis*, *Pecten* sp., *Cardium* sp., *Geloina yamanei*, *Panomya simotomensis,* and *Littolinopsis miodelicatula*. Of these, *Geloina yamanei* and *Littolinopsis miodelicatula* are characteristic species of late early Miocene mangrove swamp fauna (Oyama, 1950). However, these species names were only listed up from unknown localities and have never been described nor illustrated. Moreover, the exact age of this member has not been determined from microfossils.

Many marine fossils have been recovered from a previously unknown locality in the Budo Member. The species composition including a new arcid species is very different from the above listed species. In this paper, we determine the age by dinoflagellate cysts, describe the new bivalve species of *Arca* and discuss the paleobiological significance of the fauna.

MATERIALS AND METHODS

The fossils were collected from a small outcrop along a rice field at 250m east from Budo (Figure 1; 38°23′23″ N, 139°33′27″ E). At the fossil locality, hard gray mudstones yielding many shell-dissolved fossils are exposed. From this locality, the following molluscan species are recorded: ***Arca budoensis* new species**, *Arcuatula*? sp. and *Cavilucina*? sp. Moreover, the fossils also include three species of brachiopods: *Discinisca* sp., *Coptothyris grayi* (Davidson), *Terebratalia* sp. and one fragment of Cirripedia, *Capitulum*? sp.

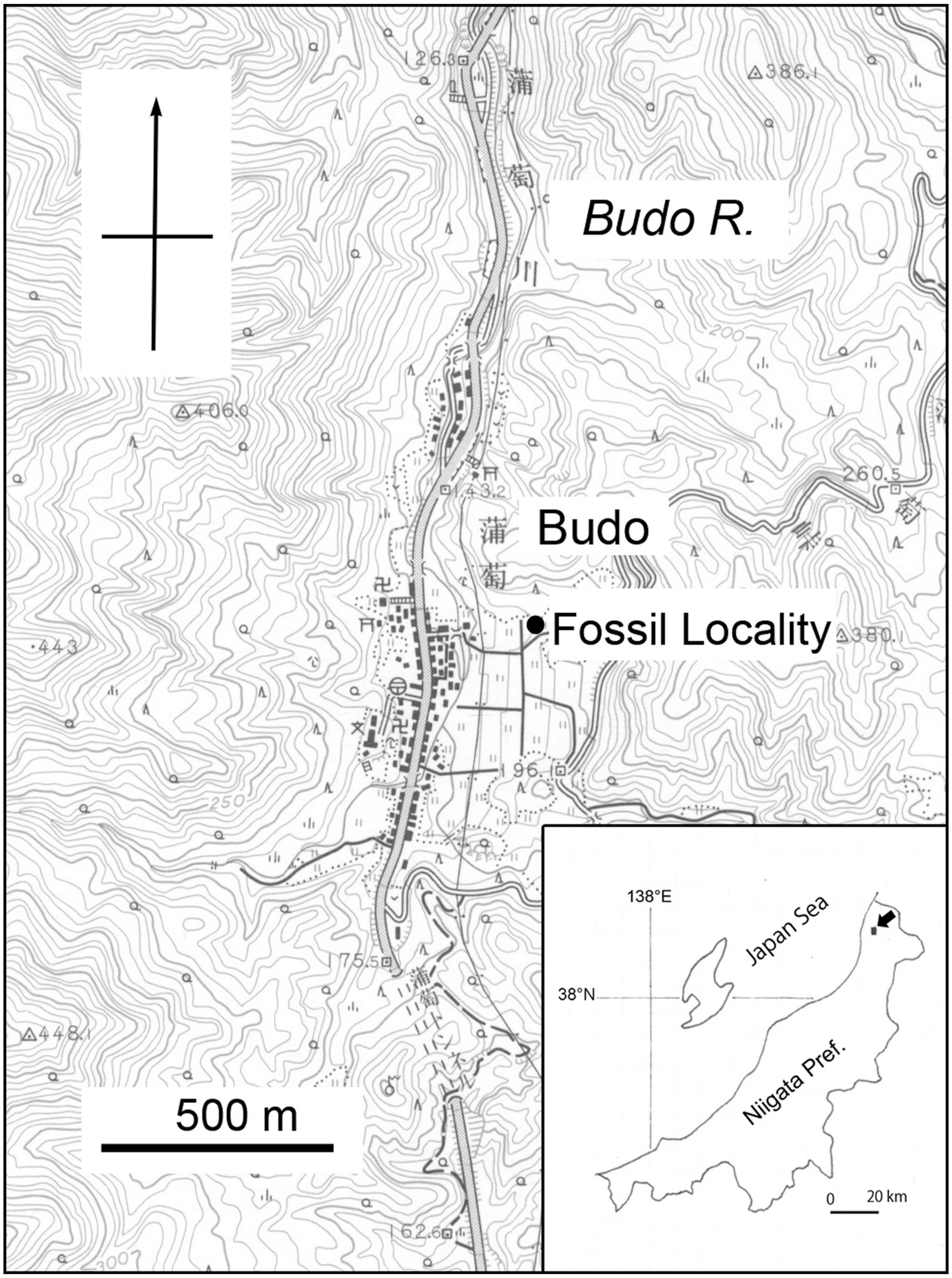


Figure 1. Locality of fossils. Base map from "Budo", original scale 1:25,000; topographical map published by the Geospacial Information Authority of Japan.

Dinoflagellate cysts were picked for age determination from the rock subsampled in the mollusk-bearing mudstone. Taxonomic identification of dinoflagellate cysts follows Fensome et al. (2008), where complete bibliographic references were provided. The sample was treated successively with HCl and HF to eliminate carbonate and silicate minerals. Then heavy liquid zinc bromide (specific gravity 2.0) was used to concentrate organic particles from the residues after the acid treatment.

We used digital calipers (Mitsutoyo Company, model CD-20) to measure specimens of *Arca* to the first decimal place. The terminology on *Arca* is follows Noda (1966). All specimens of *Arca* are deposited at the National Museum of Nature and Science, Tsukuba (NMNS).

DINOFLAGELLATE AGE

The sample yielded a number of dinoflagellate cysts whose preservation was sufficiently good for identification. Based on 393 counted specimens, the dinoflagellate cyst assemblage is characterized by abundant to common occurrences of *Achomosphaera ramulifera*, *A. spongiosa*, *Cribroperidinium giuseppei*, *C. granomembraneceum*, *Diphyes latiusculum*, *Heteraulacacysta campanula*, *Hystrichokolpoma rigaudiae*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Spiniferites pseudofurcatus* and *Systematophora placacantha* with fewer *Nematosphaeropsis lemniscata*, *Reticulatosphaera actinocoronata,* and *Tuberculodinium vancampoae*. In the assemblage, protoperidinioid species are very minor in abundance and include *Brigantedinium* sp., *Lejeunecysta* spp., and *Selenopemphix nephroides* (Table 1). In addition, a few specimens of an acritarch species *Paralecaniella indentata* and a freshwater green alga *Pediastrum* sp. were also recorded.

The abundant to common occurrences of *Cribroperidinium giuseppei*, *C. granomembraneceum*, *Diphyes latiusculum*, *Spiniferites pseudofurcatus* and *Systematophora placacantha* indicate evident correlation with the basal part of the Subzone b of *Diphyes latiusculum* Zone originally proposed by Matsuoka et al. (1987) and subsequently modified by Obuse and Kurita (1999). According to Obuse and Kurita (1999), this part is coeval with the diatom *Denticulopsis praelauta* Zone (NPD3B) that is calibrated to the age interval of 16.6–15.9 Ma (latest early Miocene) by Yanagisawa and Akiba (1998) and Watanabe and Yanagisawa (2005).

Table 1. List of dinoflagellate cysts and acritarchs associated with the molluscan fossils. Relative abundance of each dinoflagellate cyst taxon is expressed as VA (very abundant, 20 % and more of the total specimen count), A (abundant, 20–10 %), C (common, 10–3 %), R (rare, 3–1 %) and VR (very rare, less than 1 %).

Species	Abundance
DINOFLAGELLATA	
Achomosphaera ramulifera	C
Achomosphaera spongiosa	C
cf. *Achomosphaera spongiosa*	R
Batiacasphaera ? spp.	VR
Brigantedinium sp.	VR
Cleistosphaeridium ancyrea	VR
Cribroperidinium giuseppei	C
Cribroperidinium granomembraneceum	C
Diphyes latiusculum	C
Heteraulacacysta campanula	R
Hystrichokolpoma rigaudiae	R
Impagidinium sp.	VR
Lejeunecysta spp.	VR
Lingulodinium machaerophorum	C
Lingulodinium sp.	VR
Nematosphaeropsis lemniscata	VR
Operculodinium centrocarpum	C
Reticulatosphaera actinocoronata	VR
Selenopemphix nephroides	VR
Spiniferites membraneceus	R
Spiniferites pseudofurcatus	C
Spiniferites ramosus	R
Spiniferites sp.	A
Systematophora placacantha	VA
Tuberculodinium vancampoae	R
Other organic algal microfossils	
Paralecaniella indentata	present
Pediastrum sp.	present

SYSTEMATICS

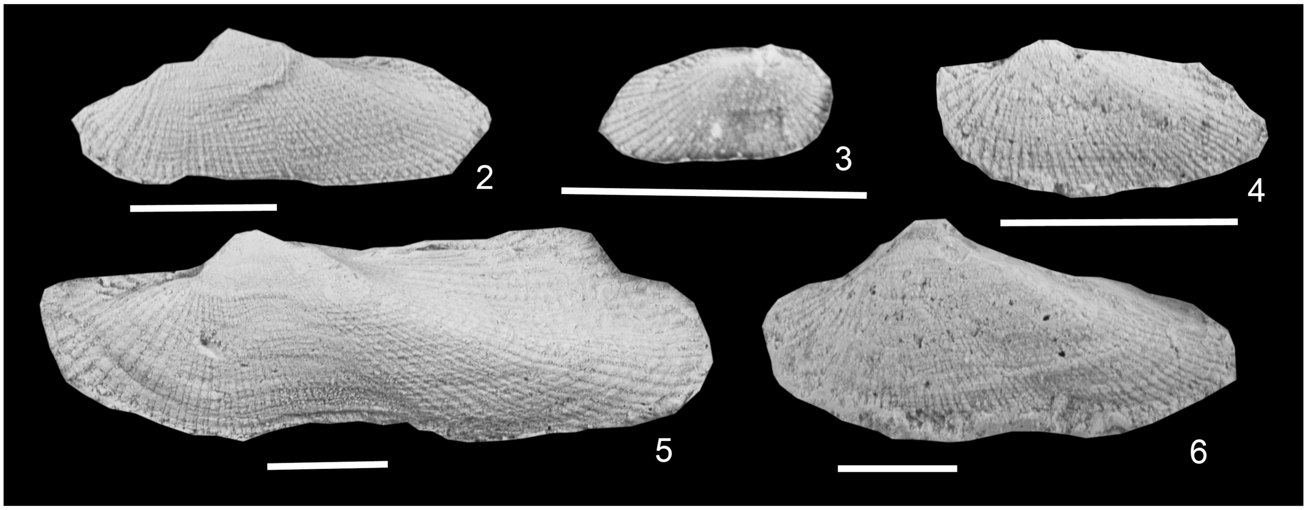
Family Arcidae Lamarck, 1809
Subfamily Arcinae Lamarck, 1809
Genus *Arca* Linnaeus, 1758
Subgenus *Arca* Linnaeus, 1758

Type Species: *Arca noae* Linnaeus, 1758 by subsequent designation.

Remarks: The senior author, Kazutaka Amano, is the single author of the new species. Reinhart (1935) recognized four subgenera: *Arca*, *Litharca* Gray, 1842, *Arcoptera* Heilprin, 1887, and *Eonavicula* Arkell, 1929. According to Lutaenko and Maestrati (2007), *Litharca* is an independent genus and *Arcoptera* is independent from *Arca* (s.s.). Oliver and Chesney (1994) recognized *Tetrarca* Nordsieck, 1969 (type species: *Arca tetragona* Poli, 1795). When Oliver and Holmes (2006) subdivided *Arca* into *A. noae*, *A. avellana,* and *A. tetragona* groups, they did not treat the last group as a separate subgenus. Consequently, Lutaenko and Maestrati (2007) separated the extinct *Arcoptera* as a subgenus and *Arca* (s. s.) into three types: Type 1 (*A. avellana, A. boucardi*, *A. tetragona*), Type 2 (*A. navicularis, A. pacifica, A. zebra*) and Type 3 (*A. koumaci*), based on the presence of postero-dorsal wing and posterior sulcus. Huber (2010) subdivided the modern *Arca* into four subgenera as *Arca* (s. s.), *Tetrarca,* unnamed I (*A. avellana, A. imbricata, A. mutabilis, A. ventricosa*) and unnamed II (*A. boucardi*). From the view point of valve margins, Vermeij (2013) subdivided *Arca* into three groups as *A. imbricata* group with smooth edge (*A. avellana, A. imbricata, A. mutabilis*), *A. zebra* group with obsolete ventral crenulations and well-developed anterior and posterior ones (*A. zebra, A. pacifica, A. navicularis, A. ventricosa, A. noae*). Vermeij (2013) separated *A. boucardi* from these two groups by its continuously crenulated ventral margin and a much narrower hinge plate. Molecular data by Feng et al. (2015) and Kong et al. (2020) support the subdivision of *Arca* (s. s.) by Oliver and Holmes (2006) and Lutaenko and Maestrati (2007) except for the separation of *A. boucardi* as a subgenus level supporting Huber's (2010) and Vermeij's (2013) opinions. In this paper, the new species is treated as a *A. noae* group (Subgenus *Arca* s. s.) from its shell shape.

Arca (*Arca*) *budoensis* Amano new species
(Figures 2–6)

Diagnosis: Small *Arca* having low elongate shell, pointed anterior end, truncated posterior margin, strong radial ridge from umbo to postero-ventral corner and posterior sulcus. Surface ornamented with 64 radial ribs and granulated with growth lines on posterior part.



Figures 2—6. ***Arca*** **(*Arca*)** ***budoensis*** **Amano new species. 2. Paratype**, left valve, NMNS PM 65048. **3. Paratype**, right valve, NMNS PM 65050. 4. **Paratype**, left valve, NMNS PM 65049. **5. Holotype**, left valve, NMNS PM 65046. **6. Paratype**, left valve, NMNS PM 65047. Scale bars = 5 mm.

Description: Shell small (to 25.8 mm long), elongate quadrate, much lower than high especially in adults (H/L= 0.33 to 0.56), inequilateral (AL/L= 0.27 to 0.41), strong radial ridge extending from umbo to postero-ventral corner. Antero-dorsal margin straight and horizontal; anterior end of dorsal margin pointed; antero-ventral margin posteriorly oblique; middle to posterior ventral margin broadly concave as byssal notch in adult but straight in younger specimens (length <7.3 mm); postero-ventral corner acutely rounded; posterior margin subtruncated and concave; postero-dorsal margin straight and horizontal making right angle with posterior margin. Umbo produced above dorsal margin; beak located at anterior about one-third to two-fifths. Surface of anterior part of shell in front of radial ridge ornamented with 51 flat and fine radial ribs separated by nearly equal interspaces; anterior eight stronger than other ribs; posterior area of shell behind radial ridge sculptured by 13 radial ribs, lamellated growth ribs making granules at their crossing points; granulation sometimes seen in front of radial ridge in younger shells. Small taxodont teeth observable in terminal of hinge. Inner structure unknown.

Type Material: Holotype: Left valve (NMNS PM no. 65046), length 25.8 mm, height 8.6 mm, anterior length 7.6 mm. Paratypes: Left valve (NMNS PM no. 65047), length 19.6 mm, height 7.7 mm, anterior length 8.0 mm; left valve (NMNS PM nos. 65048), length 13.8 mm, height, 5.0 mm+; left valve (NMNS PM no. 65049), length 7.3 mm, height 4.1 mm, anterior length 2.9 mm; right valve (NMNS PM no. 65050), length 3.7 mm, height 1.9 mm, anterior length 1.0 mm.

Type Locality: 250m east from Budo, Murakami City; upper lower Miocene Budo Mudstone Member of Asahi Formation.

Material Examined: Twenty-eight specimens from the type locality.

Remarks: From the point of view of shell shape**,** there is no similar modern or fossil species in Japan. *Arca* sp. from the uppermost lower Miocene Kubohara Formation in Gifu Prefecture by Itoigawa et al. (1981, 1982) has a similar shell size and an elongate shell. However, ***Arca*** **(*Arca*)** ***budoensis*** **new species** has a pointed anterior end and lower shell than *Arca* sp.

Arca **(*Arca*)** ***budoensis*** **new species** can be included in the *A. noae* group of Oliver and Holmes (2006) and Type 2 by Lutaenko and Maestrati (2007) because of its wing shape and posterior sulcus. In the western Pacific, there is no fossil record other than the modern species, *Arca* (*Arca*) *navicularis* Bruguière, 1789 belonging to the same group and type. However, the oldest record of *A.* (*A.*) *navicularis* is from the Pliocene in Indonesia (Kase et al., 2008). ***Arca*** **(*Arca*)** ***budoensis*** **new species** differs from *A.* (*A.*) *navicularis* by having a lower shell, no pointed postero-dorsal end and finer radial ribs. In contrast, some similar species have been described from the eastern Pacific. *Arca* (*Arca*) cf. *hawleyi* Reinhart, 1943 from the Eocene Tejon Formation in California, is similar to the new species by having a similar size elongated shell with a pointed anterior end and a strong ridge from beak to postero-ventral corner. However, ***Arca*** **(*Arca*)** ***budoensis*** **new species** has a more posteriorly situated beak and more distinct radial ribs. A Recent species, *Arca* (*Arca*) *pacifica* (Sowerby, 1833) from Baja California to the Galápagos Islands (Coan and Valentich-Scott, 2012) is similar to the new species in having pointed anterior end and a concave area behind the strong ridge from beak to postero-ventral margin. However, ***Arca*** **(*Arca*)** ***budoensis*** **new species** has a lower elongate-quadrate shell, no pointed posterior end, shallower byssal notch and more numerous fine radial ribs and is much smaller than *A.* (*Arca*) *pacifica*. Another similar species is *Arca* (*Arca*) *truncata* (Sowerby, 1833) from San Lucas, Baja California to the Galápagos Islands (Coan and Valentich-Scott, 2012). It resembles ***Arca* (*Arca*) *budoensis* new species** in its low elongate quadrate outline. ***Arca* (*Arca*) *budoensis* new species** has a pointed antero-dorsal end, a posterior sulcus and an oblique posterior margin which are never observed in the much larger *A.* (*A.*) *truncata*.

Distribution: Only from the type locality.

Etymology: Named for locality from where this species was collected.

DISCUSSION

The present paper is the first to describe and illustrate fossils from the Budo Member. ***Arca* (*Arca*) *budoensis* new species** and its associated species indicate a shallow-marine environment. The occurrences of the dinoflagellate cysts *Lingulodinium machaerophorum* (cold-intolerant/thermophilic) and *Tuberculodinium vancampoae* (tropical to subtropical) suggest the influence of a warm current (Head, 1997; de Vernal and Marret, 2007). Moreover, the occurrence of a freshwater alga *Pediastrum* sp. suggests proximity to a river that fed the embayment. This inference was also supported by the sedimentary facies analysis (Igarashi and Kurita, 2007). The shallow-marine molluscan fauna herein described is different from the tropical to subtropical Arcid-Potamid fauna (Tsuda, 1965), despite them sharing a similar paleoenvironment. Recently Yanagisawa and Watanabe (2017) postulated that the occurrence of the Arcid-Potamid fauna in Japan was confined to the interval of 17.0 to 16.7 Ma. As the Budo Member was deposited slightly later (16.6 to 15.9 Ma) than the Arcid-Potamid fauna, it does not include any characteristic species of the fauna. However, most species of Type 2 and *the Arca noae* group to which ***Arca* (*Arca*) *budoensis* new species** belongs live in warm water which is concordant with the paleoenvironment inferred by the dinoflagellate cysts.

As described here, ***Arca* (*Arca*) *budoensis* new species** resembles both fossil and modern species from the eastern Pacific, not from the western Pacific. In the early Miocene, six bivalve genera and one subgenus have been recognized as immigrants from the eastern Pacific to the west during the early to early middle Miocene. The taxa include the venerids *Securella*, *Kaneharaia*, *Compsomyax*, the hiattelid *Panomya*, the rock-boring myid *Platyodon*, the Pholadid *Penitella*, and the tellinid subgenus *Rexithaerus* (Amano, 2005). One modern species of the Type 2 (Lutaenko and Maestrati, 2007) in the western Pacific, *Arca* (*Arca*) *navicularis* first appeared only in the Pliocene of Java, Indonesia (Kase et al., 2008). Thus, ***Arca* (*Arca*) *budoensis* new species** was derived from the ancestor which migrated from the eastern Pacific to Japan at least by the early Miocene.

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