

# Fusuline biotic turnover across the Guadalupian–Lopingian (Middle–Upper Permian) boundary in mid-oceanic carbonate buildups: Biostratigraphy of accreted limestone in Japan

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## Abstract

Two sections in Upper Middle to Lower Upper Permian shallow-water limestones at Kamura and Akasaka in southwest Japan were analyzed for detailed lithostratigraphy and biostratigraphy. Both sections represent ancient seamount-capping carbonate buildups developed on a basaltic basement in a mid-oceanic environment. The occurrence of abundant Tethyan fusulines allows the recognition of well-defined biostratigraphic zonation in both sections and their mutual correlation. The Upper Guadalupian (Middle Permian) *Lepidolina/Yabeina* Zone is overlain conformably by the Lower Lopingian (Upper Permian) *Codonofusiella–Reichelina* Zone with a 13 m-thick transitional interval barren of index taxa. The Guadalupian–Lopingian (G–L) boundary is marked by the First Appearance Datum (FAD) of the Lopingian *Codonofusiella–Reichelina* assemblage in both sections. This study recognizes for the first time the G–L boundary horizon in a mid-oceanic shallow-water environment. In addition, the shallow-water carbonates in the study sections record the extinction of the Middle Permian large-sized fusuline family Verbeekiniidae at the G–L boundary in mid-Panthalassa, as well as in shallow-water Tethyan shelf areas, demonstrating positively that the G–L boundary mass extinction occurred on a global scale. The abrupt elimination of large-shelled fusulines, followed by the domination of small-shelled fusulines may indicate that environmental stress occurred at the end of Guadalupian. The dying-out of symbiotic algae may have caused the selective extinction of the large-shelled fusulines.

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## 1. Introduction

The end-Permian mass extinction has long been regarded as a single event (e.g. Logan and Hills, 1974; Erwin, 1993) but the extinction actually occurred in two distinct phases at the end of the Guadalupian (Middle Permian) and at the end of the Lopingian (Late Permian), as first pointed out by Stanley and Yang (1994) and Jin et al. (1994). The extinction rate of all skeletal marine animal genera at the end-Guadalupian event is estimated at 58%, almost the same as the end-Ordovician extinction, and even higher than those of other mass extinctions in the Late Devonian, end-Triassic and end-Cretaceous (Stanley and Yang, 1994). Thus the end-Guadalupian event represents one of the major mass extinction events of the Phanerozoic. This suggests

development of a major environmental change on a global scale nearly 10 million years before the Permo-Triassic boundary; however, some details, including its cause, are still unclear (e.g. Chung et al., 1998; Isozaki et al., 2004).

For the end-Guadalupian event, major sources of information come mostly from shallow marine sedimentary rocks deposited along the Tethyan shelf areas around the supercontinent Pangea, particularly in South China with its abundant fossil occurrences. In order to assess the global environmental change that may have led to the end-Guadalupian extinction, further information from the superocean Panthalassa is required. Isozaki (1994, 1997a) first reported contemporaneous mid-oceanic deep-sea cherts and the associated global redox change at the G–L boundary in the deep superocean. In addition, recently recognized, mid-oceanic shallow-water carbonates provide a valuable additional dataset for the study of the G–L boundary (Isozaki and Ota, 2001).

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Upper Permian to Jurassic accretionary complexes in Japan contain many allochthonous blocks of Carboniferous to Triassic limestone and chert (e.g. Yamato–Omine Research Group, 1981; Wakita, 1988; Isozaki et al., 1990). Their basement, composed of basaltic greenstones with an oceanic island-type basalt (OIB) affinity (e.g. Maruyama and Yamasaki, 1978; Nishimura et al., 1979; Tatsumi et al., 2000), suggests that these exotic limestone blocks were derived from Permo-Carboniferous carbonate buildups deposited on ancient mid-oceanic seamounts (Kanmera and Nishi, 1983; Isozaki, 1987; Sano and Kanmera, 1988). Their mode of occurrence (i.e. blocks-in-matrix within younger clastics) indicates that they were accreted to Japan along the South China continental margin considerably later than their deposition (e.g. Isozaki, 1997b). Permian limestone blocks of this kind yield abundant Permian fossils, in particular Tethyan fusulines and rugose corals. Despite the dismembered nature of the limestone, the fusuline biostratigraphy has been reconstructed in detail, and a correlation has been established by previous workers mainly with South China (e.g. Toriyama, 1967; Ishii, 1990; Ueno, 1996).

The fine-scale biostratigraphy of the G–L boundary interval has not yet been fully documented in these accreted limestone sequences in Japan, except for preliminary results by Sakagami (1980) and Ozawa and Nishiwaki (1992). Our study aims to establish the detailed lithostratigraphy and fusuline biostratigraphy for the G–L boundary interval in two new sections; i.e. Kamura in Kyushu and Akasaka in central Honshu (Fig. 1). Following reconnaissance reports (Ota et al., 2000; Isozaki and Ota, 2001), this article describes details of the litho- and bio-stratigraphy of the sections at Kamura and Akasaka on the basis of field research and microscopic study of over 600 thin sections. In addition, we demonstrate the biostratigraphic correlation of these sections mainly with continental shelf sequences in South China, and discuss the significance of the G–L

boundary fusuline turnover in the mid-superocyan that may provide new constraints on the cause of the G–L boundary mass extinction.

## 2. Geologic setting

We have studied two sections in southwest Japan; one at Kamura located in Takachiho-cho in northern Miyazaki Prefecture, Kyushu, and the other in Gifu Prefecture, central Honshu (Fig. 1). Both study sections occur in kilometer-size allochthonous limestone blocks surrounded by Middle Jurassic disordered sandstone/mudstone matrix of the Jurassic accretionary complex. The Jurassic complex in the Akasaka area belongs to the Mino-Tanba Belt, and that in the Kamura area to the Chichibu Belt; the Chichibu Belt represents an outlier of the Mino-Tanba Belt. For the general aspects of the Jurassic accretionary complexes and their allochthonous blocks in Japan, refer to Wakita (1988), Isozaki et al. (1990) and Isozaki (1997b).

### 2.1. Kamura area

The Permo-Triassic limestone in the Kamura area is composed of the Permian Iwato Formation, Mitai Formation (Kanmera and Nakazawa, 1973) and the Triassic Kamura Formation, in ascending order (Saito et al., 1958; Kambe, 1963; Kanmera and Nakazawa, 1973; Watanabe et al., 1979; Koike, 1996). Various Permo-Triassic fossils, including fusulines, rugose corals, pelecypods and ammonites have been reported from limestone blocks in the area (e.g. Kambe and Saito, 1957; Saito et al., 1958). On the basis of these paleontological data and field research, Kambe (1963) defined the fusuline-bearing Permian Iwato Formation and overlying Triassic Kamura Formation. Later, Kanmera and Nakazawa (1973) distinguished the Mitai Formation between these two formations on the basis of Changhsingian (Upper Lopingian) fusulines including *Palaeofusulina*. In addition, Ota et al. (2000) recognized a Wuchiapingian (Lower Lopingian) interval within the Mitai Formation. Also Watanabe et al. (1979) and Koike (1996) added conodont data to confirm the Triassic stratigraphy of the Kamura Formation.

A geologic sketch map of the Kamura area is shown in Fig. 2. The Permian to Triassic limestone blocks occur as elongate lenses, extending for about 3 km in an ENE–WSW direction from Hirokino to Hatanaka via Shioinouso. The limestone generally strikes ENE–WSW, and dips northward. The maximum stratigraphic thickness of the Permian-Triassic limestone is estimated to be 135 m (Kambe, 1963; Kanmera and Nakazawa, 1973; Watanabe et al., 1979).

The Iwato Formation consists mainly of black limestone and yields Guadalupian fusulines of typical Tethyan affinity, such as *Neoschwagerina margaritae* Deprat, *N. larga* Morikawa and Suzuki, *N. minoensis* Deprat em. Ozawa, *N. (= Lepidolina) megasphaerica* Deprat, *Yabeina*

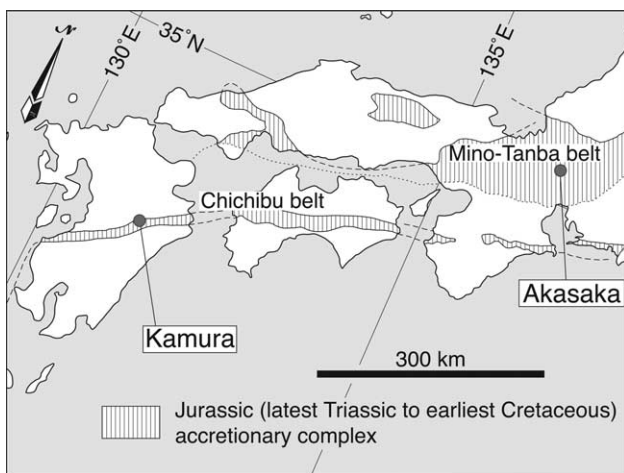


Fig. 1. Index map of the Kamura and Akasaka sections in Southwest Japan. Distribution of the Jurassic accretionary complex is after Isozaki (1997b).

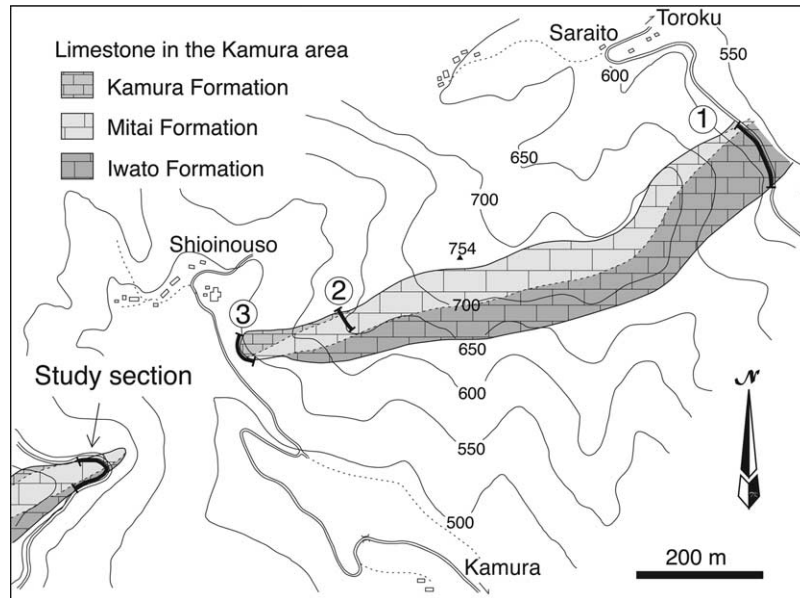


Fig. 2. Geological sketch map of the Kamura area, Takachiho-cho, Nishiuzuki-gun, Miyazaki Prefecture, Kyushu (modified from Watanabe et al., 1979). Blank area indicates the Jurassic sandstone/mudstone. Solid lines 1–3 represent previously studied sections by Kambe (1963), Kanmera and Nakazawa (1973) and Watanabe et al. (1979), respectively.

cf. *katoi* Ozawa, *Y. cf. globosa* (Yabe), and *Lepidolina cf. shiraiwensis* (Ozawa) (Saito et al., 1958; Ota et al., 2000; Murata et al., 2003). The Mitai Formation consists of white to light gray dolomitic limestone, yielding a Lopingian fusuline assemblage including *Codonofusiella kwangsiana* Sheng, *Reichelina media* Miklukho-Maklay, *R. changhsingensis* Sheng, *Palaeofusulina* sp., *Nankinella* sp. and *Staffella* sp. (Kanmera and Nakazawa, 1973; Ota et al., 2000). The Kamura Formation consists of dark to light gray micritic limestone, and yields Lower to Upper Triassic conodonts (Watanabe et al., 1979; Koike, 1996). All these units are composed of almost pure carbonates, excluding coarse-grained, quartzo-feldspathic, terrigenous clastics.

The study section crops out along a new logging road about 300 m SSW of Shioinouso in Takachiho-cho (32°45'12", 131°20'10"E) (Fig. 2). This outcrop is the western extension of sections previously studied by Kambe (1963), Kanmera and Nakazawa (1973) and Watanabe et al. (1979). In the study section, the allochthonous Permian limestone is in fault contact on both sides with the disorganized Jurassic sandstone and mudstone.

## 2.2. Akasaka area

The Middle to Upper Permian limestone in the Akasaka area is composed of the Lower, Middle, and Upper members of the Akasaka Limestone Formation plus the Ichihashi Formation (newly designated) in ascending order. Since, the late 19th century, the occurrence of various Guadalupian fusulines, rugose corals, and mollusks has been reported from the Akasaka limestone (Gümbel, 1874; Schwager,

1883). Abundant occurrences of fusulines, in particular, led to the detailed stratigraphic subdivision of the limestone (e.g. Ozawa, 1927; Akasaka Research Group, 1956). Later, a Wuchiapingian fusuline fauna including *Reichelina* was found in the overlying unit above the Upper Member (Murata et al., 1978; Sakagami, 1980); i.e. the Ichihashi Formation defined in this article. On the basis of additional information, the fusuline biostratigraphy of the limestone has been updated (Ozawa and Nishiwaki, 1992; Zaw Win, 1999). Zaw (1999) provided a detailed historical review of the studies on the Akasaka limestone.

The geological sketch map of the Akasaka area is shown in Fig. 3. The Permian Akasaka limestone forms a large allochthonous block contained within Jurassic sandstone, although its eastern margin is covered by Quaternary sediments. The limestone has long been mined for cement and construction materials, and most of the limestone body is exposed in quarry surfaces. The limestone generally strikes NNE–SSW and dips 45°–65° westward. The total stratigraphic thickness of the limestone is estimated at over 250 m according to previous studies (Ozawa and Nishiwaki, 1992; Zaw Win, 1999).

The lower Member consists of light gray to white limestone, bearing abundant fusulines such as *Parafusulina granum-avenae* (Romer), *Parafusulina nakamigawai* Morikawa and Horiguchi, *Verbeekina sphaera* (Ozawa), and *Cancellina nipponica* (Ozawa) (Ozawa and Nishiwaki, 1992; Zaw Win, 1999). The Middle Member consists of dark gray to black limestone, containing lower Middle Permian fusulines such as *Neoschwagerina simplex* Ozawa, *Pseudodoliolina ozawai* (Yabe and Hanzawa), *Parafusulina japonica* (Gumbel), *N. craticulifera* (Schwager), and



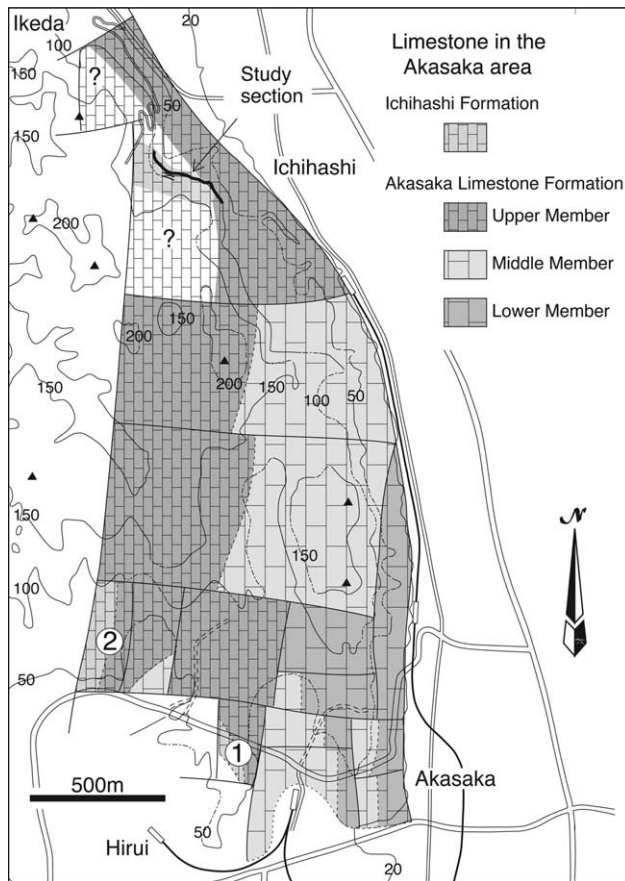


Fig. 3. Geological sketch map of the Akasaka area, Oogaki city, Gifu Prefecture, Central Honshu (modified from Akasaka Research Group, 1956). Blank area on the west indicates the Jurassic sandstone/mudstone. Localities numbered 1–2 represent previously studied sections by Sakagami (1980) and Ozawa and Nishiwaki (1992), respectively.

*N. margaritae* Deprat (Ozawa and Nishiwaki, 1992; Zaw Win, 1999).

The Upper Member consists mainly of muddy black limestone, bearing Upper Middle Permian fusulines such as *Yabeina igoi* Morikawa and Suzuki, *Yabeina katoi* (Ozawa), *Yabeina globosa* (Yabe), *Neoschwagerina minoensis* Deprat and *Neoschwagerina margaritae* Deprat (Ozawa and Nishiwaki, 1992; Zaw Win, 1999). The Ichihashi Formation consists mainly of gray to white dolomitic limestone, characterized by Wuchiapingian fusulines of the *Codonofusiella kueichowensis*–*Reichelina changhsingensis* assemblage (Sakagami, 1980). All units are composed of almost pure carbonates. Zaw Win (2000) presented a possible reconstruction of intertidal to subtidal depositional environments with local patch reefs, lagoons and shoals for the Middle Permian units, and a supratidal environment for the Upper Permian rocks.

The study section crops out in the northern part of the limestone body (35°25'N, 136°35'E) (Fig. 3), where it exposes the uppermost part of the Upper Member and the overlying Ichihashi Formation.

### 3. Lithology

On the basis of our fieldwork and microscopic observations, we describe here the lithology of the study sections in the Kamura and Akasaka areas.

#### 3.1. Kamura section

The Permian limestone is approximately 36 m thick, and composed of the Iwato Formation and the conformably overlying Mitai Formation (Fig. 4). The limestone strikes ENE–WSW and dips almost vertically (80° southward–northward). We studied 304 thin sections from this section for analysis of lithofacies and microfossils.

The Iwato Formation is 19 m thick, but its base is not exposed. It consists mainly of carbonaceous, massive, black limestone, partly including large fusulines and bivalves. This formation is divided into a ca.6 m-thick lower part and a ca.13 m-thick upper part. The lower part comprises wackestone with a black, organic-rich matrix and yields abundant large bivalves (probably *Shikamaia*) and fusulines. Bioclasts include fragments of bivalves, dasycladacean algae, crinoids, fusulines and other small foraminifera. Large bivalve shells are up to 3 cm thick and 12 cm long. Unidentified gastropods 2–3 cm in diameter are also present.

The upper part of the Iwato Formation comprises peloidal wackestone. Black organic matter probably of microbial origin is concentrated in peloids. Bioclasts comprise small foraminifera, calcareous algae, ostracodes, crinoids, and brachiopods. Megafossils are absent in this interval, except for very rare rugose coral (*Waagenophyllum*) from the upper part (Sample 5e).

The Mitai Formation is about 17 m thick, and consists mainly of light gray dolomitic limestone and white dolomite. Its top is not exposed in this section. The limestone is fossiliferous, mostly massive, and partly includes 1 cm-thick, continuous to discontinuous bands with concentrations of peloids and algae. The lowermost 1 m-thick bed is characterized by white bands containing abundant dolomitized dasycladacean algae (Fig. 4). The limestone of the Mitai Formation comprises mostly grainstone/wackestone with lesser amounts of lime–mudstone. Bioclasts are derived from calcareous algae, crinoids, ostracodes, gastropods, bivalves, crinoids, brachiopods, coral, fusulines and small foraminifera. Overall, the Iwato Formation was formed in a subtidal to intertidal environment, and the Mitai Formation in an intertidal and partly supratidal setting.

The boundary between the Iwato and Mitai formations has a conformable contact that is clearly observed in the outcrop. Both the uppermost 55 cm of the Iwato Formation and the lowermost 30 cm of the Mitai Formation are composed of dark gray limestone, the color of which is transitional from black in the Iwato Formation to light gray in the Mitai Formation. Sample 5–7a just below the

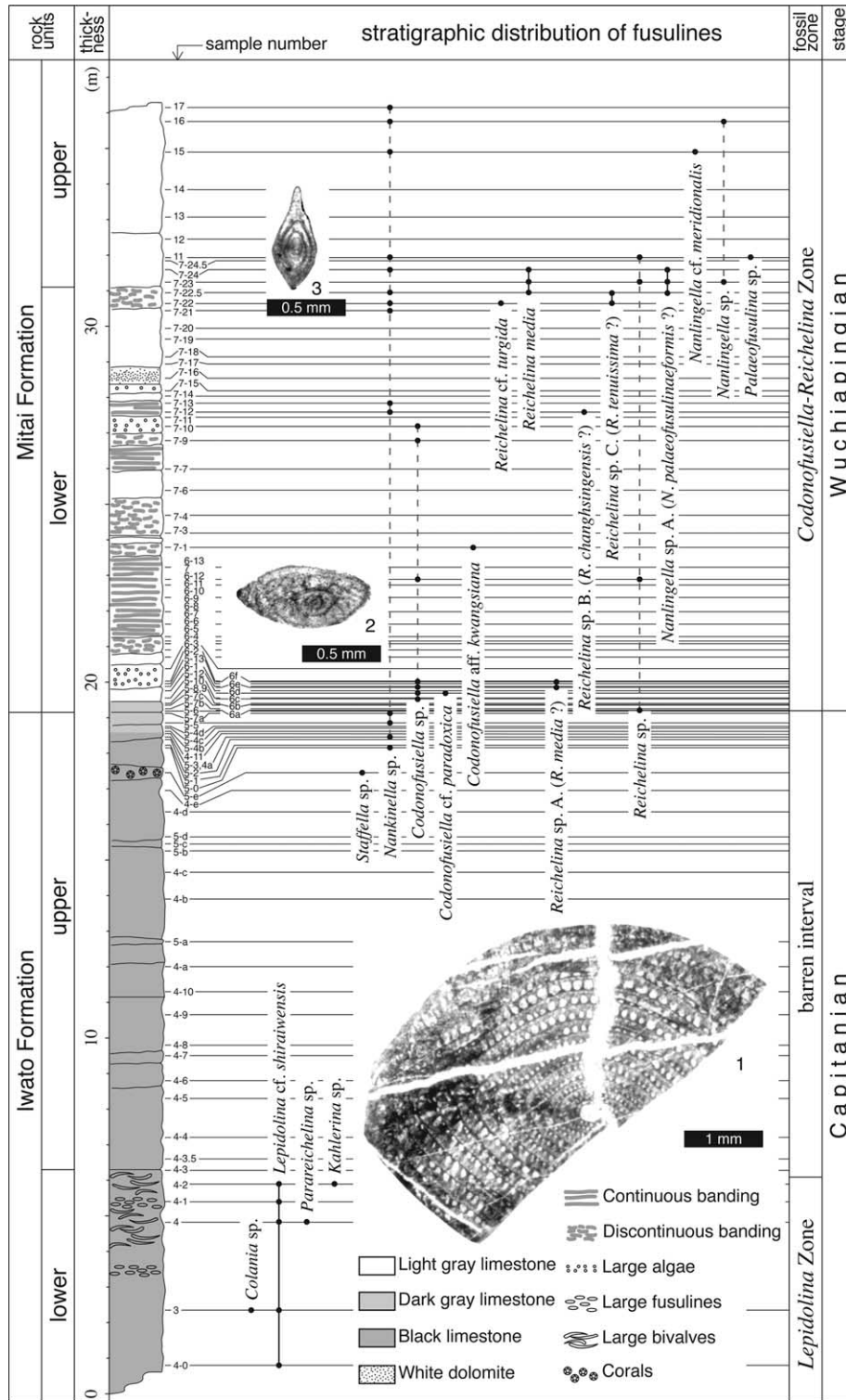


Fig. 4. Stratigraphic column and fusuline distribution in the Middle Permian Iwato Formation and the Upper Permian Mitai Formation along the study section at Kamura. Horizontal bars represent horizons checked by thin section observation. (1) *Lepidolina cf. shiraiwensis* (Ozawa) (Sample 4), (2) *Codonofusiella cf. paradoxica* Dunbar and Skinner (Sample 6d), (3) *Reichelina media* Miklukho-Maalay (Sample 7–22.5).

boundary is peloidal wackestone and grainstone with smaller foraminifera, fusulines, dasycladacean algae, and ostracodes. Samples 5–6 and 6a from immediately above the boundary are mainly peloidal wackestone with small

foraminifera, dasycladacean algae, ostracodes and gastropods. The boundary horizon is marked by a 2 mm-thick, light green, clayey layer probably of acidic tuff origin (Isozaki and Ota, 2001).

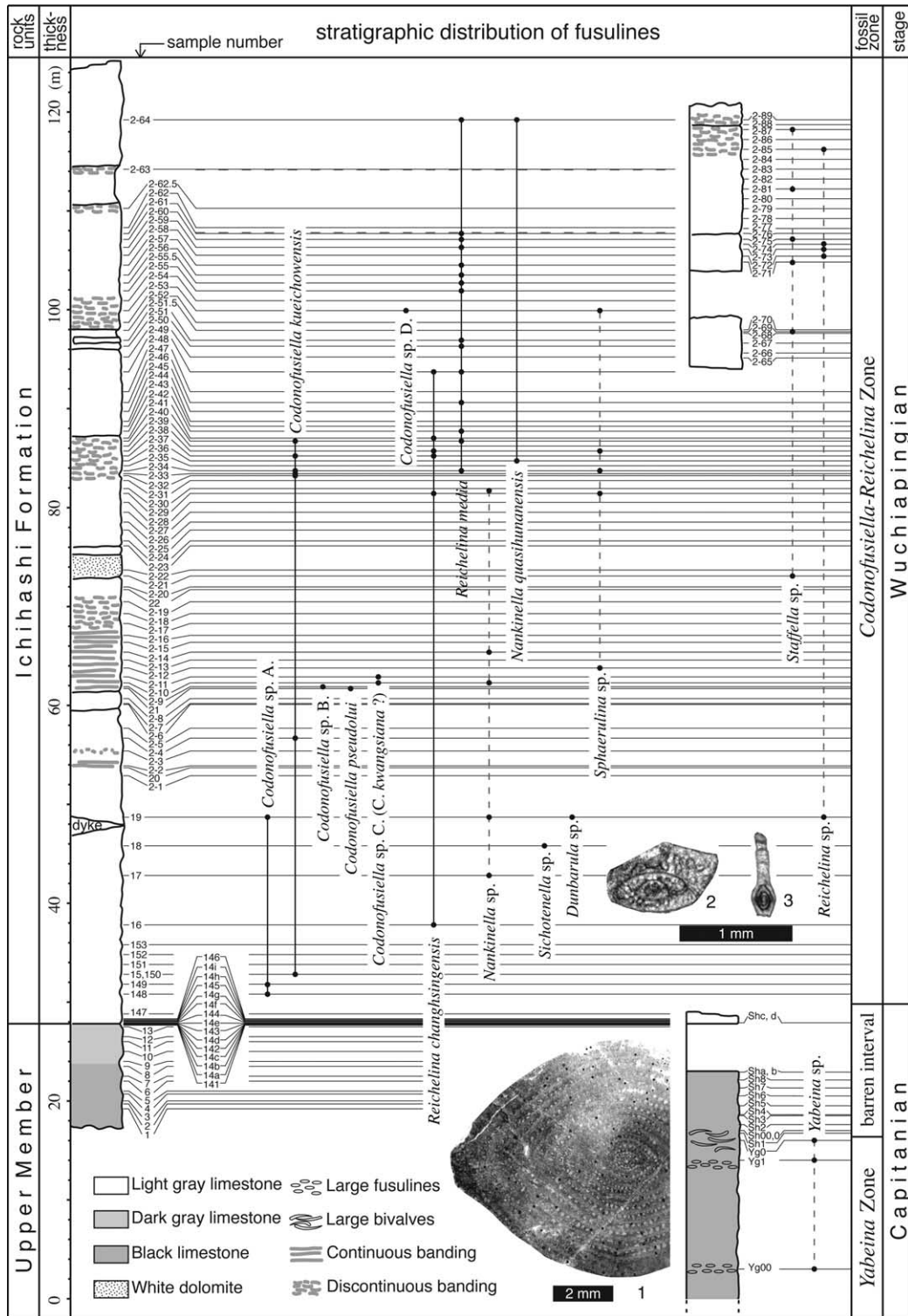


Fig. 5. Stratigraphic column and fusuline distribution in the Middle Permian Upper Member and the Upper Permian Ichihashi Formation along the study section at Akasaka. Horizontal bars represent horizons checked by thin section observation. (1) *Yabeina* sp. (Sample Yg-0), (2) *Codonofusiella kueichoensis* Sheng (Sample 15), (3) *Reichelina changhsingensis* Sheng and Chang (Sample 16).

3.2. Akasaka section

The Permian limestone in this section is approximately 124 m thick (Fig. 5), strikes NNW–SSE, and dips 35°

southward. The section consists of two units, i.e. the Upper Member of the Akasaka limestone (Akasaka Research Group, 1956) and the conformably overlying Ichihashi Formation (newly designated). Descriptions of lithofacies



are given below on the basis of microscopic observation of 313 thin sections from this section.

The Upper Member of the Akasaka Limestone in the study section is 28 m thick, but its bottom is not exposed. It consists mainly of massive, carbonaceous, black limestone, partly including horizons with large fusulines and fragments of large bivalves aligned parallel to bedding. The Upper Member is divided lithologically into a lower 17 m-thick part and an upper 11 m-thick part. The lower part comprises black, organic-rich wackestone. Bioclasts are derived from calcareous algae and small foraminifera. The lower part yields large bivalve shells, probably *Shikamaia* up to 1 cm thick and 8 cm long. The upper part comprises peloidal wackestone/grainstone. Black, organic matter is concentrated in the peloids. Bioclasts include fragments of small foraminifera, calcareous algae and ostracodes. The black color comes from a high content of organic carbon; total organic carbon of the black limestone is up to 1.2 wt%, whereas average gray limestones in Akasaka have TOC around 0.08 wt% (Watanabe et al., 1967).

The Ichihashi Formation is over 96 m thick, and its top is unknown. It consists mainly of massive, light gray grainstone and wackestone, partly characterized by 1 cm-thick, continuous to discontinuous bands (Fig. 5). A 1 cm-thick, dark gray band contains abundant peloids and algae. Bioclasts include fragments of calcareous algae, crinoids, ostracodes, small fusulines and other foraminifera. Overall, the Upper Member was formed in subtidal to intertidal environments, and the Ichihashi Formation in intertidal and partly supratidal regime, in accordance with the interpretation of Zaw Win (2000).

The Ichihashi Formation is newly defined here for the unit overlying the Upper Member of the Akasaka Limestone. Since its first recognition in 1978, this post-*Yabeina* interval was studied preliminarily by Murata et al. (1978) and Sakagami (1980), and later named as the 'Uppermost Member' by Ozawa and Nishiwaki (1992). The outcrops of the Uppermost Member described at Hanaokayama and Iwahara were unfortunately destroyed by quarry developments. Later, Kawai et al. (1997) found the present outcrop near Ichihashi (Fig. 3) which we analyzed in this study. Under the present circumstance, without the originally described type sections for the Uppermost Member, we here establish a new stratigraphic unit, the Ichihashi Formation, for the interval. Concerning the category of the stratigraphic unit, 'formation' is preferred to 'member', because there is a remarkable contrast in lithology between the limestone-dominated lower units and the overlying dolomite-dominated unit. The formation name is after the nearby town, and the study section is designated as the type section of the formation.

The boundary between the Upper Member and the Ichihashi Formation is conformable and is clearly observed in the study section. The boundary is located between a dark gray limestone and an overlying light gray

limestone. Sample 14d–u just below the boundary comprises algal boundstone (blady stromatolite), yielding algae and small foraminifera. Sample 14e–l from just above the boundary mainly comprises algal wackestone, yielding calcareous algae, small foraminifera, and ostracodes. This boundary horizon is characterized by a light green clayey layer, ca. 5 mm thick (Isozaki and Ota, 2001).

#### 4. Fusuline biostratigraphy

In recent years, conodonts have become one of the most reliable fossil groups for dating and correlation of the Permian, in particular for the Guadalupian–Lopingian boundary interval (e.g. Jin et al., 1997, 1998; Henderson et al., 2003). Both the Kamura and Akasaka sections contain various abundant mega- and microfossils, but they have yielded few conodonts (e.g. Igo, 1981; Koike, 1996). In establishing high-resolution biostratigraphy of the Kamura and Akasaka sections, fusulines play the main role by virtue of their numbers and diversity. The fusuline taxa from the study sections, including *Yabeina* and *Lepidolina*, are mostly of Tethyan affinity, suggesting a shallow, warm-water environment in low latitudes. Accordingly, fusulines facilitate biostratigraphic correlation with other Tethyan areas, in particular with South China, replete with various fusuline faunas (e.g. Sheng, 1963; Rui et al., 1984). Fusuline biostratigraphy and age assignment are described here for the Kamura and Akasaka sections.

##### 4.1. Kamura section

The Kamura section contains 10 genera and six identifiable species of fusulines on the basis of 332 thin sections from 69 sampled horizons. The section is biostratigraphically divisible into three fusuline Zones, i.e. *Lepidolina* Zone, barren interval, and *Codonofusiella*–*Reichelina* Zone, in ascending order. The stratigraphic distribution of the representative fusuline taxa in the Kamura section is shown in Fig. 4.

The *Lepidolina* Zone occurs in the lower 6 m-thick interval of the Iwato Formation. This zone is characterized by the abundant occurrence of large Verbeekiniidae (in the sense of Ross, 1995) fusulines, *Lepidolina* cf. *shiraiwensis* (Ozawa) in particular, with less dominant *Colania* sp., *Parareichelina* sp., and *Kahlerina* sp. The base of the *Lepidolina* Zone is not observed in this section, but its top is marked by the last appearance datum (LAD) of *Lepidolina* in Sample 4–2 (Fig. 4). The *Lepidolina* Zone in Kamura is correlated with the Upper Maokouan in South China (Sheng, 1963), with the Midian in Transcaucasia (Leven, 1996) and with the Upper Guadalupian (Capitanian) in Texas (Wilde et al., 1999).

The upper 13 m-thick part of the Iwato Formation and the lowermost 4 cm of the Mitai Formation yield rare rugose

corals and staffellids such as *Nankinella* sp. and *Staffella* sp. without index fusulines for dating. Accordingly, this interval is treated as a barren interval in this article. The base of the barren interval occurs immediately above the LAD of *Lepidolina*, and its top immediately below the first appearance datum (FAD) of *Reichelina* in Sample 6a (Fig. 4). The top of the barren interval corresponds approximately to the boundary between the Iwato Formation and Mitai Formation.

The *Codonofusiella*–*Reichelina* Zone corresponds mostly to the Mitai Formation except for its lowermost 4 cm. The *Codonofusiella*–*Reichelina* Zone is characterized by the dominance of small-shelled fusuline families, Schubertellidae, Ozawainellidae and Staffellidae, and by the total absence of large-sized Verbeekiniidae and Schwageriniidae. *Codonofusiella* and *Reichelina* are representative genera, and they accompany *Nanlingella*, *Palaeofusulina* (primitive small forms), and *Staffella*.

The base of the *Codonofusiella*–*Reichelina* Zone is marked by the FAD of *Reichelina* in Sample 6a, and its top is unknown. The lower 9 m of this zone is dominated by *Codonofusiella*, and the upper part by *Reichelina*. The uppermost 4 m of this section is characterized by *Nanlingella* cf. *meridionalis* Rui and Sheng, in the absence of *Codonofusiella* and *Reichelina*. Three individuals of *Palaeofusulina* sp. were identified in the upper part (Sample 11), but they are obviously small and primitive in structure with respect to the more-advanced forms such as *Palaeofusulina sinensis* Sheng from the Changhsingian in South China (Kanmera, personal communication). No typical Changhsingian fusuline assemblage has been detected from the study section.

The *Codonofusiella*–*Reichelina*-dominated assemblage without Verbeekiniidae, Schwageriniidae and advanced *Palaeofusulina* indicates that the *Codonofusiella*–*Reichelina* Zone of the Kamura section correlates with the Wuchiapingian (Lower Lopingian) in South China (Sheng, 1963; Rui et al., 1984). The interval around Samples 7–1, bearing *Codonofusiella kwangsiana* Sheng in particular, is directly correlated with the Wuchiapingian because the taxon is an index fossil of the type Wuchiapingian in South China (Rui et al., 1984). The uppermost 4 m without *Codonofusiella* and *Reichelina* may possibly range up into the Changhsingian, however, without positive evidence, this part is tentatively regarded as belonging to the Wuchiapingian.

The present fusuline study confirms that the Kamura section ranges from the Capitanian (Upper Guadalupian) to Wuchiapingian (Lower Lopingian), and that this conformable section contains the contiguous G–L boundary horizon. There is no definitive evidence for determining the age of the barren interval. As the barren interval occurs immediately below the horizon of rapid development of the Wuchiapingian *Codonofusiella*–*Reichelina* fauna, it is regarded as belonging to the topmost part of the Capitanian. Accordingly, the G–L boundary is placed at the top of the barren interval or at the base of the *Codonofusiella*–

*Reichelina* Zone that corresponds approximately to the base of the Mitai Formation.

#### 4.2. Akasaka section

The Akasaka section yielded nine fusuline genera, three of which contain nine identifiable species on the basis of 273 thin sections from 154 sampled horizons. The study section is divided into three fusuline zones, i.e. *Yabeina* Zone, barren interval, and *Codonofusiella*–*Reichelina* Zone, in ascending order. The stratigraphic distribution of the recovered fusuline taxa is shown in Fig. 5. The *Yabeina* Zone represents the lower 16 m of the Upper Member. The *Yabeina* Zone is characterized by the concentrated occurrence of the nominal genus. The *Yabeina*-enriched beds are often associated with large bivalves, probably *Shikamaia*. The base of the *Yabeina* Zone is not exposed, whereas its top is marked by the LAD of *Yabeina* in Sample Yg-0 (Fig. 5). The faunal composition indicates that the *Yabeina* Zone is correlated with the Upper Maokouan in South China, Midian in Transcaucasia, and the Capitanian of North America (Sheng, 1963; Leven, 1996; Wilde et al., 1999).

No mega- or microfossils occur in the upper 11 m of the Upper Member or the lower 2 m of the Ichihashi Formation. This interval without index fossils is treated as a barren interval, as in the case of the Kamura section. The base of the barren interval is immediately above the LAD of *Yabeina*, and its top is immediately below the FAD of *Codonofusiella* in Sample 148 (Fig. 5). The top of the barren interval corresponds approximately to the boundary between the Upper Member and the Ichihashi Formation.

The *Codonofusiella*–*Reichelina* Zone is 94 m thick, representing almost the entire Ichihashi Formation except for the basal 2 m. The *Codonofusiella*–*Reichelina* Zone is characterized by an abundance of small-shelled Schubertellidae, Ozawainellidae and Staffellidae, and by the absence of Verbeekiniidae and Schwageriniidae. Also present are tiny fusulines such as *Nankinella*, *Sichotenella*, *Dunbarula*, *Sphaerulina* and *Staffella*. The base of the *Codonofusiella*–*Reichelina* Zone is marked by the FAD of *Codonofusiella* in Sample 148, whereas its top is unknown. The lower to middle parts of this zone, 70 m thick, yield *Codonofusiella kueichowensis* Sheng, *C. pseudolui* Sheng, *C. sp.* that resembles *C. kwangsiana* Sheng, *Reichelina changhsingensis* Sheng and Chang and *R. media* Miklukho-Maclay. The upper part, 24 m thick, is dominated by *Reichelina media* Miklukho-Maclay and *Staffella* sp., without *Codonofusiella*. According to Sheng (1963), *Reichelina changhsingensis* Sheng and Chang is dominant in the middle Wuchiapingian to Changhsingian in South China. Typical Changhsingian fusulines described from South China, such as *Palaeofusulina sinensis* Sheng, have not been detected in the study section nor from any part of the Akasaka limestone. The *Codonofusiella kueichowensis* Sheng-bearing interval, ca. 57 m thick part between Samples 148 and 2–40 of the Ichihashi Formation, is



correlated with the Middle–Upper Wuchiapingian, whereas the rest of the formation, ca. 38 m-thick part above Sample 2–41 (LAD of *R. changhsingensis* Sheng and Chang and *R. media* Miklukho-Maclay), may possibly range up to the Changhsingian.

The present fusuline study confirms that the Akasaka section ranges from the Capitanian to Wuchiapingian, and that the conformable section contains the G–L boundary horizon. The barren interval is regarded as belonging to the topmost part of the Capitanian, as in the case of the Kamura section. Likewise, the G–L boundary is placed at the top of the barren interval or at the base of the *Codonofusiella*–*Reichelina* Zone.

## 5. Local correlations in Kamura and in Akasaka

### 5.1. Fusuline zones in Kamura

The Middle–Upper Permian fusuline stratigraphy was previously analyzed by Kambe (1963), Kanmera and Nakazawa (1973), and Sano and Nakashima (1997) at two other sections in the Kamura area (sections 1 and 2 in Fig. 2). Here, we try to correlate them with the study section in order to document the general stratigraphy of the limestone in Kamura.

At section 1, Kambe (1963) divided the 60–100 m-thick Iwato Formation into the *Neoschwagerina* Zone and the overlying *Yabeina* Zone. The dominance of the extremely evolved Verbeekinae and similarity in rock type indicates that the *Yabeina* Zone of Kambe (1963) is correlated with

the *Lepidolina* Zone of the study section. Judging from the thickness at section 1, the 19 m-thick Iwato Formation of the study section probably represents the upper one third to one quarter of the entire formation.

At section 2, Kanmera and Nakazawa (1973) established the 40–45 m-thick Mitai Formation with *Codonofusiella kueichowensis* Sheng, *Reichelina changhsingensis* Sheng and Chang, *Palaeofusulina* sp., *Nankinella* sp., and *Staffella* sp. (Fig. 6). On the basis of the resemblance of their *Palaeofusulina* sp. and *P. sinensis* Sheng, they correlated the Mitai Formation with the Changhsingian of South China. From the Mitai Formation near section 2 (Fig. 2), Sano and Nakashima (1997) additionally found *Palaeofusulina simplicata* Sheng, *P. ellipsoidalis* Sheng, and *P. ex gr. fusiformis* Sheng, together with *Codonofusiella ex gr. kueichowensis* Sheng, *Reichelina ex gr. changhsingensis* Sheng and Chang, *Nankinella* sp., and *Staffella* sp. These *Palaeofusulina* species are advanced forms characteristic of the Changhsingian. The *Palaeofusulina*-bearing interval reported by Kanmera and Nakazawa (1973) and Sano and Nakashima (1997) is 33–37 m thick.

In contrast, the 17 m-thick Mitai Formation in the study section is characterized solely by the *Codonofusiella*–*Reichelina* assemblage of the Wuchiapingian. *Palaeofusulina* sp. from the study section is apparently smaller than the advanced *Palaeofusulina* species of the Changhsingian, thus it is regarded as a Wuchiapingian element of the *Codonofusiella*–*Reichelina* Zone (Kanmera, personal communication). Accordingly, the Mitai Formation of the study section represents a stratigraphically lower interval than that

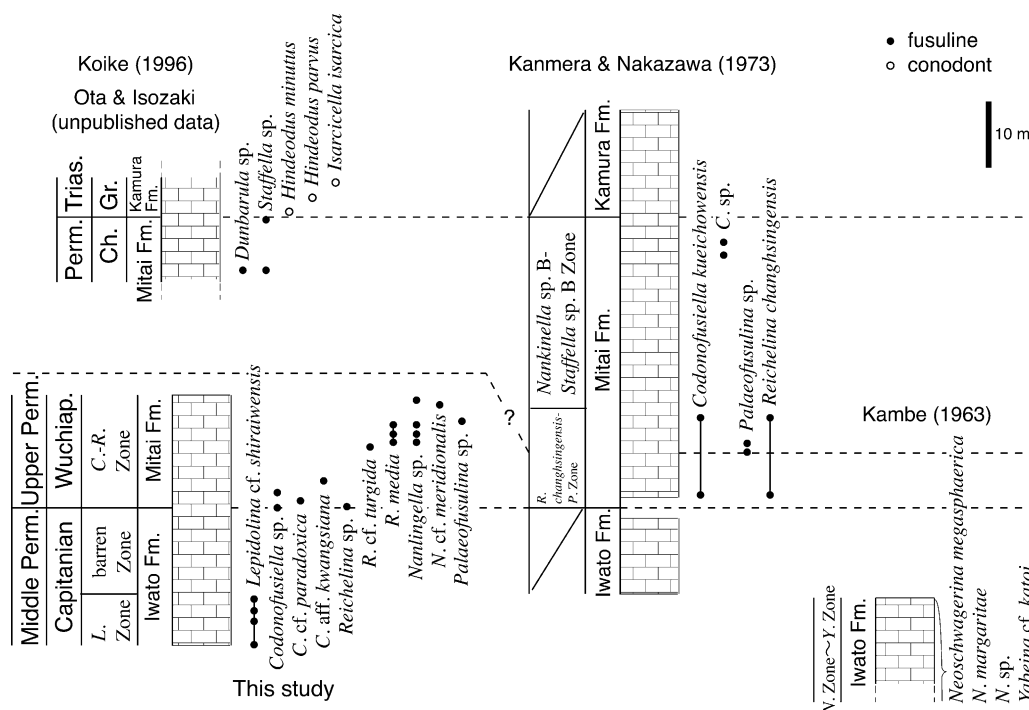


Fig. 6. Biostratigraphic correlation among the four sections in the Kamura area studied by Kambe (1963), Kanmera and Nakazawa (1973) and Sano and Nakashima (1997), and the present study section. For the section reported by Koike (1996), our unpublished data on fusuline are added.

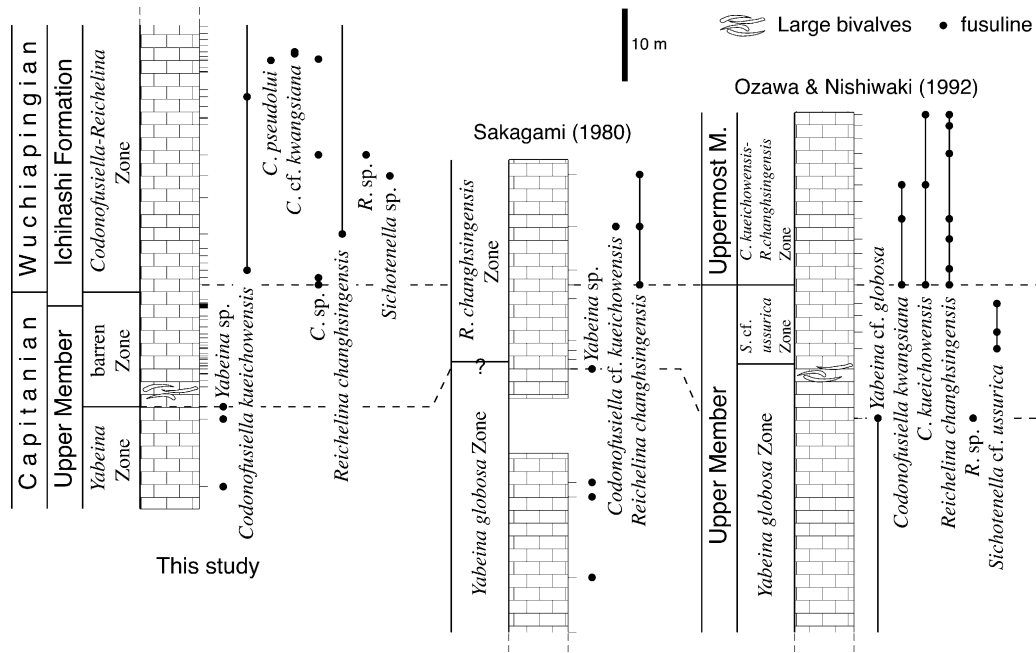


Fig. 7. Biostratigraphic correlation among the three sections in the Akasaka area studied by Sakagami (1980) and Ozawa and Nishiwaki (1992), and the present study section.

with advanced *Palaeofusulina* in section 2. This confirms that the Mitai Formation ranges from the Wuchiapingian to the Changhsingian, although not yet observed in a single section, and that the total thickness of the Mitai Formation is greater than 54 m.

In summary, the Guadalupian–Lopingian limestone in the Kamura area consists of the Capitanian *Yabeina* Zone (over 20 m thick) plus the barren interval (13 m thick), the Wuchiapingian *Codonofusiella*–*Reichelina* Zone (over 17 m thick) and the Changhsingian *Palaeofusulina* Zone (over 37 m thick), in ascending order (Fig. 6).

## 5.2. Fusuline zones in Akasaka

The framework of the Guadalupian fusuline stratigraphy in Akasaka was summarized by the Akasaka Research Group (1956), Ozawa and Nishiwaki (1992) and Zaw Win (1999). Research focused on the G–L boundary interval has been limited, however, simply because the relevant exposures across the G–L boundary, described preliminarily by Sakagami (1980) and Ozawa and Nishiwaki (1992) (sections 1 and 2 in Fig. 3), were soon destroyed by quarrying. These two sections are here correlated with the study section (Fig. 7).

The total stratigraphic thickness of the *Yabeina globosa* Zone is estimated as over 45 m thick (Zaw Win, 1999). The *Yabeina* Zone of the study section, 17 m thick, is properly correlated with the *Y. globosa* Zone of the previous studies. It corresponds probably to the upper one third to one fifth of the latter, because the study section is exposed in a higher quarry bench immediately above another bench composed

of the *Y. globosa* Zone. This quarry face is located adjacent to the section 1 of Zaw Win (1999).

At sections 1 and 2, Ozawa and Nishiwaki (1992) discriminated the *Sichotenella cf. ussurica* Zone (13 m thick) between the *Y. globosa* Zone and the *Codonofusiella kueichowensis*–*Reichelina changhsingensis* Zone. This zone yields solely small-shelled Schubertellidae and Ozawainellidae fusulines and lacks large-shelled Verbeekiniidae and Schwagerinidae. Judging from the faunal content and stratigraphic relationships, the barren interval of the study section corresponds to the *S. cf. ussurica* Zone of Ozawa and Nishiwaki (1992). In section 1, Sakagami (1980) also described a similar relationship between the *Y. globosa* Zone and the conformably overlying *Reichelina changhsingensis* Zone. Likewise, there is a 12 m-thick barren interval between the LAD of *Yabeina* and FAD of *Reichelina*, thus it is reasonably correlated with the barren interval of the study section.

The similarity in faunal composition indicates that the *Codonofusiella*–*Reichelina* Zone of the study section is correlated with the *C. kueichoensis*–*R. changhsingensis* Zone at sections 1 and 2 described by Ozawa and Nishiwaki (1992). In the study section, *Codonofusiella kueichowensis* Sheng and *Reichelina changhsingensis* Sheng occur throughout the lower half (54 m-thick interval between Samples 15 and 2–40) of the Ichihashi Formation (Fig. 5). On the other hand, the *C. kueichoensis*–*R. changhsingensis* Zone at section 1 is over 25 m thick. Judging from the range of the two nominal species and the difference in thickness, the *C. kueichoensis*–*R. changhsingensis* Zone of Ozawa and Nishiwaki (1992) probably corresponds to the lower two-

fifths of the 94 m-thick *Codonofusiella*–*Reichelina* Zone in the study section.

In summary, the Guadalupian–Lopingian limestone in Akasaka is composed in ascending order of the Capitanian *Yabeina globosa* Zone (90 m thick) and barren interval (13 m thick), plus the Wuchiapingian *Codonofusiella*–*Reichelina* Zone (94 m thick). The Changhsingian *Palaeofusulina* Zone has not yet been recognized.

## 6. Mid-oceanic correlation between Kamura and Akasaka

On the basis of the above description of lithology and fossil content, plus previous studies, we here aim to correlate the Capitanian to Wuchiapingian stratigraphy between the Kamura and Akasaka sections, focusing on the G–L boundary horizon. Concerning the Capitanian, the *Lepidolina* Zone of the Kamura section and the *Yabeina* Zone of the Akasaka section are similar in faunal composition because they both contain abundant advanced Verbeekiniidae fusulines and lack Schwageriniidae. As mentioned above, the predominant occurrence of advanced Verbeekiniidae is characteristic to the Upper Capitanian, not only in Japan, but also in Tethyan domains and North America. The main difference between the Kamura and Akasaka sections is in the dominance of *Lepidolina* in the former, and of *Yabeina* in the latter.

Compiling the Middle Permian fusuline faunas from Asia, Ishii et al. (1985) proposed three coeval, distinct fusuline provinces, i.e. the *Yabeina* territory, the *Colania* territory, and *Monodioxiodina* territory. The Akasaka limestone is regarded as a typical example of the *Yabeina* territory. For biostratigraphical convenience sake, Ishii (1990) tentatively applied the *Yabeina globosa*/*Lepidolina shiraiwensis* Zone to the Upper Guadalupian interval in order to cope with such fusuline variability in Japan and eastern Tethys. Accordingly, there is no big discrepancy in correlating the *Lepidolina* Zone of Kamura with the *Yabeina* Zone of Akasaka in a broad sense.

The two study sections both contain *Lepidolina* and *Yabeina*. As described above, the Kamura section yields both *Yabeina* and *Lepidolina*, whereas the Akasaka limestone is characterized almost solely by *Yabeina*. Nonetheless, in Akasaka limestone, *Lepidolina* rarely occurs in association with *Yabeina igoi* Morikawa and Suzuki, as reported under the name of *Neoschwagerina* (*Sumatrina*) *multiseptata* Deprat or *Yabeina* (*Lepidolina*) *multiseptata* (Deprat) by Deprat (1914) and Zaw Win and Sakagami, (1996). Additionally reported from Akasaka was *Colania* (Ozawa and Nishiwaki, 1992), a genus regarded to have evolved into *Lepidolina*. Given that the two provinces existed then, the occurrence of mixed fauna in Kamura and that of the *Colania*–*Lepidolina* lineage from Akasaka suggests that the proposed paleogeographical dichotomy was not strict enough to give a sharp boundary between the two territories. There is likely to have been a certain

transitional domain with mixed biota between the two, and the Kamura limestone may possibly represent such an example. The so-called Late Guadalupian fusuline provinciality, therefore, does not negate, but rather support the mutual correlation between the *Lepidolina* Zone in Kamura and *Yabeina* Zone in Akasaka.

The lithology of this interval is also similar in both the Kamura and Akasaka sections. The Iwato Formation at Kamura (*Lepidolina* Zone) and the Upper Member at Akasaka (*Yabeina* Zone) share the similar carbonaceous black limestone and wackestone. In addition, both the *Lepidolina* and *Yabeina* Zones are characterized by unique large-shelled mollusks. The dark gray limestone of the Upper Member in Akasaka, in particular, is well known for bearing extraordinarily large-sized pelecypods (*Shikamaia*, *Solenomorpha*, etc.) and gastropods (*Bellerophon*, *Pleuratomaria*, etc.). Toriyama (1967) emphasized the uniqueness of this fossiliferous black limestone of the Upper Member in Akasaka and other Upper Guadalupian equivalents in southwest Japan, as the rest of the accreted Permian limestones in Japan are mostly light gray to white.

The barren interval is also common in both the Kamura and Akasaka sections. Between the Capitanian *Lepidolina*/*Yabeina* Zone and the Wuchiapingian *Codonofusiella*–*Reichelina* Zone in both sections, this interval excludes not only large-shelled Verbeekiniidae and Schwageriniidae, but also the *Codonofusiella*–*Reichelina* assemblage. The rock types of the barren interval and its thickness are almost the same in the two sections. The disappearance of Verbeekiniidae appears quite sharp at the bottom of this interval in both sections. In the underlying *Yabeina*/*Lepidolina* Zone, large-shelled Verbeekiniidae occur abundantly in many horizons, often forming fusuline-granule conglomerate-like beds. The LAD horizon of Verbeekiniidae in both sections occurs in such fusuline-enriched bed (Sample 4–2 in Kamura and Sample Yg-0 in Akasaka) and all the overlying rocks completely lack Verbeekiniidae, even as allochem fragments. This implies a regional and simultaneous extinction of the Guadalupian Verbeekiniidae in mid-oceanic shallow-marine carbonate complexes. The sharp extinction of large bivalves also supports the extinction event almost at the same horizon in both sections.

Judging from their almost identical faunal composition, the *Codonofusiella*–*Reichelina* Zone of the Kamura section (i.e. the Mitai Formation) and of the Akasaka section (i.e. Ichihashi Formation) are reasonably mutually correlated. The main difference lies in their thickness, i.e. the *Codonofusiella*–*Reichelina* Zone of the Akasaka section is about five times thicker than at Kamura. The biostratigraphically recognized G–L boundary is equally set at the bottom of this zone in both sections. Comprising almost the same light gray limestone, the Mitai Formation of the Kamura section lithologically resembles the lower 54 m of the Ichihashi Formation in Akasaka. The upper 42 m of the Ichihashi Formation, however, are different from the lower in the predominance of calcareous sponge-bearing



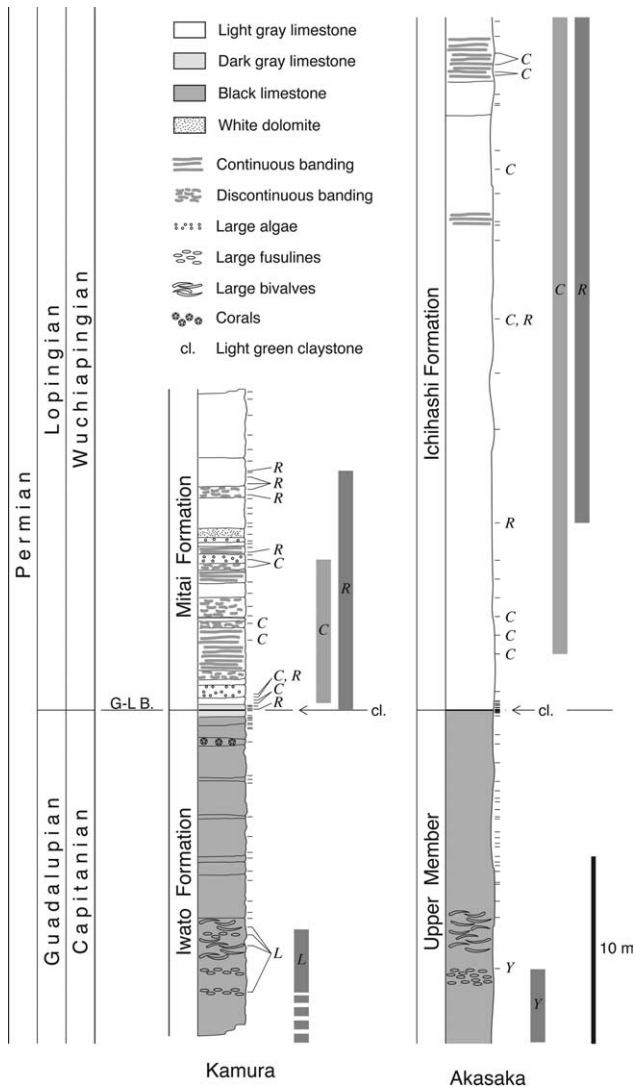


Fig. 8. Stratigraphic correlation between the Middle–Upper Permian Kamura and Akasaka limestone. Letters L, Y, C, and R indicate *Lepidolina*, *Yabeina*, *Codonofusiella*, and *Reichelina*, respectively.

grainstone; this rock type is absent in the Mitai Formation at Kamura. An equivalent for the upper part of the Ichihashi Formation may be missing or not exposed in the Kamura area. These relations indicate that the Mitai Formation may potentially have a much thicker Wuchiapingian interval than currently recognized.

Overall, the Capitanian to Wuchiapingian limestones in the Kamura and Akasaka sections are bio- and lithostratigraphically well correlated (Fig. 8). At present, these two sections are separated from each other by nearly 500 km (Fig. 1). Judging from modern examples of mid-oceanic seamounts, the Kamura and Akasaka limestones accumulated not on a single seamount but on different seamounts, probably separated from each other by several hundred kilometers, even in the same ancient oceanic domain (Isozaki and Ota, 2001). These relations suggest that all the Capitanian to Wuchiapingian stratigraphic records from

the two sections, including the sharp extinction of large-shelled Verbeekiniidae and the turnover by the *Codonofusiella*–*Reichelina* assemblage across the G–L boundary, are of regional context in the mid-oceanic domain of the superocean Panthalassa.

## 7. Geological implications

The present study has clarified that the stratigraphically continuous sections at Kamura and Akasaka range from the Upper Guadalupian to the Lower Lopingian, and has confirmed that both retain an undisturbed G–L boundary interval characterized by a remarkable fusuline biotic turnover. On the basis of this new finding, we discuss here: (1) the significance of the G–L boundary section from the ancient mid-superocean; (2) the biological implication of the end-Guadalupian fusuline extinction; and (3) possible environmental stress at the end of the Guadalupian.

### 7.1. G–L boundary interval from ancient mid-Panthalassa

The G–L boundary represents one of the major Phanerozoic mass extinctions (Jin et al., 1994; Stanley and Yang, 1994), when a pronounced environmental change is considered to have occurred on a global scale. Previously, the source of paleoenvironmental information around the G–L boundary was limited solely to the continental shelf facies, mainly in the Tethyan domain, except for deep-sea chert from the lost superocean (Isozaki, 1997a). As the study sections in Kamura and Akasaka were derived from shallow mid-Panthalassa, the present research confirms for the first time, that a marine biotic turnover occurred in a global context across the G–L boundary throughout Pangean shelf areas plus both shallow and deep sites in mid-Panthalassa.

The Capitanian (the *Lepidolina/Yabeina* Zone and barren interval) in Kamura and Akasaka is composed of the unique black limestone called the Kinshozan facies (Toriyama, 1967). In contrast, the overlying Wuchiapingian consists totally of light gray dolomitic limestone, completely replacing black to dark gray limestone, and the same lithology continues upward in both sections, even to the Uppermost Changhsingian in Kamura (Sano and Nakashima, 1997; Musashi et al., 2001). The Capitanian black limestone and Wuchiapingian light gray dolomitic limestone were deposited in more or less the same very shallow marine environment, and the boundary beds of the both study sections are stratigraphically continuous without hiatus. Such a remarkable lithologic contrast between the Guadalupian and Lopingian is also recognized elsewhere in accreted Permian limestones in Japan (e.g. the Tsukumi limestone in Kyushu—Sano and Tamada, 1994), although other sections are not as continuous as those in Kamura and Akasaka. These observations suggest that the lithological change from Capitanian black carbonaceous limestone to Wuchiapingian light gray dolomitic limestone is a general

feature of all the accreted Permian limestones in Japan. The clear lithologic change observed at the G–L boundary in Kamura and Akasaka probably reflects a unidirectional or irreversible environmental change in a mid-superocean with a profound regional significance.

On the other hand, many shallow marine sections of shelf facies in South China have a remarkable hiatus across the G–L boundary at the so-called ‘pre-Lopingian unconformity’ (Jin et al., 1994), where the critical interval just around the boundary is missing. In the exceptionally well-preserved, continuous sections at Tieqiao and Penglaitan in Laibin, Guangxi (selected as Global Stratotype Section and Point of the G–L boundary), the Capitanian to Wuchiapingian fusulines were reported together with index conodonts (Jin et al., 1998). However, these fusulines are far-transported individuals incorporated into a turbidite, thus they do not provide a high enough stratigraphic resolution to document a detailed fusuline turnover pattern across the G–L boundary. Correlation and comparison is definitely needed between the study sections in Japan and the GSSP of the G–L boundary in order to scrutinize the nature and synchronicity of the boundary event. However, at present, precise correlation, either by fusulines or by conodonts, is not likely. For a better correlation, chemostratigraphic analysis is underway in both study sections, the results of which will be published elsewhere.

### 7.2. Fusuline turnover across the G–L boundary

On the basis of biostratigraphic data from Tethyan domains and mid-continental North America, previous workers noticed the remarkable end-Guadalupian extinction of two major large shelled fusuline families, i.e. Schwagerinidae and Verbeekinidae, and the survival into the Lopingian of three other families with mostly small shells, i.e. Schubertellidae, Ozawainellidae and Staffellidae (e.g. Sheng, 1963; Kanmera et al., 1976; Leven, 1996; Ross, 1995; Wilde et al., 1999). Stanley and Yang (1994) further pointed out that the extinction rate of fusulines at the end of Guadalupian was estimated to be nearly 76% in generic level, and that large-shelled fusulines preferentially became extinct. Such understanding and statistics, however, were derived from data compiled mainly from Pangean shelf sequences, and the detailed extinction pattern of end-Guadalupian fusulines has not yet been fully clarified in any single continuous section. By virtue of their stratigraphic continuity, coupled with continuous occurrence of fusulines, the Kamura and Akasaka limestones are promising targets for further detailed analysis of the extinction pattern of the fusulines with respect to the alleged global environmental change.

At Kamura and Akasaka, the extinction of large-shelled Verbeekinidae appears to be abrupt, indicating that a rapid environmental change may have appeared in the late Capitanian ecosystem in shallow mid-Panthalassa. In both sections, Schwagerinidae, the other large-shelled fusuline

family, became extinct apparently below the G–L boundary (Kambe, 1963; Ozawa and Nishiwaki, 1992). In contrast, all the earliest Wuchiapingian fusulines are members of small-shelled families, i.e. Schubertellidae, Ozawainellidae and Staffellidae. Although these three families have already appeared in the Carboniferous, considerably prior to the G–L boundary, they were less dominant under the proliferation of giant Verbeekinidae and Schwagerinidae during the Guadalupian. After surviving the end-Guadalupian crisis, in turn, they became predominant in the Early Wuchiapingian, filling an empty niche following the extinction. Therefore, the fusuline turnover at the G–L boundary was not a total replacement of one distinct fauna by another, but was a one-sided severe screening of large- and complex-shelled families. The dramatic expansion of the *Codonofusiella–Reichelina* assemblage represents a mirror image of the selected extinction of giant fusulines. The small-shelled families probably had certain advantages in surviving the end-Guadalupian environmental change, even though all fusulines became extinct at the end of the Permian. The results of this study, plus previous works clearly confirm that the extinction of large-shelled Verbeekinidae and Schwagerinidae occurred not only in Pangean shelf areas but also in mid-Panthalassa by the end of the Capitanian. This positively suggests that the end-Guadalupian extinction of large-shelled fusulines occurred in a global scale, and was probably triggered also by geological event(s) on the same scale.

Compiling the fusulines of the *Yabeina* Zone in South China, Stanley and Yang (1994) pointed out that large species (larger than 2 mm in diameter) almost always possess an advanced wall structure called keriotheca, whereas smaller ones do not. Paying attention to the difference in size and superstructure of shells, Ross (1972) speculated that activity of photosynthetic symbiotic algae was critical for the survival of Permian large fusulines. Ross’s classic notion was recently followed by a study of keriothecal wall of Guadalupian large-shelled species that is regarded to have functioned in algal symbiosis (Wilde, 2003; Yang et al., 2004; Vachard et al., 2004). In general, many modern benthic foraminifera, mostly large-shelled with ample internal accommodation space for voluminous cytoplasm, are highly dependent on symbiotic algae metabolically (e.g. Leutenegger, 1984; Hallock, 1999). By analogy, the Permian large-shelled fusulines with keriothecal walls (Verbeekinidae and Schwagerinidae) are likely have fostered symbiotic algae (Ross, 1972; Wilde, 2003; Yang et al., 2004; Vachard et al., 2004). In contrast, small-shelled fusulines with simple wall structure are regarded to have been free from algal symbiosis. This suggests that the end-Guadalupian fusuline extinction occurred in highly selective manner in terms of symbiosis-related shell size and/or of shell structure. Judging from the size-screening across the G–L boundary, we speculate that decline or dying-out of symbiotic algae by certain reason may have played a key role in the extinction of the Guadalupian large-shelled fusulines.

### 7.3. Barren interval and environmental stress(es)

It is noteworthy that the rock type and thickness of the barren interval is similar in the two study sections, despite the supposed great distance between the two paleo-seamounts of Kamura and Akasaka. The common feature of a barren interval probably represent the end-Guadalupian regional environmental conditions in low-latitude, shallow mid-Panthalassa. The bottom of the barren interval corresponds to LAD of *Lepidolina/Yabeina*, i.e. that of the family Verbeekinidae, whereas its top marks the abrupt domination of the Wuchiapingian *Codonofusiella-Reichelina* assemblage. The bioclast composition of black limestone in the barren interval suggests that a harsh environment prevailed, suppressing biodiversity and the body size of benthic organisms. The enigmatic occurrence of *Waagenophyllum* from the upper part of the barren interval at Kamura may be explained as due to reworking; however, a detailed check is needed. Thus we speculate that the barren interval, immediately below the G–L boundary, represents a period of high environmental stress(es), in which the pre-existing fauna were pressured and subsequent

appearance/radiation of newcomers was suppressed (Fig. 9). In this regard, the biostratigraphically recognized G–L boundary corresponds to the onset of a new ecosystem, immediately after the disappearance of the stress. Although the nature of the environmental stress(es) is still unknown, the remarkable reduction in fusuline size across the barren interval may suggest a possible cause of the end-Guadalupian global environmental change and extinction.

As mentioned above, the dying-out of symbiotic algae may have driven the elimination of large fusulines. From similar point of view Yang et al. (2004) speculated that a sea-level drop was responsible for killing large fusulines with algal symbiosis; however, they did not present any direct evidence. For suppressing algal photosynthesis on a regional scale, several causes can be responsible; i.e. global cooling, warming and/or darkening etc. Among all the possible causes, the blocking of sunlight appears most effective. Under a dim light even in shallow seas, photosynthesis of symbiotic algae may have declined or almost ceased below the critical level to sustain large fusulines and other symbiont-dependant animals such as rugose corals. This seems apparently consistent with the notion that the oxygen-depleted condition (superanoxia) started in the deep-sea just around the G–L boundary (Isozaki, 1994, 1997a).

Violent volcanism, such as gave rise to the Emeishan continental flood basalts in South China, was possibly an ultimate cause of the end-Guadalupian mass extinction on the basis of synchronicity (e.g. Chung et al., 1998). On the other hand, Isozaki (2000) suggested that the end-Permian double mass extinction event was caused by extraordinarily large-scale, violent volcanism, not of basaltic but of silicic, thus highly explosive, nature, which shut off photosynthesis on a global scale. This interpretation is supported partly by the recent recognition of acidic tuff at the G–L boundary horizon in both a mid-oceanic carbonate buildup (Isozaki and Ota, 2001) and a carbonate platform on a continental shelf in South China (Isozaki et al., 2004).

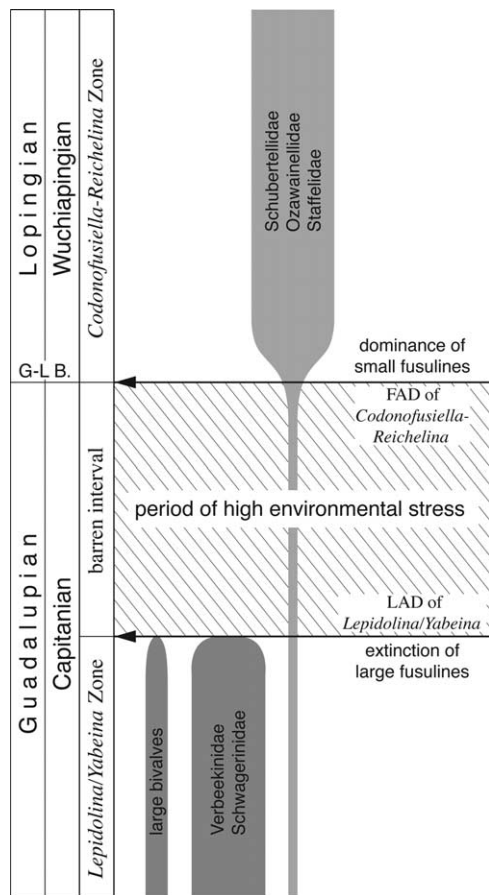


Fig. 9. Schematic diagram showing the high environmental stress period in mid-Panthalassa immediately before the Guadalupian–Lopingian boundary.

## 8. Conclusion

The current study has demonstrated that shallow marine carbonates of mid-Panthalassa record a major biotic turnover in fusulines across the G–L boundary. Particularly important is the recognition of the barren interval immediately below the biostratigraphically recognized G–L boundary that probably represents a critical duration of high environmental stress(es). Thus concerning the G–L boundary event, this barren interval should be checked elsewhere in the world by litho-, bio- and chemostratigraphic analyses.



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## References

- Akasaka Research Group, 1956. Geological studies of the Akasaka limestone. *Chikyu-Kagaku* 26–27, 10–18 (in Japanese).
- Chung, S.L., Jahn, B.M., Wu, G.Y., Lo, C.H., Cong, B.L., 1998. The Emeishan flood basalt in SW China: a mantle plume initiation model and its connection with continental breakup and mass extinction at the Permian–Triassic boundary. In: Flower, M.F.J., Chung, S.L., Lo, C.H., Lee, T.Y. (Eds.), *Mantle Dynamics and Plate Interaction in East Asia* American Geophysical Union, Geodynamic Series. 27, pp. 47–58.
- Deprat, J., 1914. Etude des Fusulinides du Japon, de Chine et d'Indochine. Etude comparative des Fusulinides d'Akasaka (Japon) et des Fusulinides de Chine et d'Indochine. *Memoires du Service Géologique de d'Indochine* 3, 1–45.
- Erwin, D.H., 1993. *The Great Paleozoic Crisis*. Columbia University Press, New York, p. 327.
- Gümbel, C.W., 1874. Das japanische gesteine. *Das Ausland* Stuttgart 47 (24), 479.
- Hallock, P., 1999. Symbiont-bearing foraminifera. In: Gupta, B.K.S. (Ed.), *Modern Foraminifera*. Kluwer, New York, pp. 123–139.
- Henderson, C.M., Mei, S.L., Wardlaw, B.R., 2003. New conodont definition at the Guadalupian–Lopingian boundary. In: Hills, L.V., Henderson, C.M., Bamber, E.W. (Eds.), *Carboniferous and Permian of the World*. Canadian Society of Petroleum Geologists, 19, pp. 72–735.
- Igo, H., 1981. Permian conodont biostratigraphy of Japan. *Palaeontological Society of Japan, Special Paper* 24, pp. 1–50.
- Ishii, K., 1990. Provinciality of some fusulinacean faunas in Japan. In: Ichikawa, K., Mizutani, S., Hara, I., Hada, S., Yao, A. (Eds.), *Pre-Cretaceous Terranes of Japan*. Nihon-Insatsu, Osaka, pp. 297–305.
- Ishii, K., Okimura, Y., Ichikawa, K., 1985. Notes on Tethys biogeography with reference to Middle Permian fusulinaceans. In: Nakazawa, K., Dickins, J.M. (Eds.), *The Tethys: Her Paleogeography and Paleobiogeography from Paleozoic to Mesozoic*. Tokai University Press, Tokyo, pp. 139–155.
- Isozaki, Y., 1987. End-Permian convergent zone along the northern margin of the Kurasegawa landmass and its products in central Shikoku, southwest Japan. *Journal of Geosciences Osaka City University* 30, 51–131.
- Isozaki, Y., 1994. Superanoxia across the Permo-Triassic boundary: record in accreted deep-sea pelagic chert in Japan. In: Embry, A.F., Beauchamp, B., Glass, D.J. (Eds.), *Pangea: Global Environments and Resources*. Canadian Society of Petroleum Geologists, Memoir. 17, pp. 805–812.
- Isozaki, Y., 1997a. Permo-Triassic boundary superanoxia and stratified superocean: records from lost deep-sea. *Science* 276, 235–238.
- Isozaki, Y., 1997b. Jurassic accretion tectonics of Japan. *The Island Arc* 6, 25–51.
- Isozaki, Y., 2000. Plume winter: a scenario for the greatest biosphere catastrophe across the Permo-Triassic boundary. Abstracts of 31st International Geological Congress, CD-ROM.
- Isozaki, Y., Ota, A., 2001. Middle/Upper Permian (Maokouan/Wuchapingian) boundary in mid-oceanic paleo-atoll limestone in Kamura and Akasaka, Japan. *Proceedings of Japan Academy* 77(B), 104–109.
- Isozaki, Y., Maruyama, S., Furuoka, F., 1990. Accreted oceanic materials in Japan. *Tectonophysics* 181, 179–205.
- Isozaki, Y., Yao, J.K., Matsuda, T., Sakai, H., Ji, Z.S., Shimizu, N., Kobayashi, N., Kawahata, H., Nishi, H., Takano, M., Kubo, T., 2004. Stratigraphy of the middle–upper Permian and Lowermost Triassic at Chaotian, Sichuan, China—record of end-Permian double mass extinction event. *Proceedings of Japan Academy* 80(B), 10–16.
- Jin, Y.G., Zhang, J., Shang, Q.H., 1994. Two phases of the end-Permian mass extinction. In: Embry, A.F., Beauchamp, B., Glass, D.J. (Eds.), *Pangea: Global Environments and Resources*. Canadian Society of Petroleum Geologists, Memoir. 17, pp. 813–822.
- Jin, Y., Wardlaw, B.R., Glenister, B.F., Kotlyar, G.V., 1997. Permian chronostratigraphic subdivisions. *Episodes* 20, 10–15.
- Jin, Y., Mei, S., Wang, W., Wang, X., Shen, S., Shang, Q., Chen, Z., 1998. On the Lopingian series of the Permian system. *Palaeoworld* 9, 1–18.
- Kambe, N., 1963. On the boundary between the Permian and Triassic Systems in Japan with the description of the Permo-Triassic formations at Takachiho-cho. Miyazaki Prefecture in Kyushu and the Skytic fossils contained. *Geological Survey of Japan, Report* 198, 1–68.
- Kambe, N., Saito, M., 1957. The Lower Triassic discovered in the Takachiho district, Miyazaki prefecture. *Bulletin of the Geological Survey of Japan*, 8.
- Kanmera, K., Nakazawa, K., 1973. Permian–Triassic relationships and faunal changes in the eastern Tethys. In: Logan, A., Hills, L.V. (Eds.), *The Permian and Triassic Systems and their Mutual Boundary*. Canadian Society of Petroleum Geologists, Memoir. 2, pp. 100–119.
- Kanmera, K., Nishi, H., 1983. Accreted oceanic reef complex in Southwest Japan. In: Hashimoto, M., Ueda, S. (Eds.), *Accretion Tectonics in the Circum-Pacific Regions*. Terra Science, Tokyo, pp. 195–206.
- Kanmera, K., Ishii, K., Toriyama, R., 1976. The evolution and extinction patterns of Permian fusulinaceans. In: Kobayashi, T., Hashimoto, W. (Eds.), *Geology and Palaeontology of Southeast Asia*. 17, 129–154.
- Kawai, K., Ono, T., Hori, M., 1997. Report on the new area of *Codonofusiella-Reichelina* zone from Akasaka Limestone. *Research Report of Gifu Prefecture Museum* 18, pp. 11–17 (in Japanese).
- Koike, T., 1996. The first occurrence of Griesbachian conodonts in Japan, *Transaction and Proceedings of the Palaeontological Society of Japan, New Series*, vol. 181 pp. 337–346.
- Leutenegger, S., 1984. Symbiosis in benthic foraminifera: specificity and host adaptations. *Journal of Foraminiferal Research* 14, 16–35.
- Leven, E.J., 1996. The Midian stage of the Permian and its boundary. *Stratigraphy and Geological Correlation* 4, 540–551.
- Logan, A., Hills, L.V. (Eds.), 1974. *The Permian and Triassic Systems and their Mutual Boundary*. Canadian Society of Petroleum Geologists, Memoir. 2, p. 766.
- Maruyama, S., Yamasaki, M., 1978. Paleozoic submarine volcanoes in the high-P/T metamorphosed Chichibu system, eastern Shikoku, Japan. *Journal of Volcanology and Geothermal Research* 4, 199–216.
- Murata, T., Ishii, K., Okimura, Y., 1978. Late Permian microfauna above the *Yabeina globosa* Zone in the Akasaka limestone, Abstracts, 85th Annual Meeting of the Geological Society of Japan 240, 1978 (in Japanese).
- Murata, K., Goto, H., Hada, S., 2003. Late Permian fusulinids yielded in limestone blocks in the Jurassic accretionary complex of the Sambosan Terrane in the Kamura area, Kyushu, Southwest Japan *Bulletin of Kobe Women's University* 36, 49–62 (in Japanese).
- Musashi, M., Isozaki, Y., Koike, T., Kreulen, R., 2001. Stable carbon isotope signature in mid-Panthalassa shallow-water carbonates across the Permo-Triassic boundary: evidence for <sup>13</sup>C-depleted ocean. *Earth and Planetary Science Letters* 196, 9–20.

- Nishimura, Y., Hase, A., Okimura, Y., Kuwata, M., 1979. Paleozoic greenstones in and around Taishaku-dai, Chugoku district, Southwest Japan. *The Journal of the Geological Society of Japan* 85, 413–426.
- Ota, A., Kanmera, K., Isozaki, Y., 2000. Stratigraphy of the Permian Iwato and Mitai Formations in the Kamura area, Southwest Japan: Maokouan, Wuchiapingian, and Changhsingian carbonates formed on paleo-seamount. *The Journal of the Geological Society of Japan* 106, 853–864 (in Japanese).
- Ozawa, Y., 1927. Stratigraphical studies of the fusulina limestone of Akasaka, province of Mino. *Journal of Faculty of Science, Imperial University of Tokyo, Sect. II* 2, 1146–1221.
- Ozawa, T., Nishiwaki, N., 1992. Permian Tethyan Biota and Sedimentary Facies of the Akasaka Limestone Group, Field Trip Guidebook of International Geological Congress B13. 189–195.
- Ross, C.A., 1972. Paleobiological analysis of fusulinacean (Foraminiferida) shell morphology. *Journal of Paleontology* 46, 719–728.
- Ross, C.A., 1995. Permian fusulinaceans. In: Scholle, P.A., Peryt, T.M., Ulmer-Scholle, D.S. (Eds.), *The Permian of Northern Pangea 1: Paleogeography, Paleoclimates, Stratigraphy*. Springer, New York, pp. 167–185.
- Rui, L., Zhao, J.M., Mu, X.N., Wang, K.L., Wang, Z.H., 1984. Restudy on the Wujiaping Limestone in Lianshan, Hanzhong, Shaanxi. *Journal of Stratigraphy* 8, 179–193.
- Saito, M., Kambe, N., Katada, M., 1958. Mitai 1/50,000 geological sheet-map and explanatory text. Geological Survey of Japan (in Japanese).
- Sakagami, S., 1980. Preliminary note on the upper part of the Akasaka Limestone Group, Japan. *Proceedings of Japan Academy* 56, 25–29.
- Sano, H., Kanmera, K., 1988. Paleogeographic reconstruction of accreted oceanic rocks, Akiyoshi, southwest Japan. *Geology* 16, 600–603.
- Sano, H., Nakashima, K., 1997. Lowermost Triassic (Griesbachian) microbial bindstone–cementstone facies, Southwest Japan. *Facies* 36, 1–24.
- Sano, H., Tamada, E., 1994. Collisional collapse-related internal destruction of Carboniferous–Permian limestone in Jurassic accretionary complex, southwest Japan. *Journal of Geological Society of Japan* 100, 828–847.
- Schwager, C., 1883. Carbonische Foraminiferen aus China und Japan, Richthofen's China, Band IV, pp. 106–159.
- Sheng, J.C., 1963. Permian fusulinids of Kwangsi, Kueichow and Szechuan. *Palaeontologica Sinica, New Series*, vol. 1–115, pp. 129–247.
- Stanley, S.M., Yang, X., 1994. A double mass extinction at the end of the Paleozoic Era. *Science* 266, 1340–1344.
- Tatsumi, Y., Kani, T., Ishizuka, H., Maruyama, S., Nishimura, Y., 2000. Activation of Pacific mantle plumes during the Carboniferous: evidence from accretionary complexes in southwest Japan. *Geology* 28, 580–582.
- Toriyama, R., 1967. Fusulinacean zones of Japan, *Memoir of the Faculty of Science, Kyushu University, Series D*, 18, 35–260.
- Ueno, K., 1996. Late Early to Middle Permian fusulinacean biostratigraphy of the Akiyoshi Limestone Group, Southwest Japan, with special reference to the verbeekiniid and neoschwageriniid fusulinacean biostratigraphy and evolution. *Szience Archeologia, Storia e Scienze naturali* 11, 77–104.
- Vachard, D., Munnecke, A., Servais, T., 2004. New SEM observations of keriothecal walls: implications for the evolution of Fusulinida. *Journal of Foraminiferal Research* 34, 232–242.
- Wakita, K., 1988. Origin of chaotically mixed rock bodies in the Early Jurassic to Early Cretaceous sedimentary complex of the Mino terrane, central Japan. *Bulletin of Geological Survey of Japan* 39, 675–757.
- Watanabe, K., Kanmera, K., Nakashima, K., 1979. Conodont biostratigraphy in the Kamura limestone (Triassic), Takachiho-cho, Nishiusukigun, Miyazaki Prefecture. In: Koike, T., Igo, H. (Eds.), *Biostratigraphy of Permian and Triassic Conodonts and Holothurian Sclerites in Japan*, pp. 127–137 (in Japanese).
- Watanabe, M., Abe, S., Fujiwara, S., 1967. Study of carbonaceous materials in Akasaka limestone. *Geochemistry* 1, 1–6 (in Japanese).
- Wilde, G.L., 2003. End Permian; end fusulinaceans. In: Hills, L.V., Henderson, C.M., Bamber, E.W. (Eds.), *Carboniferous and Permian of the World*. Canadian Society of Petroleum Geologists, *Memoir* 19, pp. 616–629.
- Wilde, G.L., Rudine, S.F., Lambert, L.L., 1999. Formal designation: Reef Trail Member, Bell Canyon Formation, and its significance for recognition of the Guadalupian–Lopingian boundary. *Society of Economic Geology, Paleontology and Mineralogy, Special Publication* 65, 63–83.
- Yamato-Omine Research Group, 1981. Paleozoic and Mesozoic Systems in central area of the Kii Mountains, *Excursion Guidebook of Annual Meeting of the Association for the Geological Collaboration in Japan*, Osaka p. 88 (in Japanese).
- Yang, X.N., Liu, J.R., Shi, G.J., 2004. Extinction process and patterns of Middle Permian fusulinaceans in southwest China. *Lethaia* 37, 139–147.
- Zaw Win, W., 1999. Fusuline biostratigraphy and palaeontology of the Akasaka limestone, Gifu prefecture, Japan. *Bulletin of Kitakyushu Museum of Natural History* 18, 1–76.
- Zaw Win, W., 2000. Paleoenvironmental and paleogeographical consideration on the Akasaka limestone, Gifu prefecture, Japan. *Bulletin of Kitakyushu Museum of Natural History* 19, 9–23.
- Zaw Win, W., Sakagami, S., 1996. Preliminary note on the rediscovery of '*Neoschwagerina (Sumatrina) multiseptata* Deprat' from Akasaka, Japan, *Transactions and Proceedings of the Palaeontological Society of Japan, New Series*, vol. 183 pp. 547–550.