

# SHRIMP U-Pb age of the radiolarian-bearing Yoshiki Formation in Japan

MANCHUK NURAMKHAAN, KENJI HORIE & KAZUHIRO TSUKADA



The dating of radiolarian biostratigraphic zones from the Silurian to Devonian is only partially understood. Dating the zircons in radiolarian-bearing tuffaceous rocks has enabled us to ascribe practical ages to the radiolarian zones. To extend knowledge in this area, radiometric dating of magmatic zircons within the radiolarian-bearing Yoshiki Formation, Japan, was undertaken. The Yoshiki Formation is mainly composed of alternating beds of tuffaceous sandstones, tuffaceous mudstones, and felsic tuff. The felsic tuff and tuffaceous mudstone yield well-preserved radiolarian fossils. Radiolarians and zircon grains were collected from 21 tuffaceous mudstone and 30 tuff horizons of the Yoshiki Formation. The following radiolarian species which can be ascribed to the *Zadrappolus yoshikiensis-Futobari solidus* assemblage were identified: *Oriundogutta(?) kingi*, *Oriundogutta(?) varispina*, *Zadrappolus yoshikiensis*, *Zadrappolus tenuis*, *Zadrappolus hitoeganensis*, *Zadrappolus lunaris*, *Zadrappolus(?) nudus*, *Zadrappolus(?) sp.*, *Futobari solidus*, *Futobari morishitai*, *Rotasphaera(?) sp.*, and *Ceratoikiscum armiger*. U-Pb SHRIMP ages of  $420.5 \pm 2.5$  Ma and  $421.0 \pm 1.9$  Ma were obtained from the zircon grains. Thus the lower limit of the *Zadrappolus yoshikiensis-Futobari solidus* assemblage, that has previously been assigned to an age from Prídolian to Pragian, is in reality before Ludlowian. The technique in this paper has the capability of refining and making more accurate the dating of many radiolarian zones worldwide, and potentially of changing the direction of the entire study of radiolarian biostratigraphy. • Key words: U-Pb SHRIMP age, Silurian, Devonian, radiolarian, biostratigraphy.

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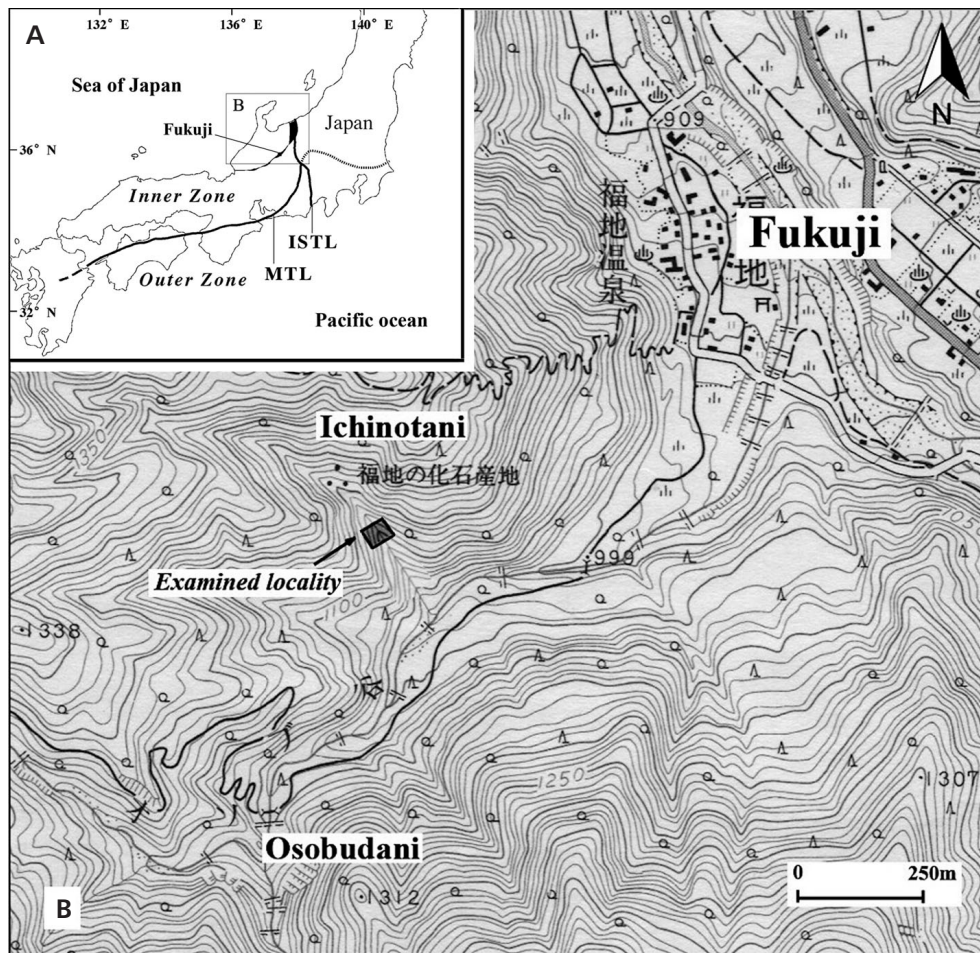
Many studies have now given us a clear picture of worldwide post-Carboniferous radiolarian biostratigraphy, and radiolaria nowadays receive wide recognition as an important tool, especially in tectonics, for revealing the Earth's history. In contrast, the biostratigraphy of pre-Devonian radiolaria is still not well understood. Although studies of Silurian to Devonian radiolarians in Australia, North America, Urals and Japan have made significant advances in establishing biostratigraphic zonation, assigning an age to each zone is still controversial (Aitchison & Stratford 1997, Aitchison *et al.* 1999, Amon *et al.* 1995, Furutani 1990, Kurihara 2004, Kurihara & Sashida 2000, Noble 1994, Noble & Aitchison 2000, Obut & Shcherbanenko 2008, Stratford & Aitchison 1997, Umeda 1998). Some Silurian to Devonian formations in Japan which yield radiolarian fossils are intercalated with felsic tuff layers with euhedral zircons. Determining the isotopic age of the zircons

therefore enables us to confirm the practical ages of the Silurian to Devonian radiolarian zones.

In order to determine the age of upper Silurian to Lower Devonian radiolarian zones, we have undertaken radiometric dating of magmatic zircons within the radiolarian bearing beds of the Yoshiki Formation in the Fukuji area, Takayama City, Southwest Japan.

## Geological outline of the Fukuji area

The study area is in the Hida Gaïen belt, Southwest Japan. The Hida Gaïen belt is composed largely of Ordovician to Cretaceous sedimentary and volcanic rocks with minor amounts of ultramafic rocks and crystalline schist. This belt occurs in a narrow zone between the Hida belt, which is mainly composed of Paleozoic gneiss and meta-granite,



**Figure 1.** Index map of the study area. The topographical map is part of the 1:25,000 scale map sheet “Yakedake” published by the Geospatial Information Authority of Japan.

and the Mino belt, which is composed of Jurassic to Cretaceous accretionary complexes.

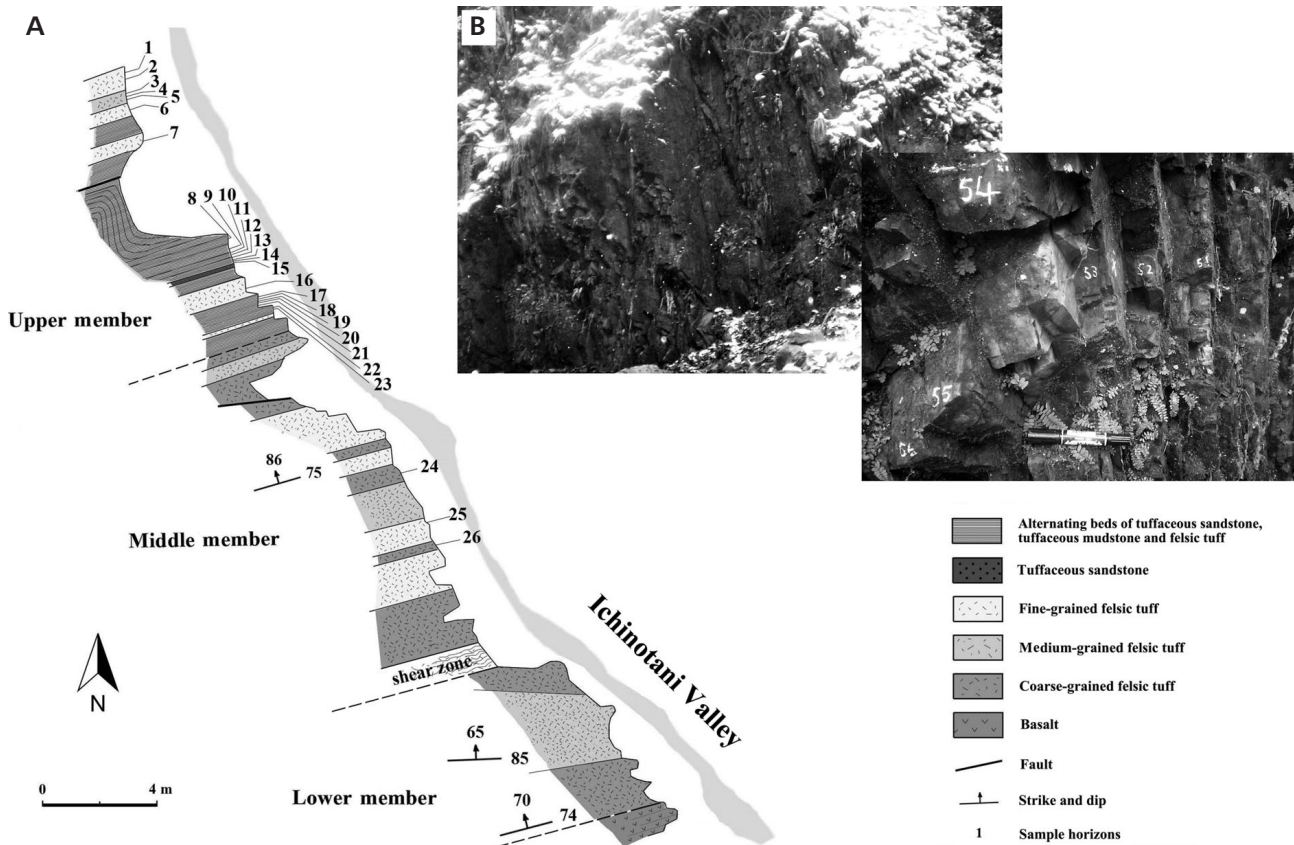
The Paleozoic rocks in the Fukuji area trend ENE and are divided into the following five formations in ascending order; 1) upper Silurian (?) to Devonian Yoshiki Formation (felsic tuff and tuffaceous clastic rocks), 2) Devonian Fukuji Formation (mainly limestone), 3) Carboniferous Ichinotani Formation (mainly limestone), 4) Lower Permian Mizuyagadani Formation (mainly clastic rocks), 5) Lower Permian Sorayama Formation (mainly mafic volcanic rocks) (e.g. Igo 1990, Tsukada & Takahashi 2000). The Yoshiki Formation is unconformably overlain by the Fukuji Formation (Igo 1990, Kurihara 2003). Although the Fukuji, Ichinotani, and Mizuyagadani formations are in fault contact with each other, they are likely to form conformable or unconformable succession. The Sorayama Formation conformably overlies the Mizuyagadani Formation (Tsukada *et al.* 1999, Tsukada & Takahashi 2000). The Paleozoic formations in the Fukuji area are folded around the axis that plunges steeply southeast, and are cut by several younger North-south sub-vertical oblique-slip faults (Tsukada *et al.* 1999, Tsukada & Takahashi 2000). All these formations are intruded by many small dikes

of felsic to intermediate rocks, and are unconformably covered by Cenozoic volcanoclastic rocks.

The Yoshiki Formation is mainly composed of alternating beds of tuffaceous sandstone, tuffaceous mudstone and felsic tuff and it yields well-preserved radiolarian fossils. Although this formation was once believed to be Ordovician in age, based on the ostracods from a mudstone float beside outcrop (Igo *et al.* 1980), it is now assigned to from upper Silurian to Lower Devonian as a result of recent radiolarian studies (Kurihara 2004).

### Geological description of the Yoshiki Formation

The stratotype section of the Yoshiki Formation (Igo *et al.* 1980, Tsukada *et al.* 1999) along the Ichinotani Valley, south hillside of Mt. Sorayama, Fukuji area was examined in this study. Here, a 30 m thickness of fine- to coarse-grained felsic tuff and alternating beds of tuffaceous sandstone, tuffaceous mudstone and felsic tuff is continuously exposed. The rocks of this formation can be divided into lower, middle, and upper members. The



**Figure 2.** Route map showing lithology (a) and photographs showing the mode of occurrence of the alternating beds of fine-grained felsic tuff and tuffaceous mudstone in the upper member (b) of the Yoshiki Formation.

middle and lower members are mostly made up of bedded felsic tuff intercalated with characteristic coarse-grained tuff layers. The upper member consists mainly of alternating beds of tuffaceous sandstone, tuffaceous mudstone and felsic tuff. This formation, which trends east and dips steeply north, exhibits graded beddings indicating northward facing. The lower member is in fault contact with the middle member with a remarkable shear zone. The shear zone, one meter wide, is composed of fissile muddy cataclasite that trends NW-SE. The upper member conformably overlies the middle member. The upper member is folded with an axis that plunges steeply northeast.

The lower member consists of bedded medium- to coarse-grained felsic tuff (Fig. 3). Each bed, 5 to 7 cm thick, strikes E-W to N 74° E and dips 65° to 70° north. Well-bedded fine- to coarse-grained felsic tuff is the major facies of the middle member. The felsic tuff exhibits graded beddings indicating northward facing, strikes N 75° E and dips 86° north. Each bed is from 7 to 10 cm thick. The felsic tuff of the lower and middle members includes many phenocrysts of euhedral to subhedral laths of plagioclase, biotite, quartz and zircon with scattered flakes of opaque minerals, volcanic rock fragments and flattened

pumice. A swirly mass of irregularly shaped altered volcanic glass shards is seen in some parts in the matrix of the tuff. Zircons are included not only in the matrix but also in the volcanic rock fragments. The upper member consists of alternating beds of tuffaceous sandstone, tuffaceous mudstone and fine-grained felsic tuff. The beds are graded, indicating northward facing, and each bed is from 5 to 10 cm thick. The fine-grained felsic tuff and tuffaceous mudstone generally includes radiolarian fossils (Fig. 4). Layers of coarse-grained felsic tuff, less than 7 cm thick, with numerous felsic volcanic rock fragments are intercalated in the alternating beds. The tuff of this member includes phenocrysts of euhedral to subhedral laths of plagioclase, biotite, quartz and zircon with scattered flakes of opaque minerals, volcanic rock fragments and flattened pumice similarly with that of the lower and middle members.

### Radiolarian fossils

Radiolarians were recovered from the fine-grained felsic tuff and the tuffaceous mudstone by etching in dilute hydrofluoric acid for 24 hours. Individual radiolarians liberated from the matrix were washed and sieved at 63 and

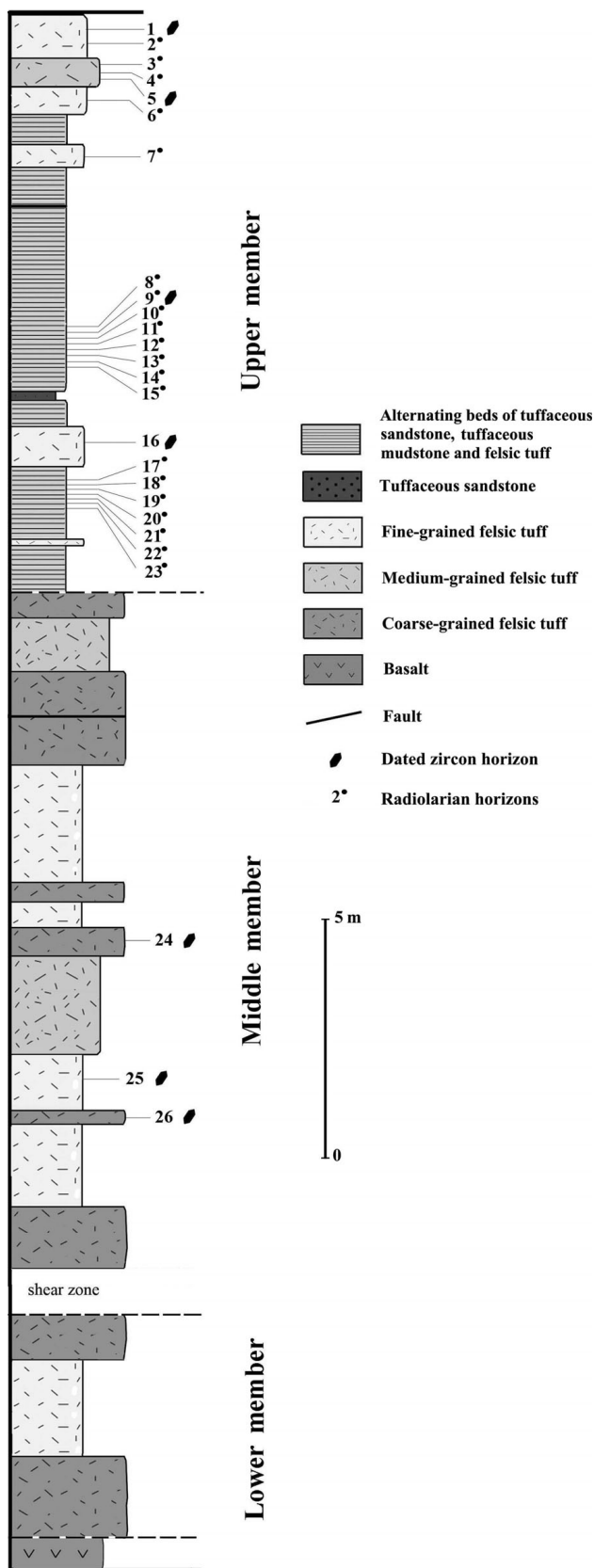


Figure 3. Columnar section of the Yoshiki Formation.

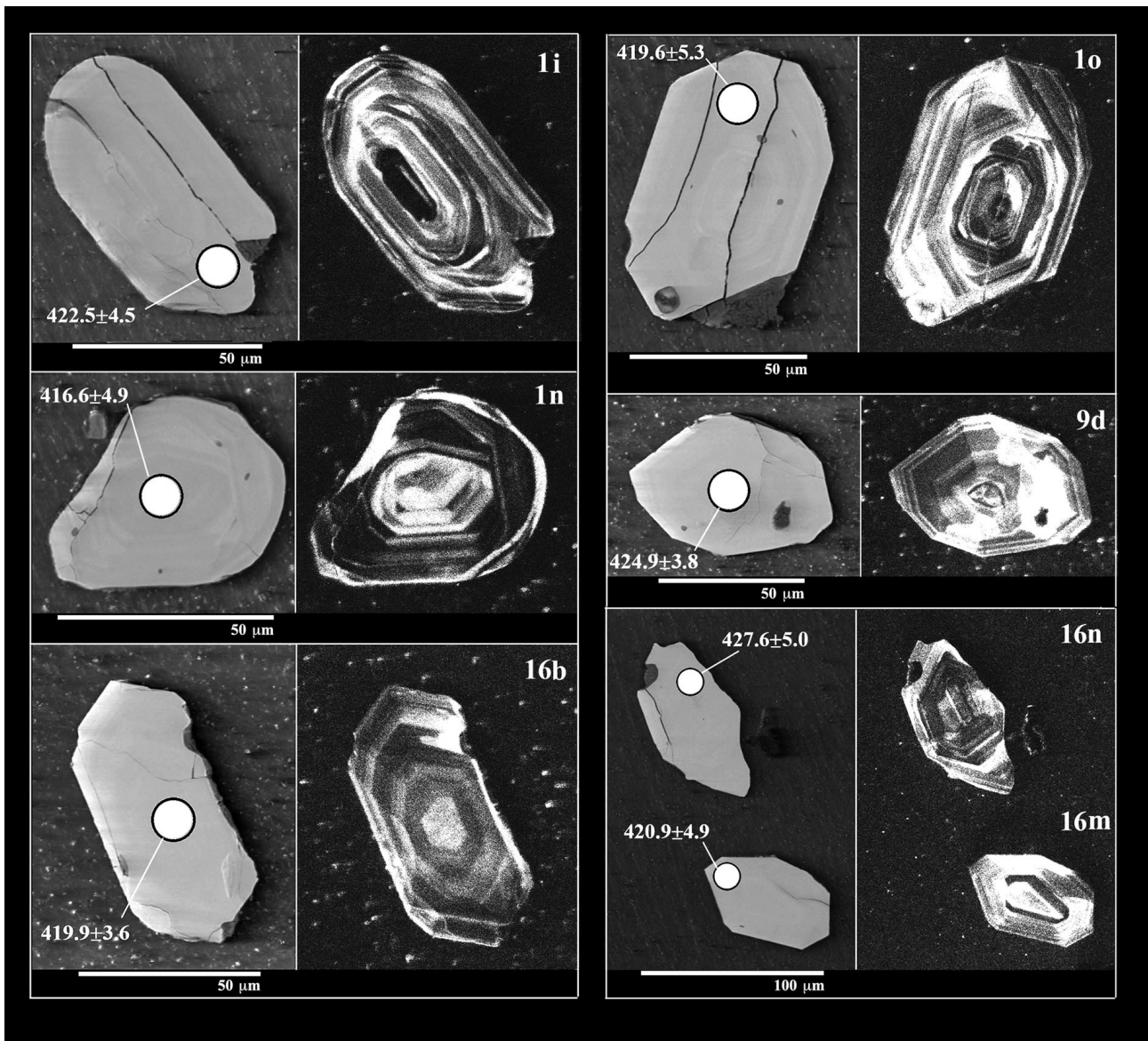
108-micron fractions. Radiolarians were picked from the dried residues and identified with the aid of reflected light and scanning electron microscopes. Well-preserved radiolarians were obtained only from the upper member, but some poorly-preserved unidentifiable radiolarians were also extracted from the middle member. The following species of radiolarians were identified from 15 tuffaceous mudstone and 5 fine-grained felsic tuff horizons of the upper member (Fig. 5); *Oriundogutta(?) kingi*, *O.(?) varispina* Noble, 1994, *Zadrappolus yoshikiensis* Furutani, 1990, *Z. tenuis* Furutani, 1990, *Z. hitoeganensis* Furutani, 1990, *Z. lunaris* Noble, 1994, *Z.(?) nudus* Kurihara 2007, *Z.(?) sp. in* Kurihara, 2007, *Futobari solidus* Furutani, 1990, *F. morishitai* Furutani, 1990, *Rotasphaera(?) sp.*, *Ceratoikiscum armiger* Furutani, 1990. The most characteristic species of this assemblage is *Z. yoshikiensis*, *Z. tenuis*, *Z.(?) nudus*, and *F. solidus*. The species present, *Z. yoshikiensis*, *Z. tenuis*, *F. solidus* and *F. morishitai*, are characteristic of the *Z. yoshikiensis* assemblage of Furutani (1990) that have been previously presumed to be latest Silurian to early Devonian (Furutani 1990). Kurihara (2007) proposed the *F. solidus*-*Z. tenuis* assemblage as an equivalent of the *Z. yoshikiensis* assemblage. Kurihara (2007) supposed that the *F. solidus*-*Z. tenuis* assemblage ranges from Přídolian to Pragian.

### Description of zircons and U-Pb SHRIMP age

Eight rock samples, Nos. 1, 5, 9 and 16 from upper member and Nos. 24 to 26 from middle member, were used for U-Pb SHRIMP dating. Each sample (*ca* 1 kg) was collected from a single outcrop. Zircons were concentrated using conventional mineral-separation techniques, including crushing and pulverizing, followed by separation using hand magnetic and heavy liquid techniques. About 233 zircon grains were mounted with standard materials in a mega-mount epoxy resin disc (Niihara *et al.* 2010), and diamond polished to expose the interior. In order to investigate internal structures of individual zircon grains, backscattered electron (BSE) images were obtained by electron probe microanalyzer (EPMA) and cathodoluminescence (CL) images by scanning electron microscope (SEM) at Nagoya University. Both images provided a guide for selection of the SHRIMP spots.

Observation and interpretation of zircon morphology is critical for understanding the isotopic data. For example, euhedral, concentric oscillatory zoning (in CL) and euhedral, prismatic external morphology are generally regarded as evidence for crystallization of zircon from a magma. In contrast, zircon that forms in a high-grade metamorphic environment tends to have patchwork zoning and a multifaceted, equant, tabular external morphology (Kroner *et al.* 2000, Pidgeon *et al.* 2000, van Breemen *et al.* 1986, Vavra *et al.* 1999). At very high metamorphic grade, these distinctions of origin become





**Figure 6.** Scanning electron microscope (SEM, left side) and cathode luminescence (right side) images of representative zircons from the felsic tuff of the Yoshiki Formation. White circles on the SEM images show the SHRIMP analytical spots.

of metamorphic origin. However, equant igneous zircons can be distinguished from metamorphic zircons by their simpler crystallography (lower-order crystal faces) and concentric oscillatory zoning in CL. Equant zircons of detrital origin in sedimentary rocks tend to be spherical (not discoidal), usually have pitted or frosted, rounded surfaces (not flat faces), and truncated zoning in CL.

Fifteen zircon grains from sample 1, one from sample 5, six from sample 9, fifteen from sample 16, two from sample 24, three from sample 25, fifty-one from sample 26 were analyzed. The analyzed zircons occur in different colors, including brown, yellow and colorless. The zircons are about 70 μm in length and their length-to-width ratio is ~2–1.5. These zircons mostly occur as subhedral to

euhedral prisms, and commonly contain distinct cores with concentric zoning, consistent with crystallization from a viscous magma, and overgrowths (Fig. 6). The U-Pb zircon analyses were performed at 74 analytical spot on 67 grains. U-Pb measurement was conducted using the SHRIMP at National Institute for Polar Research. An O<sub>2</sub> primary ion beam of ~1.5 was used to sputter an analytical spot of 10 μm diameter on the polished mount. The procedures for Pb and U isotopic analyses of zircon follow (Williams 1998, Horie *et al.* 2006). In this study, TEMORA2 (<sup>206</sup>Pb/<sup>238</sup>U age: 416.78 ± 0.33 Ma (Black *et al.* 2004)) and SL13 (U concentration: 238 ppm, Claoué-Long *et al.* 1995) were used as standard materials for the U-Pb analysis. The U-Pb data were reduced by using the SQUID2 Excel macro

of (Ludwig 2009). A correction for common Pb was made on the basis of the measured  $^{204}\text{Pb}$  and the model for common Pb compositions proposed by Stacey & Kramers (1975). The pooled ages presented in this study are all after correction for common Pb and were calculated using the Isoplot/Ex software (Ludwig 2008). The SHRIMP analyses yielded concordant U-Pb data are scattered from *ca*  $410.2 \pm 4$  to  $434.3 \pm 5.6$  Ma (Fig. 8). Weighted means of  $^{206}\text{Pb}/^{238}\text{U}$  ages are *ca*  $420.5 \pm 2.5$  Ma (95% confidence) in the upper member, and at *ca*  $421.0 \pm 1.9$  Ma (95% confidence) in the middle member (Fig. 8).

## Discussion

### Origin of zircons

The felsic tuff of the Yoshiki Formation is of volcanic origin as evidenced by: (1) many euhedral to subhedral crystals of plagioclase, quartz and biotite are contained in the tuff, (2) many fragments of volcanic rock and flattened pumice parallel to the bedding plane are included, (3) the presence of irregularly shaped altered volcanic glass shards. All of the dated zircons occur as polygonal prisms, and show simple crystallography and concentric oscillatory zoning in CL. In addition, many volcanic rock fragments containing zircons are included in the tuff. If some of the dated zircons are detrital from an older source of rocks than the volcanism, bi- to multi-modal peaks of ages would be expected, however the results of SHRIMP dating clearly show a single peak of age around 420 Ma. This strongly suggests that the dated zircons were brought together with the other volcanic materials such as euhedral to subhedral crystals, volcanic rock fragments, pumice and glass, and their age is considered to be nearly same with the age of the age of the rock's sedimentation.

### Range of *F. solidus*-*Z. tenuis* assemblage

Noble (1994) considered that the *Z. yoshikiensis* assemblage (Furutani 1990) of the Yoshiki Formation could be correlated with the upper part of her *Praespongocoelia-Stylosphaera(?) magnaspina* zone to *St.(?) magnaspina* zone from Marathon uplift, USA due to the abundance of *Z. yoshikiensis* and *Z. tenuis*. These species are, however, not diagnostic because they range through the *St.(?) magnaspina* zone and into the *Devoniglansus unicus-Rotaspheera* zone as Noble (1994) has mentioned. In addition, *Z. yoshikiensis* and *Z. tenuis* were also reported from horizons above the *Pseudospongoprimum sagittatum* assemblage (Umeda 1998) and the *Ps. tauversi* assemblage (Kurihara 2004) which are correlative to the *D. unicus-Ps.(?) tauversi* zone of Noble (1994) (Kurihara 2004, Umeda

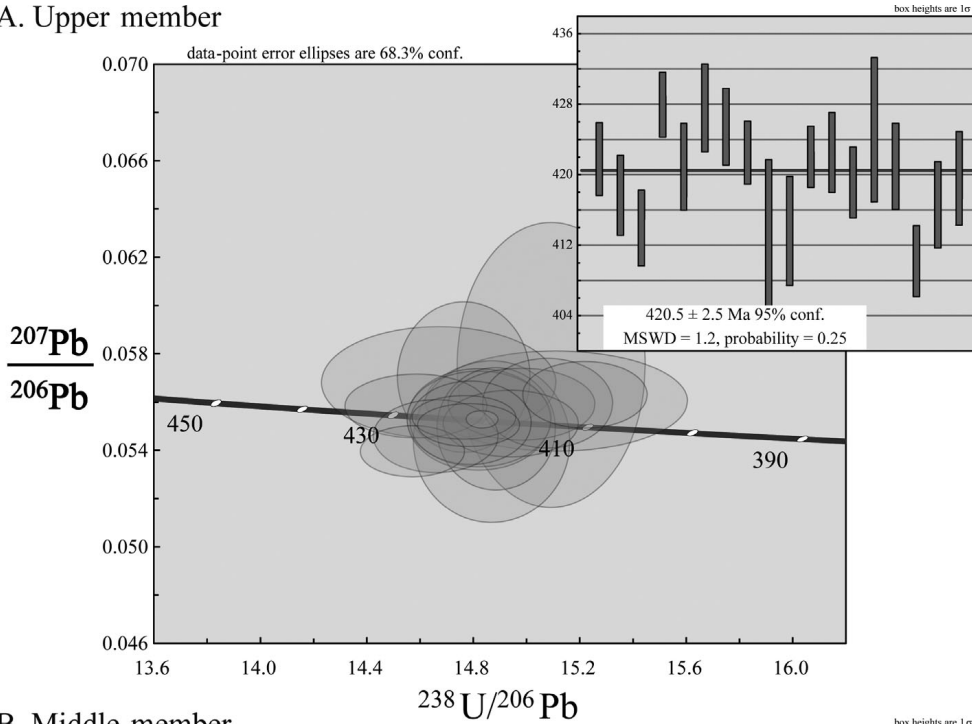
Sample No.	Grain No.	SHRIMP age		Sample No.	Grain No.	SHRIMP age			
		$^{238}\text{U}/^{206}\text{Pb}$ (Ma)	Error ( $\pm$ )			$^{238}\text{U}/^{206}\text{Pb}$ (Ma)	Error ( $\pm$ )		
Upper member	1	a	423.7	1.8	Middle member	24	a	419.5	5.1
		b	434.3	5.6			b	422.7	5.5
		c	422.6	3.1			b	418.4	6.3
		d	419.7	3.4		25	a	417.9	8.1
		e	421.4	2.8			a	424	8.2
		f	413.1	8.6			b	426.2	5.5
		g	413.6	6.2		c	412.8	5.5	
		h	422	3.5		26	a	427.9	5.4
		i	422.5	4.5			b	414.5	4.6
		j	419.1	4			c	419.1	9.8
		k	425.1	8.2			d	412.3	4.5
		l	421	4.9			e	425	4.7
		m	410.2	4			f	412.9	5.5
		n	416.6	4.9			f	426.3	5.1
	o	419.6	5.3	g	421.4		4.6		
	5	a	420.7	5.2	h		413	5.5	
9	a	423.8	5.5	i	427.6		6.1		
	b	413.1	5.8	j	422.3		4.8		
	c	422.3	6.5	k	419.9		5.6		
	d	424.9	3.8	l	426.8		8		
	e	416.7	3	m	426.7	4.7			
	f	427.3	5.4	n	419.9	7.3			
	g	418.8	3.2	o	415.8	5			
	h	420.8	4	p	431.6	4.8			
	i	422.5	3.6	q	427.7	7.3			
	j	423.3	2.4	r	421.3	6.3			
16	a	421.7	3.3	s	423.1	5.3			
	b	419.9	3.6	t	414.2	7.6			
	c	423.3	2.8	u	422.6	4.7			
	d	425	3.5						
	e	423.8	2.6						
	f	419.2	4.2						
	g	420.5	4						
	h	417.5	2.1						
	i	421.8	4.1						
	j	417.7	4.5						

Figure 7. A list of SHRIMP U-Pb ages for zircons from the Yoshiki Formation.

1998). Therefore, the *Z. yoshikiensis* assemblage is not correlated with the *St.(?) magnaspina* zone of Noble (1994).

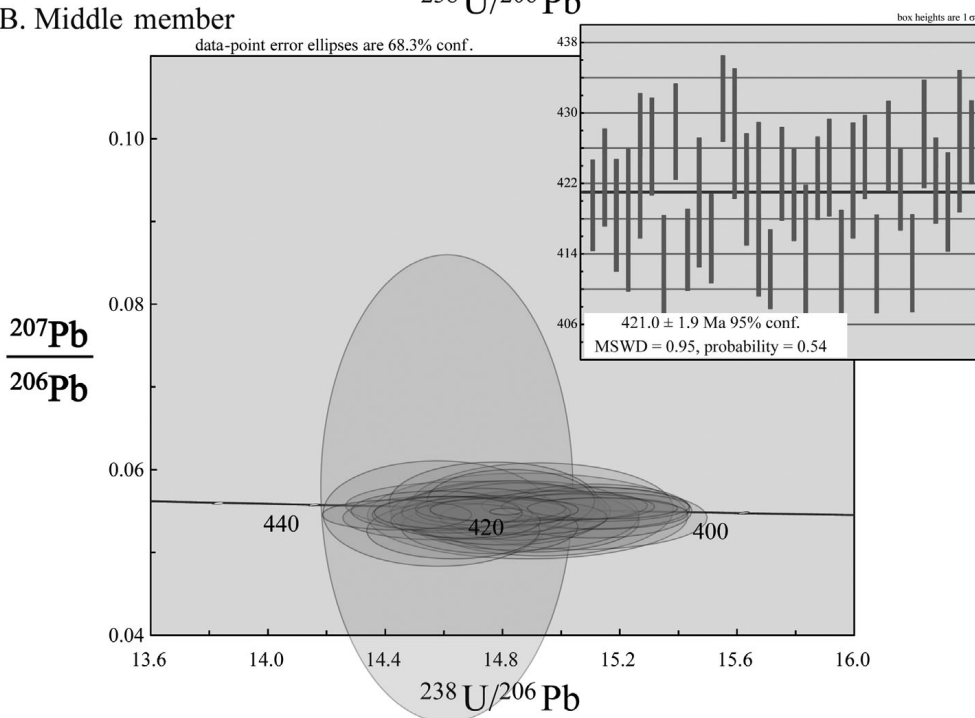
Umeda (1998) and Kurihara (2004) put the equivalents of the *Z. yoshikiensis* assemblage (*F. solidus* assemblage in Umeda 1998 and the *F. solidus*-*Z. tenuis* assemblage in Kurihara 2004) above the *D. unicus-Ps.(?) tauversi* zone (*Ps. sagittatum* assemblage in Umeda 1998 and *Ps. tauversi* assemblage in Kurihara 2004) based on biostratigraphic correlation. The *D. unicus-Ps.(?) tauversi* zone has been assigned to the Přídolian because of the co-occurrence of a Ludlowian-Přídolian conodont fauna with in (Noble 1994), and Kurihara (2004) regarded the lower limit of the *F. solidus*-*Z. tenuis* assemblage as Přídolian. However, the co-yielding of the *F. solidus*-*Z. tenuis* assemblage and *ca* 420 Ma zircons in the present study suggests that the lower limit of the *F. solidus*-*Z. tenuis* assemblage might be before the Ludlowian, and therefore the *D. unicus-Ps.(?) tauversi* zone should more correctly be assigned to the lower Ludlowian.

A. Upper member



**Figure 8.** Tera-Wasserburg Concordia diagrams of zircon SHRIMP data. The U-Pb ages from analyses shown of error ellipse shading.

B. Middle member



Aitchison *et al.* (1996) provided a U-Pb SHRIMP age of  $408.9 \pm 7.6$  Ma using zircons from tuffaceous rock of the G4 Member (Yasui 1984) in the Kurosegawa terrane, Konomori area, Shikoku Island, Japan. They reported *F. solidus* and *F. morishitai* from the same locality as the zircons and so suggested that the *Palaeoscenidium ishigai* assemblage was assigned to the Silurian based on the geological time scale that existed at the time (Odin 1994).

But, Kurihara (2007) pointed out that the age  $408.9 \pm 7.6$  Ma is equivalent to the Pragian with error bars extending from the uppermost Přídolian into the Emsian, based on a reevaluation using the latest geologic time scale by Gradstein *et al.* (2004). In addition, the precise stratigraphic level of the dated zircon is unknown and it is not clear whether the age is practical in thinking the boundary between the *F. solidus*-*Z. tenuis* assemblage



horizons radiolarians and zircon	YOSHIKI FORMATION																									
	Upper member																							Middle Member		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
<i>Oriundogutta</i> (?) <i>kingi</i>																										
<i>Oriundogutta</i> (?) <i>varispina</i>																										
<i>Zadrappolus yoshikiensis</i>																										
<i>Zadrappolus tenuis</i>																										
<i>Zadrappolus hitoeganensis</i>																										
<i>Zadrappolus lunaris</i>																										
<i>Zadrappolus</i> (?) <i>nudus</i>																										
<i>Zadrappolus</i> (?) sp.																										
<i>Futobari solidus</i>																										
<i>Futobari morishitai</i>																										
<i>Rotasphaera</i> (?) sp.																										
<i>Ceratoikiscum armiger</i>																										
U-Pb SHRIMP age of zircon (Ma)	410.2±4 to 434.3±5.6		420.7±5.2				413.1±5.8 to 423.8±5.5				417.5±2.1 to 427.9±3.7				418.4±6.3 to 422.7±5.5				412.8±5.5 to 426.2±5.5				412.3±4.5 to 427.9±5.4			

Figure 9. Summary of radiolarian and dated zircon horizons.

and the *Pa. ishigai* assemblage. Although Kurihara (2007), in his summary of radiolarian studies, suggested an Emsian upper limit for the *F. solidus*-*Z. tenuis* assemblage, the practical range of this assemblage is still open to discussion.

Dating the zircons in radiolarian-bearing tuffaceous rocks has enabled us to ascribe practical ages to the radiolarian zones in our study area. Detailed comparison between radiolarian assemblages and zircon radiometric ages is a technique that could be used elsewhere to determine the practical range of other early Paleozoic radiolarians. The technique has the capability of refining and making more accurate the dating of many radiolarian zones worldwide, and potentially of changing the direction of the entire study of radiolarian biostratigraphy.

### Systematic palaeontology

Order Spumellaria Ehrenberg, 1875

Family Inaniguttidae Nazarov & Ormiston, 1984, emend. Noble, 1994

#### Genus *Oriundogutta* Nazarov, 1988

*Type species.* – *Astroentactinia ramificans* Nazarov, 1975.

#### *Oriundogutta* (?) *kingi* Noble, 1994

Figure 11A

- 1988 *Inanihella macroacantha* (Rüst, 1892). – Nazarov, p. 209, pl. XII, fig. 1.
- 1993 *Inanihella macroacantha*? (Rüst 1892). – Nazarov & Ormiston, p. 37, pl. 2, figs 6–8.
- 1994 *Oriundogutta* (?) *kingi* Noble, p. 31, pl. 6, figs 1, 4.
- 1998 *Oriundogutta* (?) *kingi* Kurihara & Sashida, pl. 1, fig. 7.

2000 *Oriundogutta* (?) *kingi* Kurihara & Sashida, p. 58, pl. 1, figs 5, 6.

2003 *Oriundogutta* (?) *kingi* Kurihara, fig. 8–2.

1996 *Oriundogutta*? sp. cf. *O. kingi* Noble, 1994. – Aitchinson, Hada, Ireland & Yoshikura, p. 67, pl. 2, fig. 15.

2007 *Oriundogutta* (?) *kingi* Kurihara, p. 229, pl. 1, figs 15–18.

*Remarks.* – This species is characterized by one thick cortical shell with 15 to 20 long robust spines per hemisphere. Spines are highly tapered at the proximal end and contain four to five grooves. Cortical shell is very large in diameter (250 µm). Medullary shell is connected to cortical shell by rod-shaped primary bars. This species is superficially similar to species of *Zadrappolus*, especially *Zadrappolus yoshikiensis*. However, the structure and number of the medullary shells is still unclear in *Oriundogutta* (?) *kingi*, so its taxonomic position is tentative. This species differs from *Oriundogutta* (?) *varispina* Noble in possessing a larger number of robust spines and its shell is slightly smaller in diameter.

*Range and occurrence.* – Upper Silurian. Hitoegane area in the Hida-gaien terrane; Southern Urals; Marathon uplift in west Texas; Yoshiki Formation in the Hida-gaien terrane.

#### *Oriundogutta* (?) *varispina* Noble, 1994

Figure 11B–F

1994 *Oriundogutta* (?) *varispina* Noble, p. 31, pl. 6, figs 2, 3, pl. 9, fig. 4.

2007 *Oriundogutta* (?) *varispina* Kurihara, p. 229, pl. 1, figs 19, 20.

*Remarks.* – This species is characterized by a thick, latticed large cortical shell 270–300 µm in diameter with 6 or more

		FURUTANI (1990)	NOBLE (1994)	UMEDA (1998)	KURIHARA (2004)	THIS STUDY		
system	series/stage	radiolarian assemblages	radiolarian zones	radiolarian zones	radiolarian assemblages	radiolarian assemblages		
DEVONIAN	Late	359 Famennian	unzoned	unzoned	unzoned	unzoned		
		374 Frasnian						
		385 Givetian						
	Middle	392 Eifelian		unzoned	<i>Protoholoeciscus hindea</i>	unzoned	unzoned	
		398 Emsian		<i>Stylosphaera ? sp. C</i>	<i>Glanta fragilis</i>			
	Early	407 Pragian		<i>Stylosphaera ? sp. A-B</i>	<i>Trilonche (?) sp. A</i>	<i>Pc. intermedia- Pc.igoii</i>	<i>Pc. intermedia- Pc.igoii</i>	
		411 Lockhovian		<i>Z. yoshikiensis</i>	<i>Futobari solidus</i>	<i>Pl. ishigai- D. furutani</i>	<i>Pl. ishigai- D. furutani</i>	
		416 Pridolian			unzoned	<i>F. solidus- Z. tenuis</i>	<i>F. solidus- Z. tenuis</i>	
		419 Ludfordian			<i>Devoniglansus unicus- Ps. (?) tauversi</i>	<i>Pseudospongoprimum sagittatum</i>		<i>Pseudospongoprimum tauversi</i>
	Ludlow	421 Gorstian			<i>Sp. parvus</i> <i>Sp. kamitakarensis</i>	unzoned		<i>St. (?) magnaspina</i>
423 Homerian		<i>Fusulfanus osobudaniensis</i>	<i>Praespongocoelia- St. (?) magnaspina</i>					
SILURIAN	Late	unzoned	unzoned	unzoned	unzoned	unzoned		
							Ludlow	<i>Devoniglansus unicus- Rotasphaera</i>
	Wenlock	<i>St. (?) magnaspina</i>						<i>Z. spinosus- Pr. parva</i>
		<i>Praespongocoelia</i>						<i>St. (?) magnaspina</i>
	Middle	unzoned					<i>Pa. (?) asymmetrica</i>	<i>St. (?) magnaspina</i>

Figure 10. Comparison between the radiolarian assemblages and zones of Furutani (1990), Noble (1994), Umeda (1998), Kurihara (2004) and this study. Numerical ages (Ma) are from Gradstein *et al.* (2004).

robust external spines per hemisphere. The spine of this species, which is weakly grooved at its proximal portion and slightly to highly tapered, bears a strong morphological similarity to that of *Oriundogutta(?) kingi* Noble. This species, however, differs from *O. (?) kingi* in having thinner and fewer external spines.

**Range and occurrence.** – Uppermost Silurian. Hitoegane area in the Hida-gaien terrane; Marathon uplift in west Texas; Yoshiki Formation in the Hida-gaien terrane.

**Genus *Zadrappolus* Furutani, 1990**

**Type species.** – *Zadrappolus yoshikiensis* Furutani, 1990.

***Zadrappolus yoshikiensis* Furutani, 1990**

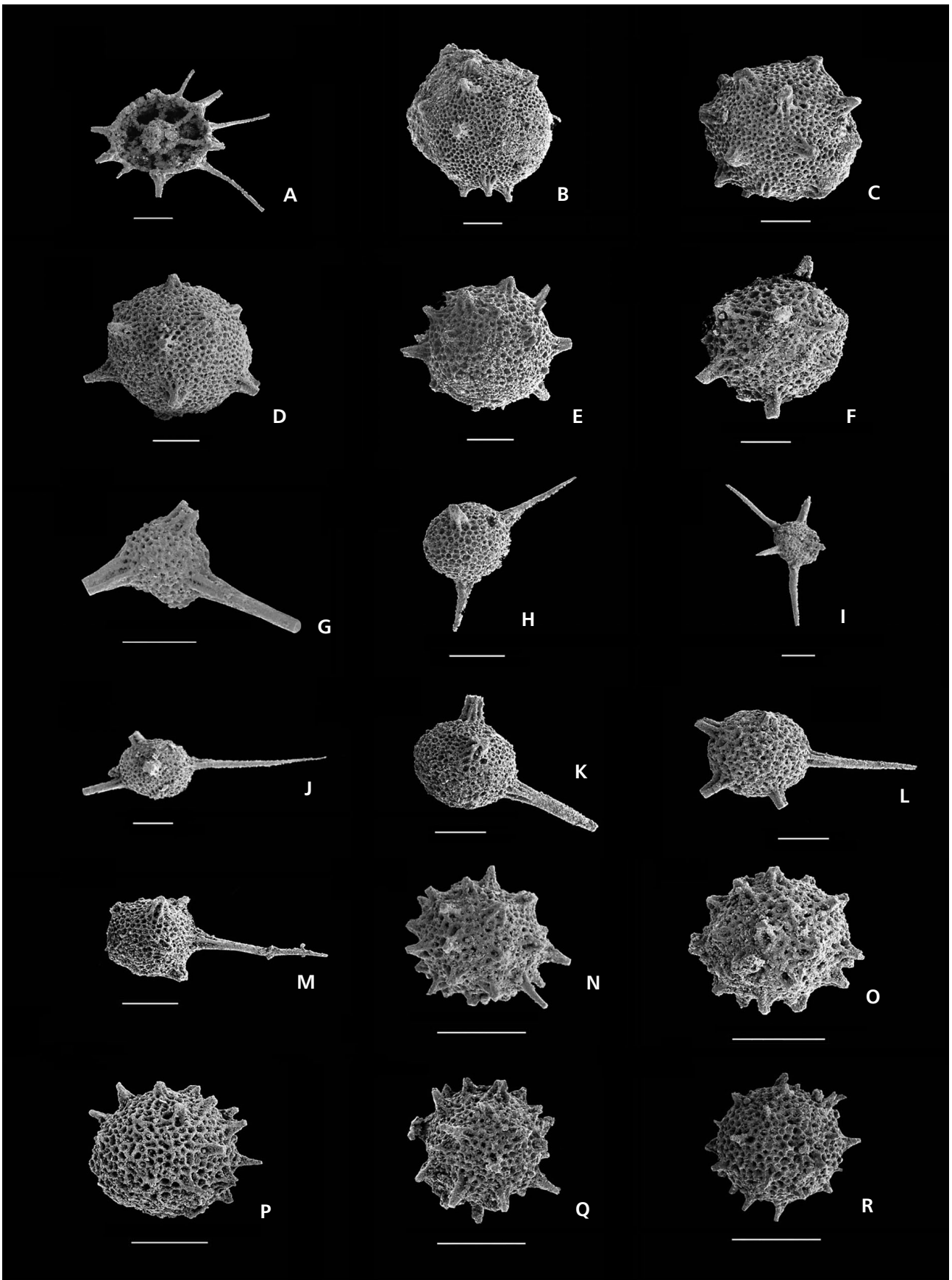
Figures 11N–R, 12A–D

1990 *Zadrappolus yoshikiensis* Furutani, pp. 35, 36, pl. 2, figs 4–6; pl. 3, figs 1, 2.

- 1994 *Zadrappolus yoshikiensis* Noble, p. 32, pl. 6, figs 14–16.
- 1997 *Zadrappolus yoshikiensis* Umeda, p. 421, pl. 4, fig. 10.
- 1998 *Zadrappolus yoshikiensis* Kurihara & Sashida, pl. 1, figs 1, 2.
- 2000 *Zadrappolus yoshikiensis* Kurihara & Sashida, p. 58, pl. 1, figs 1, 2.
- 2007 *Zadrappolus yoshikiensis* Kurihara, p. 229, pl. 1, figs 21–24.

**Remarks.** – This species is characterized by a spherical cortical shell having 10 to 15 strongly tapered spines per hemisphere. The cortical shell is latticed and 120 to 200 µm in diameter (150 µm in average) based on 8 specimens. In the proximal part of the spines, 4 to 6 grooves are shallowly developed. Although two medullary shells have been observed by Furutani (1990), detailed structures are unknown, especially in the inner medullary shell. *Zadrappolus tenuis* differs from *Z. yoshikiensis* in bearing long and cylindrical spines. *Zadrappolus yoshikiensis* is distinguished from

Figure 11. A – *Oriundogutta(?) kingi* Noble. 1, horizon 23. • B–F – *Oriundogutta(?) varispina* Noble. B – horizon 13; C – horizon 18; D – horizon 19; E – horizon 8; F – horizon 8. • G–K – *Futobari solidus* Furutani. G – horizon 23; H – horizon 15; I – horizon 11; J – horizon 10; K – horizon 10. • L, M – *Futobari morishitai* Furutani. L – horizon 15; M – horizon 10. • N–R – *Zadrappolus yoshikiensis* Furutani. N – horizon 21; O – horizon 19; P – horizon 15; Q – horizon 17; R – horizon 17. Scale bars: 100 µm.



*Zadrappolus spinosus* and *Zadrappolus hitoeganensis* by its short, thin, and numerous cylindrical spines. *Zadrappolus lunaris* is similar to *Z. yoshikiensis* in external appearance; however, the former differs from the latter in having a larger cortical shell with a smaller number of conical spines. *Zadrappolus nudus* is distinguished from *Z. yoshikiensis* by possessing a larger cortical shell with few very small spines.

**Range and occurrence.** – Upper Silurian to Lower Devonian. Fukuji, Ise, Hitoegane areas and Yoshiki Formation in the Hida-gaien terrane; Konomori area of the Kurosegawa terrane in Southwest Japan; Marathon uplift in west Texas.

### ***Zadrappolus tenuis* Furutani, 1990**

Figure 12E–P

- 1990 *Zadrappolus tenuis* Furutani, pp. 36, 37, pl. 3, figs 3–6.  
1994 *Zadrappolus tenuis* Noble, p. 32, pl. 6, figs 10, 12, 13.  
1996 *Zadrappolus tenuis* Aitchinson, Hada, Ireland & Yoshikura, p. 67, pl. 1, figs 1, 6; pl. 2, fig. 6; pl. 3, figs 1, 2, 15.  
1998 *Zadrappolus tenuis* Kurihara & Sashida, pl. 1, fig. 3.  
1998 *Zadrappolus tenuis* Umeda, fig. 9-7.  
2000 *Zadrappolus tenuis* Kurihara & Sashida, p. 58, pl. 1, fig. 3.  
2007 *Zadrappolus tenuis* Kurihara, p. 230, pl. 1, figs 25–29.  
1990 Spumellaria gen. indet sp. I Wakamatsu, Sugiyama & Furutani, p. 177, pl. 3, figs 9–11.  
1994 *Zadrappolus* sp. aff. *Z. tenuis* Furutani, 1990. – Noble, p. 32, pl. 6, fig. 11.  
1994 *Inanihella* aff. *Macroacantha* (Rüst, 1892). – Li, p. 421, pl. 2, figs 13, 16.  
1997 *Zadrappolus(?) tenuis* Furutani, 1990. – Umeda, p. 421, pl. 2, figs 8–15.  
1997 *Zadrappolus(?)* sp. aff. *Z. tenuis* Furutani, 1990. – Umeda, p. 421, pl. 4, figs 11, 12.

**Remarks.** – Thick spherical, latticed shell 120–150 µm in diameter; 15 to 20 spines visible per hemisphere. Pores are rather regular in shape and size, round or ellipsoidal in shape. Spines are long and cylindrical but strongly tapered at proximal end with three grooves near base. This

species differs from *Zadrappolus spinosus* and *Zadrappolus hitoeganensis* in possessing thicker and less numerous spines.

**Range and occurrence.** – Upper Silurian to Lower Devonian. Fukuji, Ise, Hitoegane areas and Yoshiki Formation in the Hida-gaien terrane; Konomori, Gionyama, Kasami-gawa, and Jingamori areas in the Kurosegawa terrane; Marathon uplift in west Texas; Mayila area in west Junggar, China.

### ***Zadrappolus hitoeganensis* Furutani, 1990**

Figure 12Q

- 1990 *Zadrappolus?* *hitoeganensis* Furutani, pp. 37, 38, pl. 4, figs 5, 6; pl. 5, fig. 1.  
2007 *Zadrappolus hitoeganensis* Kurihara, p. 230, pl. 2, figs 5–7.

**Remarks.** – This species is composed of a spherical cortical shell with more than 20 short external spines per hemisphere. Cortical shell diameter 140 µm. Shape and size of the pores variable round, oval, rounded-triangular, and rounded-rectangular in shape, 5–9 in diameter. This species is somewhat similar to *Zadrappolus spinosus*, except that it has a rather small shell diameter and a smaller number of external spines.

**Range and occurrence.** – Upper Silurian to Lower Devonian. Fukuji, Hitoegane areas and Yoshiki Formation in the Hida-gaien terrane.

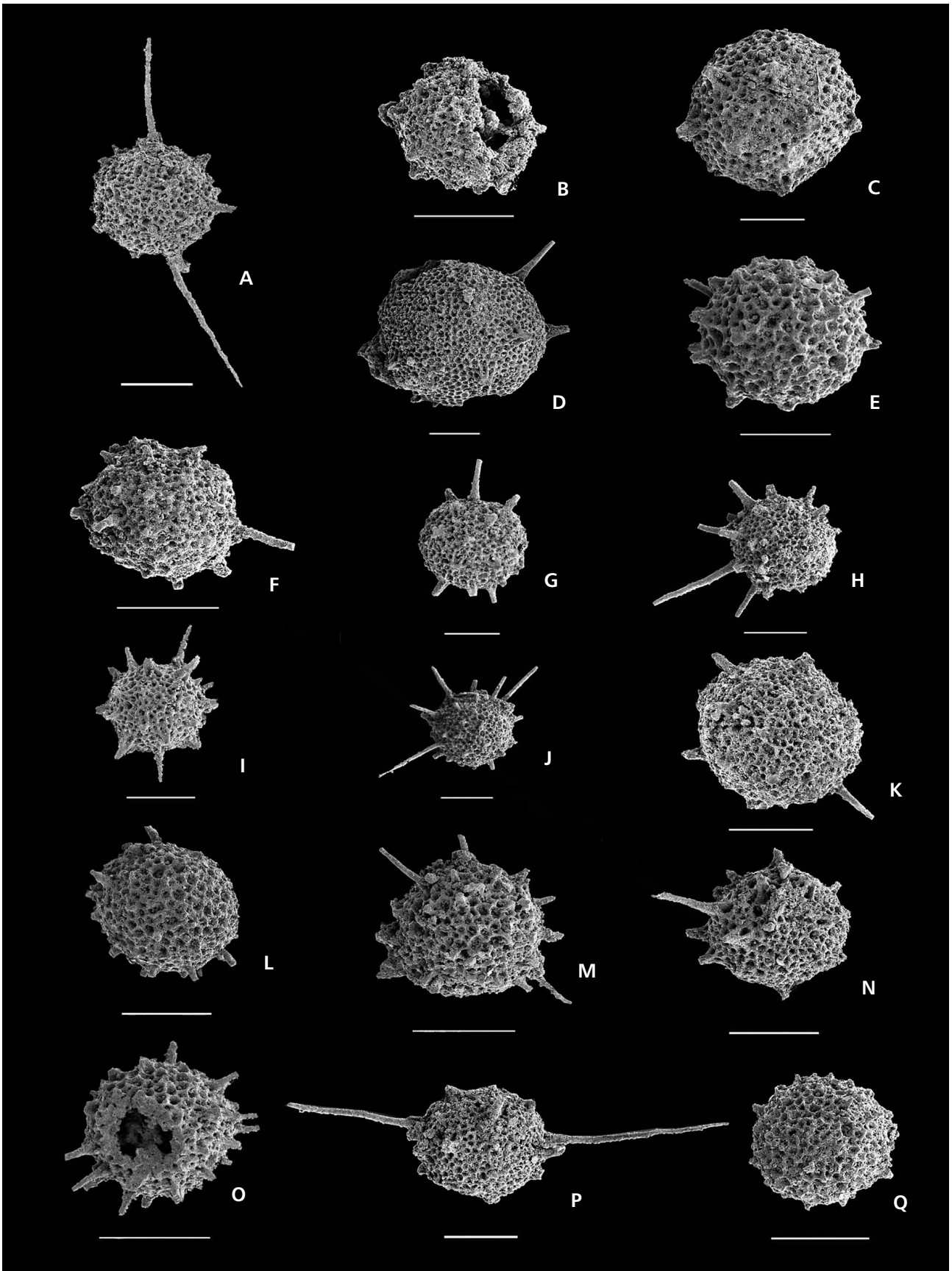
### ***Zadrappolus lunaris* Noble, 1994**

Figure 13A–D

- 1990 Spumellaria gen. indet. sp. D Wakamatsu, Sugiyama & Furutani, p. 175, pl. 8, fig. 4.  
1994 *Zadrappolus lunaris* Noble, pp. 32, 33, pl. 6, figs 7, 8; pl. 9, fig. 8.  
2007 *Zadrappolus lunaris* Kurihara, p. 230, pl. 2, figs 8–10.

**Remarks.** – Large spherical latticed cortical shell diameter 250 to 300 µm with approximately 10 spines per hemisphere. Spines short, conical, and tapered distally. Spine bases are approximately 15 to 20 µm in diameter and have 5 to 6 alternating grooves and ridges which are

**Figure 12.** A–D – *Zadrappolus yoshikiensis* Furutani. A – horizon 17; B – horizon 22; C – horizon 22; D – horizon 17. • E–P – *Zadrappolus tenuis* Furutani. E – horizon 19; F – horizon 15; G – horizon 15; H – horizon 10; I – horizon 12; J – horizon 10; K – horizon 15; L – horizon 4; M – horizon 17; N – horizon 17; O – horizon 10; P – horizon 17. • Q – *Zadrappolus hitoeganensis* Furutani; horizon 22. Scale bars: 100 µm.



approximately 50% of the spine length. Distal half of spines are rod-shaped and circular in cross section. Pore frames are irregular polygonal, approaching pentagonal, and measure 5 to 8 µm diameter. This species differs from other species of *Zadrappolus* in the presence of few short conical external spines. *Zadrappolus lunaris* is similar to *Z. yoshikiensis* in external appearance; however, the former differs from the latter in having a larger cortical shell with smaller number of conical spines.

**Range and occurrence.** – Uppermost Silurian to Lower Devonian. Hitoegane areas and Yoshiki Formation in the Hida-gaien terrane; Marathon uplift in west Texas.

***Zadrappolus(?) nudus* Kurihara, 2007**

Figure 13E–K, Q

- 1996 *Oriundogutta* sp. Aitchinson, Hada, Ireland & Yoshikura, pp. 66, 67, pl. 2, fig. 14.
- 2007 *Zadrappolus(?) nudus* Kurihara, pp. 230, 231, pl. 2, figs 11–14.

**Remarks.** – This species is easily distinguished from other species of *Zadrappolus yoshikiensis* by its very large cortical shell with only a few very small conical spines.

**Range and occurrence.** – Upper Silurian to Lower Devonian. Hitoegane area and Yoshiki Formation in the Hida-gaien terrane; Yoshinozawa-guchi area in the Kurosegawa terrane.

***Zadrappolus(?)* sp.**

Figure 13L–N

- 2007 *Zadrappolus(?)* sp. Kurihara, pp. 234, 235, pl. 2, figs 15, 16.

**Remarks.** – Large, spherical, irregular porous cortical shell with 13 to 19 short conical spines per hemisphere; spines are moderately deeply grooved in the proximal parts. This species is easily distinguished from other species of *Zadrappolus* by its very large cortical shell with many conical spines. *Zadrappolus(?)* sp. differs from *Z. yoshikiensis* in bearing long and cylindrical spines. *Zadrappolus yoshikiensis* is distinguished from *Zadrappolus spinosus* and

*Zadrappolus hitoeganensis* by its numerous short, thin, cylindrical spines. *Zadrappolus lunaris* is similar to *Z. yoshikiensis* in external appearance; however, the former differs from the latter in having a larger cortical shell with large number of conical spines. But, *Zadrappolus(?)* sp. differs from *Zadrappolus nudus* in bearing a large number of conical spines.

**Range and occurrence.** – Upper Silurian to Lower Devonian. Hitoegane area and Yoshiki Formation in the Hida-gaien terrane; Jingamori and Konomori areas in the Kurosegawa terrane.

**Genus *Futobari* Furutani, 1990**

**Type species.** – *Futobari solidus* Furutani, 1990.

***Futobari solidus* Furutani, 1990**

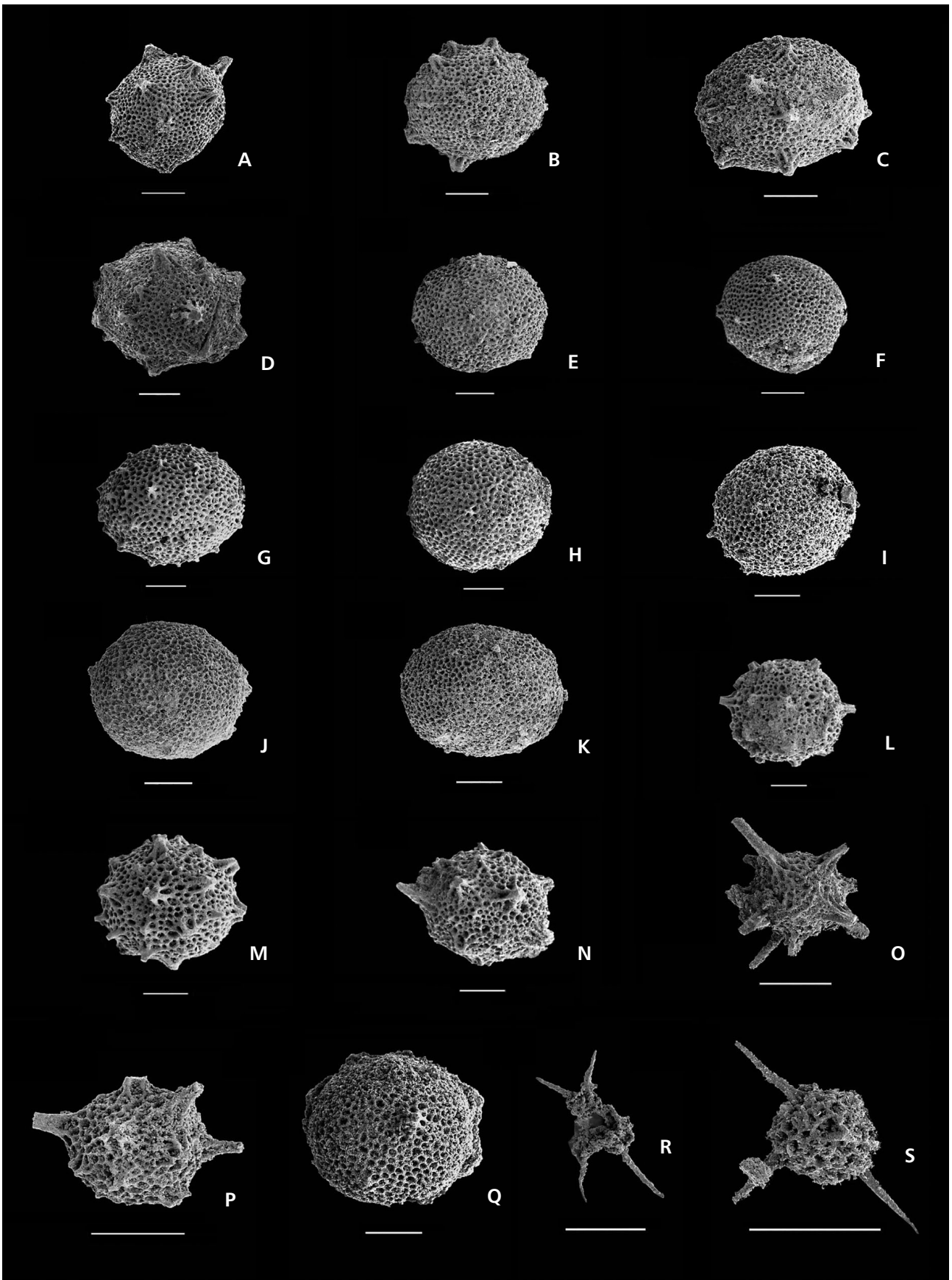
Figure 11G–K

- 1990 *Futobari solidus* Furutani, p. 34, pl. 1, figs 1–4.
- 1996 *Futobari solidus* Aitchinson, Hada, Ireland & Yoshikura, p. 65, pl. 6, figs 3, 8.
- 1997 *Futobari solidus* Umeda, p. 422, pl. 4, figs 14–17.
- 1998 *Futobari solidus* Umeda, figs 9–12.
- 2007 *Futobari solidus* Kurihara, p. 231, pl. 2, figs 17–21.
- 1990 Spumellaria gen. indet. sp. A Wakamatsu, Sugiyama & Furutani, p. 174, pl. 8, figs 1a, b.
- 1990 Spumellaria gen. indet. sp. E Wakamatsu, Sugiyama & Furutani, p. 175, pl. 8, fig. 5.

**Remarks.** – The cortical shell is single, spherical, latticed, and 100 to 150 µm in diameter. Pores of the cortical shell are regular in shape and size. Furutani (1990) noted that this species has doubled medullary shells; the outer medullary shell is spherical and consists of an irregular mesh of bars, whereas the features of the inner medullary shell are not clear. Main spines are very long, thick, gently tapered from the proximal to distal parts, and five to seven in number. The proximal part of the spines is deeply grooved, and the middle and distal parts are circular in the cross section. This species is distinguished from *Futobari morishitai* Furutani by possessing fewer main spines and slightly larger cortical shell diameter.

**Range and occurrence.** – Upper Silurian to Lower Devonian. Fukuji, Hitoegane areas and Yoshiki Formation in the

**Figure 13.** A–D – *Zadrappolus lunaris* Noble. A – horizon 14; B – horizon 4; C – horizon 3; D – horizon 6. • E–K, Q – *Zadrappolus(?) nudus* Kurihara. E – horizon 15; F – horizon 18; G – horizon 18; H – horizon 18; I – horizon 9; J – horizon 2; K – horizon 2; Q – horizon 7. • L–N – *Zadrappolus(?)* sp. Kurihara. L – horizon 20; M – horizon 19; N – horizon 19. • O, P – *Futobari morishitai* Furutani. O – horizon 17; P – horizon 15. • R – *Ceratoikiscum armiger* Furutani; horizon 17. • S – *Rotasphaera(?)* sp.; horizon 17. Scale bars: 100 µm.



Hida-gaien terrane; Konomori and Jingamori areas of the Kurosegawa terrane.

***Futobari morishitai* Furutani, 1990**

Figures 11L, M, 13O, P

- 1990 *Futobari morishitai* Furutani, p. 35, pl. 1, fig. 5, pl. 2, figs 1–3.  
1997 *Futobari morishitai* Umeda, pp. 421–422, pl. 2, fig. 16; pl. 4, fig. 13.  
1998 *Futobari morishitai* Umeda, fig. 9-6.  
2007 *Futobari morishitai* Kurihara, p. 231, pl. 2, figs 22, 23.  
1996 *Futobari* sp. cf. *F. morishitai* Furutani, 1990. – Aitchinson, Hada, Ireland & Yoshikura, p. 65, pl. 1, fig. 18; pl. 2, fig. 13; pl. 3, fig. 11.

*Remarks.* - This species characteristically has latticed moderately small cortical shell 150 to 200 µm in diameter. Shell has numerous small round pores. The spines are four to six external per hemisphere. The proximal part of the spines is deeply grooved. The external spines are slightly thinner than those of *Futobari solidus*.

*Range and occurrence.* – Uppermost Silurian to Lower Devonian. Fukuji, Hitoegane areas and Yoshiki Formation in the Hida-gaien terrane; Konomori, Yoshinosawa-guchi, and Jingamori areas in the Kurosegawa terrane.

Family Rotasphaeridae Noble, 1994,  
emend. MacDonald, 1998; Noble & Maletz, 2000;  
Won, Blodgett & Nestor, 2002

**Genus *Rotasphaera* Noble, 1994,  
emend. MacDonald, 1998**

*Type species.* – *Rotasphaera marathonensis* Noble, 1994.

***Rotasphaera* sp.**  
Figure 13S

- 1990 *Secuicollacta* sp. indet. Furutani, pl. 13, fig. 2.  
2007 *Rotasphaera* sp. Kurihara, pl. 2, fig. 25.

*Remarks.* – The specimens four or more robust tapering spines observed on per hemisphere. The shell is single spherical, latticed, and 80 µm in diameter. The specimens bear a strong morphological similarity to genus *Rotasphaera*. This genus was originally erected by Noble (1994) for taxa possessing a single lattice shell formed by the coalescence of two or more primary spine units (morphological terminology of this genus follows Noble

1994). Noble (1994) suggested that this genus is distinguished from the genus *Secuicollacta* Nazarov and Ormiston by having a smaller number of primary spines and more differentiation between primary and secondary spine morphology. However, subsequent taxonomic work by MacDonald (1998) shows that specimens belonging to the genus *Secuicollacta* have one ectopically placed spicule and additional primary spine units. As MacDonald (1998) pointed out, all species described as *Secuicollacta* by Furutani (1990) have no ectopic spicule and only primary spine units. Herein, I follow MacDonald's (1998) opinion and include the following three species within the genus *Rotasphaera*; namely, *Secuicollacta itoigawai* Furutani, *Secuicollacta horrida* Furutani, and *Secuicollacta vulgaris* Furutani.

*Range and occurrence.* – Upper Silurian to Lower Devonian. Fukuji, Hitoegane areas and Yoshiki Formation in the Hida-gaien terrane.

**Genus *Ceratoikiscum* Deflandre, 1953**

*Type species.* – *Ceratoikiscum avimexpectans* Deflandre, 1953.

***Ceratoikiscum armiger* Furutani, 1990**  
Figure 13R

- 1990 *Ceratoikiscum armiger* Furutani, pp. 51, 52, pl. 12, figs 2–4.  
1995 *Ceratoikiscum armiger* Amon, Braun & Ivanov, p. 4, pl. 1, figs 1, 2.  
1997 *Ceratoikiscum armiger* Umeda, p. 419, pl. 1, fig. 19; pl. 3, figs 15–17.  
1998 *Ceratoikiscum armiger* Umeda, fig. 9.  
1998 *Ceratoikiscum armiger* Kurihara & Sashida, pl. 1, figs 11, 12.  
2000 *Ceratoikiscum armiger* Kurihara & Sashida, p. 63, pl. 1, figs 12, 13.  
2007 *Ceratoikiscum armiger* Kurihara, pl. 2, fig. 29.  
1996 *Ceratoikiscum* sp. Furutani, figs 5–7.

*Remarks.* – This species bears a strong morphological similarity to *Ceratoikiscum armiger* Furutani. *Ceratoikiscum armiger* differs from other species of the genus *Ceratoikiscum* by possessing a simple skeleton consisting of three rods and caveal ribs (morphological terminology of the genus *Ceratoikiscum* follows Wakamatsu *et al.* 1990).

*Range and occurrence.* – Upper Silurian to Lower Devonian. Fukuji, Ise, Hitoegane areas and Yoshiki Formation in the Hida-gaien terrane; Konomori, and Yokokurayama areas in the Kurosegawa terrane; Southern Urals.



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