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Impact of long-term climate change and sea-level fluctuation on Mississippian to Permian mid-oceanic atoll sedimentation (Akiyoshi Limestone Group, Japan)

Hiroyoshi Sano

Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, 812-8581, Japan

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Abstract

To understand the impacts of long-term climatic episodes and sea-level changes on mid-oceanic atoll sedimentation, the stratigraphic changes of litho- and bio-facies, and stratigraphic levels of freshwater diagenetic alteration and biostratigraphic discontinuity of the Akiyoshi Limestone Group (upper Viséan to upper Capitanian) were reviewed. This group records approximately 70 million years of atoll sedimentation in a mid-oceanic realm of the Panthalassa Ocean, which developed nearly synchronously with the Late Paleozoic Gondwana glaciation.

The entire succession of the Akiyoshi Limestone Group was divided into four facies associations; skeletal-oolitic grainstone, muddy limestone, muddy limestone–skeletal grainstone, and reefal limestone associations. Skeletal-oolitic grainstone and reefal limestone associations (upper Viséan to Bashkirian) are characterized by an abundance of oolite and crinoidal grainstone, and reef facies of warm-adapted metazoan reef-builders (corals, *Chaetetes*, and bryozoans), respectively. Characteristics of skeletal-oolitic grainstone and reefal limestone associations indicate their deposition in a warm climate with elevated sea-level. Muddy limestone association (Moscovian to Kasimovian) records the demise of the warm-adapted metazoan reef builders and frequent emergence events of the buildup. Many geochemical data support the significant drop in temperature during Moscovian through Kasimovian time. These depositional and biotic events of muddy limestone association indicate that its sedimentation was strongly affected by cool climate and generally low sea-level. Muddy limestone–skeletal grainstone association is characterized by an upward-increasing significance of calcimicrobes, calcareous algae, and calcisponges. The succession records less frequent emergence events than that of muddy limestone association II. These characters reflect a warming climate and sea-level rise in Gzhelian to Capitanian time.

The climate episodes and sea-level changes interpreted from the Akiyoshi Limestone Group generally correspond to the global trend of Mississippian to Permian long-term climatic change and sea-level fluctuation related to the major glacial events of Gondwana glaciation. The late Viséan to Bashkirian warm climate and elevated sea-levels, Moscovian to Kasimovian cooling and sea-level lowering, and Gzhelian to Capitanian warming and sea-level rise recorded in the Akiyoshi buildup are comparable to the global climate model and sea-level fluctuation, which contain Early to Middle Mississippian pre-glacial warm climate and highstands, Middle to Late Pennsylvanian cooling and related glacio-eustatic sea-level fluctuation at the culmination of Gondwana glaciation, and Early to Middle Permian global warming and sea-level rise due to the retreat of Gondwana ice sheets.

Akiyoshi atoll sedimentation was most significantly affected Pennsylvanian global cooling and related sea-level lowering, but their impact was short-lived. The onset of the cooling and frequent emergence events in the Akiyoshi buildup occurred delayed, approximately 10 millions years later than that of comparable episodes on the Pangean shelves. The post-glacial warming in the

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E-mail address: sano@geo.kyushu-u.ac.jp.

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Akiyoshi buildup started at least several millions of years earlier than in epicontinental seas of the Pangea. This phenomenon may be due to the palaeoposition of the Akiyoshi buildup in a mid-oceanic realm of the Panthalassa Ocean.

Keywords: Atoll carbonates; Late Paleozoic global cooling; Emergence; Akiyoshi Limestone Group; Panthalassa Ocean

1. Introduction

It is widely accepted that climatic changes, especially the temperature component, and related sea-level fluctuations act as the most critical constraints on the sedimentary evolution and biotic association of ancient reefs and platform carbonates and their sequence stratigraphic architecture (e.g., Handford and Louks, 1993; Read, 1995; James, 1997; Kiessling, 2001). Many researchers have revealed the archival potential of shelf carbonates to record global climatic changes and sea-level fluctuations (e.g., Beauchamp, 1994; Steinhauff and Walker, 1995). In contrast, mid-oceanic atoll carbonates have never been at the center of the carbonate sedimentology. Though much less voluminous than shelf carbonates, mid-oceanic atoll carbonates are nevertheless important as recorders of global environmental changes and their impacts. Sedimentological, paleontological, geochemical, sequence stratigraphic, and geomorphologic studies of atoll-type buildups in the modern Pacific Basin have greatly contributed to the understanding of the post-Cretaceous global climate changes and related sea-level fluctuation (e.g., Schlanger and Silva, 1986; Lincoln and Schlanger, 1991; Jenkyns and Wilson, 1999; Flood, 2001; Dickinson, 2004). Nevertheless, the sedimentary evolution and biotic assemblage of pre-Jurassic mid-oceanic atoll carbonates have been poorly documented and remain uncertain. This is largely because most pre-Jurassic mid-oceanic atoll carbonates were involved in subduction-generated tectonic events, and consequently experienced pervasive and intense deformation (e.g., Struik et al., 2001). As pointed out by Kiessling et al. (2002), the Paleozoic and Mesozoic global paleoenvironmental reconstruction has been done with shortage of data from mid-oceanic atoll carbonates and reflects primarily the continental records.

To emphasize upon the significance of mid-oceanic atoll carbonates for more “global” paleoenvironmental reconstruction, Sano et al. (2004) examined depositional and biotic responses of the Akiyoshi Limestone Group, reconstructed as remnant of a Mississippian to Permian mid-oceanic atoll-type buildup by Sano and Kanmera (1988), to the global cooling and sea-level lowering at the peak time of Gondwana glaciation. Also, Nakazawa and Ueno (2004) recognized a sequence stratigraphic boundary formed by a Mid-Permian sea-level change in the Akiyoshi Limestone Group.

These recent studies show the archival potential of the Akiyoshi Limestone Group to record the global climate change and related sea-level fluctuation. These authors, however, examined only limited parts of the Akiyoshi atoll sedimentation, that is, Moscovian–Kasimovian strata that were deposited concurrently with Gondwana glaciation (Sano et al., 2004), and Middle Permian strata that accumulated in the post-glaciation period (Nakazawa and Ueno, 2004). The entire Akiyoshi Limestone Group is expected to record the impacts of middle Mississippian onset of glaciation (Smith and Reed, 2000), middle to late Pennsylvanian culmination (Otto-Bliesner, 1996), as well as middle Early to early Middle Permian deglaciation (Beauchamp and Baud, 2002) in a mid-oceanic setting.

In order to interpret the impacts of the long-term climatic change and sea-level fluctuation on a mid-oceanic atoll sedimentation and biotic assemblages, this paper reviews the stratigraphic distribution of the major limestone facies and biotic components, diagenetic alteration, and hiatuses throughout the Akiyoshi Limestone Group. On the basis of facies interpretation of this group within a well constrained chronostratigraphic framework, this paper infers the climatic changes and sea-level fluctuation in the Akiyoshi buildup. It also compares the climate events and sea-level fluctuation recorded in the Akiyoshi buildup with those recorded in the Late Paleozoic Pangean shelf sediments.

2. Geologic outline

Rocks of the Akiyoshi terrane crop out in several separate areas of southwest Japan (Fig. 1). The Akiyoshi terrane comprises a Permian subduction-generated accretionary complex, consisting of a tectonic aggregate of Mississippian to Permian unmetamorphosed oceanic and terrigenous rocks (Kanmera and Nishi, 1983). Kanmera et al. (1990) interpreted the Akiyoshi terrane as having been formed by a tectonic collision and subsequent accretion of seamounts capped by shallow-marine limestone and flanked by deep-water chert, all of which were tectonically intermingled with a trench-fill sediment and then incorporated into an accretionary wedge. These accretion events are in-

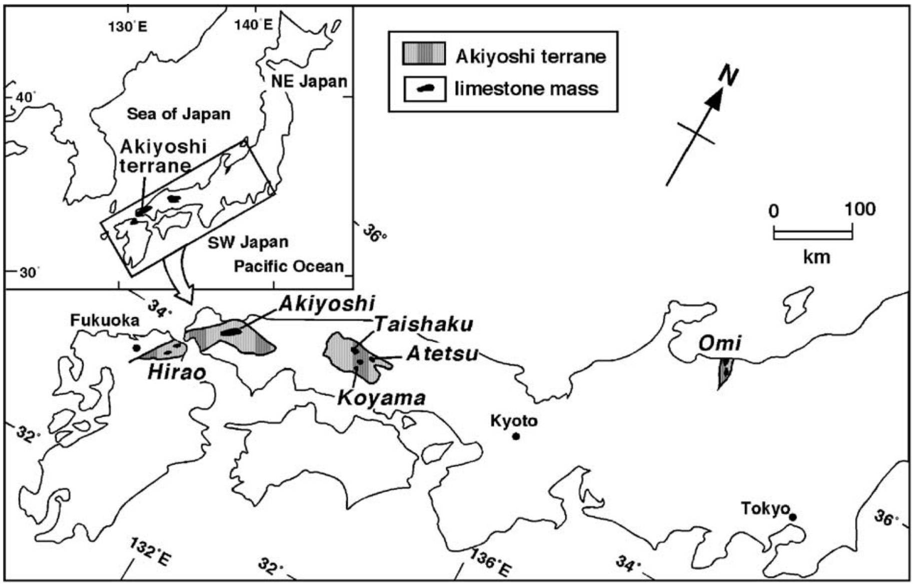

Fig. 1. Index map showing approximate distribution of Akiyoshi terrane and its major limestone masses, which are composed of Mississippian to Permian seamount-top shallow-marine limestone units equivalent with the Akiyoshi Limestone Group.

ferred to have happened in late Middle to earliest Late Permian on the basis of the youngest age of the trench-fill sediment (Sano and Kanmera, 1991c).

Major lithologic components of the Akiyoshi terrane include shallow-marine limestone, basaltic rocks, chert, graywacke, mudstone, and silicic tuff. Sano and Kanmera (1988) grouped Akiyoshi terrane rocks into two tectonostratigraphic units. One comprises a terrigenous rock assemblage of upper Middle to lower Upper Permian graywacke, mudstone, silicic tuff with slump blocks of shallow-marine limestone, and is interpreted to be a trench-fill deposit. The other unit consists of an oceanic

Fig. 2. Gently rolling hills of central part of Akiyoshi-dai plateau, with numerous limestone pinnacles Foreground view is approximately 200 m wide.

rock assemblage of Mississippian to Permian shallow-marine limestone, and deep-water spicular chert and radiolaria-bearing chert, all resting upon basaltic rocks formed by off-ridge, hotspot volcanic activity in an equatorial zone of the Panthalassa Ocean (Fujiwara, 1967; Ozawa, 1987; Sano et al., 2000).

Sano and Kanmera (1988) subdivided the oceanic rock unit into four facies assemblages: (A) seamount-top facies of shallow-marine limestone, (B) bank margin-to-slope and slope-to-basin facies composed of shallow-marine allodapic limestone with spicular chert, (C) deep-water basin facies of spicular chert with allodapic limestone, which was displaced down from the seamount-top area, and (D) deep-water radiolarian-bearing chert facies with no allodapic limestone of shallow-marine origin. Biostratigraphic studies reveal that both the shallow-marine limestone and deep-water siliceous rocks units are nearly coeval with each other, dated as upper Viséan to upper Capitanian (Uchiyama et al., 1986; Sano and Kanmera, 1988). Though tectonically separated from one another at present, the sediments of the four facies assemblages are interpreted to be sediments deposited on and around a seamount and having lateral continuity with one another.

3. Litho- and bio-facies of Akiyoshi Limestone Group

3.1. General stratigraphic remarks of litho- and bio-facies

The Akiyoshi Limestone Group is the most thoroughly investigated unit of seamount-top shallow-marine limestone facies throughout the entire Akiyoshi terrane (Fig. 1). The rocks of the Akiyoshi Limestone Group are exposed as a large mass, approximately 7 × 15 km, forming gently rolling hills of the Akiyoshi-dai plateau with a spectacular karst landscape near Akiyoshi (Fig. 2). Two other units of the Akiyoshi terrane rocks, deep-water spicular chert unit and terrigenous rocks unit, designated as the Ota Group and Tsunemori Formation, respectively, crop out adjoining the Akiyoshi Limestone Group (Fig. 3).

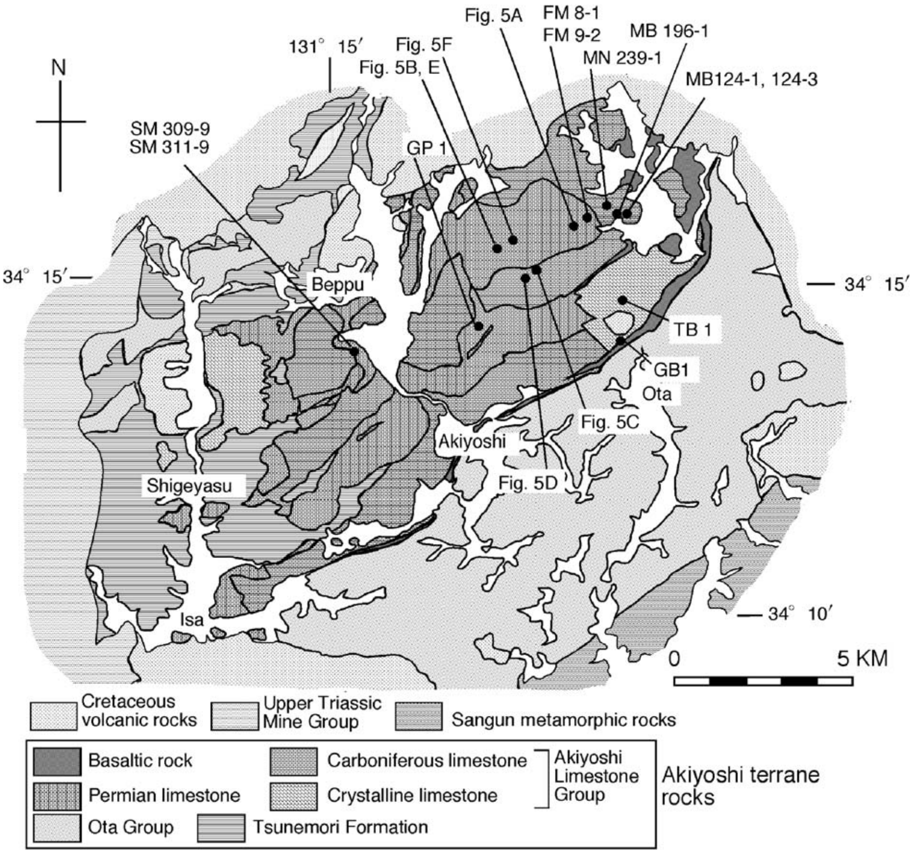

Fig. 3. Simplified geologic map of Akiyoshi area after Kanmera and Nishi (1983). Localities of outcrop photos in Fig. 5 and specimens illustrated in Figs. 7 and 8 are indicated with sample numbers.

The Akiyoshi Limestone Group comprises a basal unit of basaltic rocks and an overlying thick pile wholly of shallow-marine limestone (Fig. 4). Its entire succession of 700 to 800 m (Ota, 1968) is devoid of land-derived clastic materials and records atoll sedimentation at the top of a seamount (Kanmera and Nishi, 1983; Sano and Kanmera, 1988).

The basal unit consists mainly of basaltic volcaniclastic rocks with minor pillow lavas and lenticular beds of reddish oolite and crinoidal grainstone having a great admixture of volcaniclastic detritus (Fig. 4). The basaltic volcaniclastic rocks grade upward into upper Viséan, reddish, volcaniclastic debris-rich, oolite-oolitic grainstone and skeletal grainstone, which are, in turn, followed by a thick succession of light gray skeletal limestones rich in diverse, shallow-marine organic debris, with metazoan reefal facies and microbialite facies. The limestone occupying the main part of the Akiyoshi Limestone Group is entirely massive (Fig. 5A) and lacks impurities such as carbonaceous matter and volcaniclastic debris. Depositional surfaces are recognized only as indistinct laminae crowded with skeletal debris in places, where rocks are excellently exposed (Fig. 5B).

Carbonate rocks of the Akiyoshi Limestone Group have been dated chiefly by fusulinids (e.g., Ota, 1968; Ota and Ota, 1993; Ueno, 1989, 1995; Ozawa and Kobayashi, 1990; Watanabe, 1991), and also by smaller foraminifers (e.g., Matsusue, 1995), corals (e.g., Ota, 1968; Haikawa, 1986), brachiopods (e.g., Yanagida, 1962; Yanagida et al., 1971), bryozoans (e.g., Sakagami, 1964a,b; Sakagami and Sugimura, 1979, 1981), and conodonts (e.g., Igo and Koike, 1965; Igo, 1973; Haikawa, 1988). A great deal of fusuline and smaller foraminifer biostratigraphic work, pioneered by Toriyama (1958), show that the Akiyoshi Limestone Group ranges from upper Viséan to the upper Capitanian (Fig. 4; *Endothyra* Zone to *Lepidolina multiseptata shiraiwensis* Zone). Akiyoshi atoll sedimentation is thought to have ended at the end of the Capitanian, because no reliable Upper Permian fossils have been so far documented in the Akiyoshi Limestone Group.

3.2. Major limestone facies and biotic components

Mainly on the basis of literature review along with new observations, diverse limestone-types of the Aki-

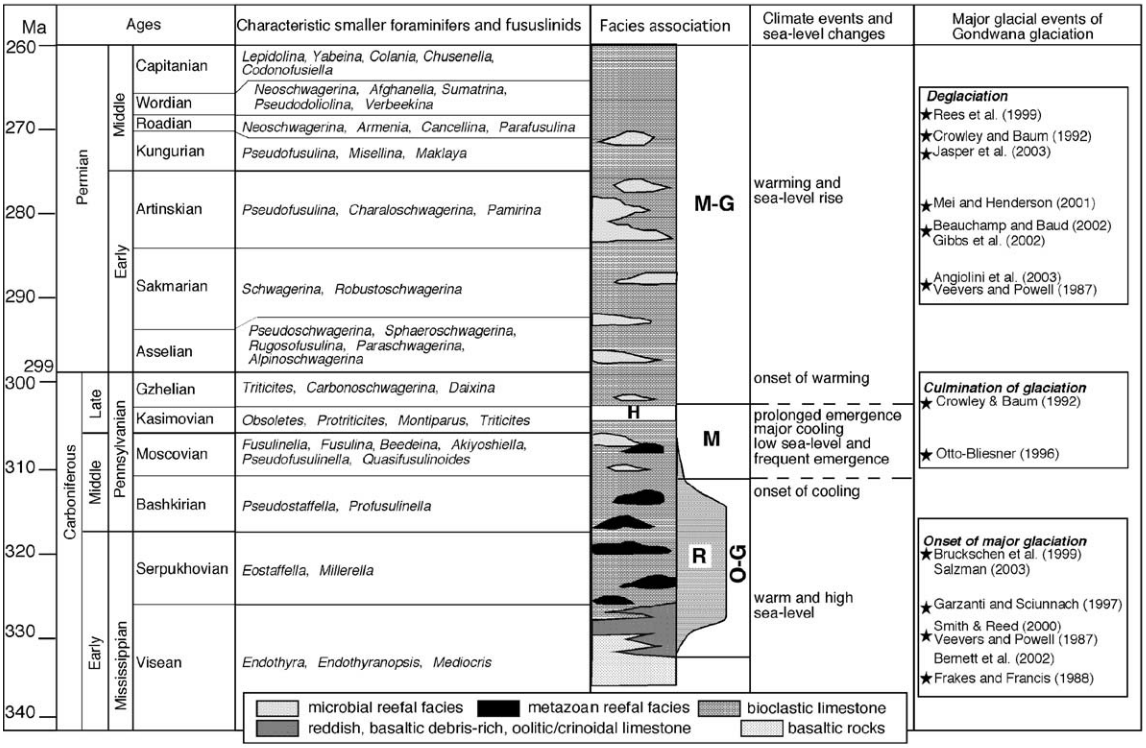

Fig. 4. Time distribution of four facies associations of Akiyoshi Limestone Group and major glacial events of Gondwana glaciation, with characteristic fusulines and smaller foraminifers of Viséan to Capitanian stages. Composite columnar section modified after Sano and Kanmera (1996). Abbreviation G-O, M, M-G, and R stand for skeletal-oolitic grainstone, muddy limestone, muddy limestone–skeletal grainstone, and reefal limestone associations. Radiometric age and stage division from Davydov et al. (2004) and Wardlaw et al. (2004).

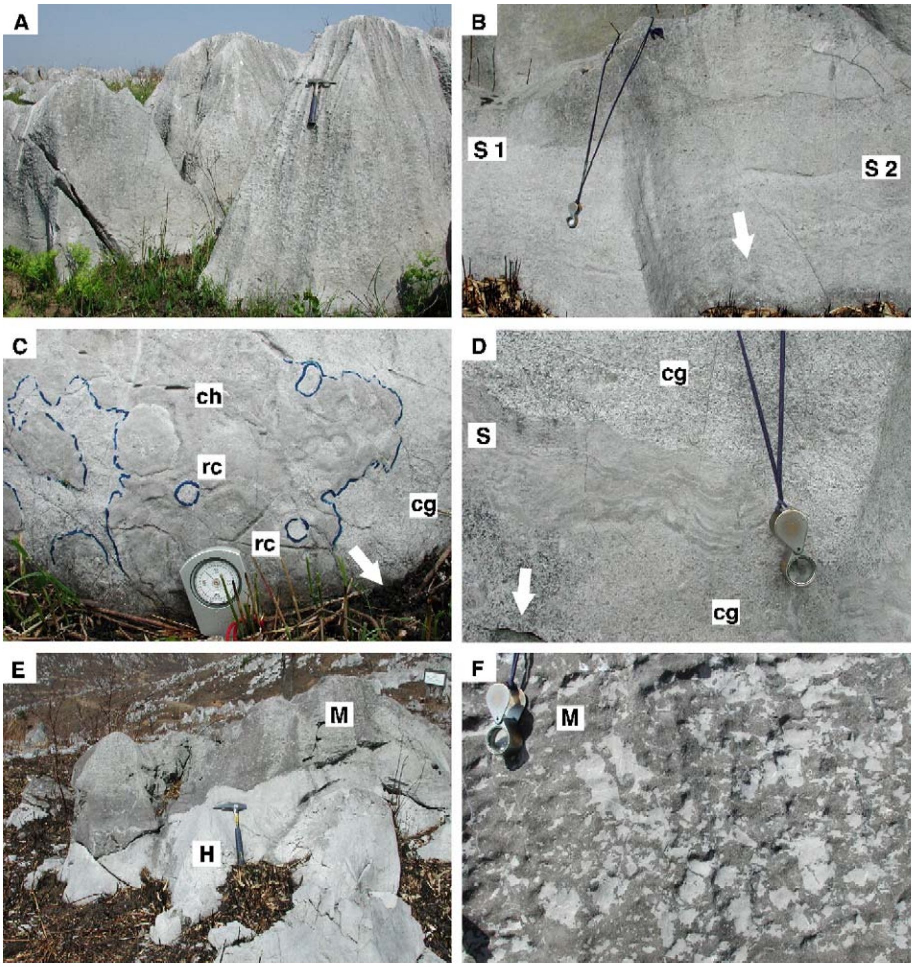

Fig. 5. Outcrop photos of bedding styles, reefal facies, and "microcodium" structure of Akiyoshi Limestone Group. Localities are shown in Fig. 3. (A) Massive, light gray limestone exposed as numerous pinnacles on Akiyoshi-dai plateau. Asselian. "*Alpinoschwagerina*" *fusiformis* Zone. (B) Nearly horizontal-lying and gently undulating bedding surfaces, denoted as S1 and S2, recognized in fully overturned, crudely graded coarse-grained crinoidal packstone-grainstone. Kasimovian. Arrow indicates stratigraphic top. Gzhelian. *Triticites* "*simplex*" Zone. (C) *Chaetetes* boundstone. Bulbous to massive forms of densely crowded, in situ grown *Chaetetes* (ch) are outlined. rc=incorporated rugose corals. Spaces between boundstone are filled with coarse-grained crinoidal grainstone (cg). Arrow indicates stratigraphic top. Bashkirian. (D) Stromatolitic boundstone (S) formed on coarse-grained crinoid-rich oolitic grainstone (cg). Arrow indicates stratigraphic top. Upper Bashkirian. *Pseudostaffella antiqua* Zone. (E) Microcodium-replaced dark gray limestone (M) having an irregularly rugged and sharp boundary, with light gray host limestone (H). Probably middle Kasimovian. (F) Complex and irregular, vermicular distribution of dark gray to brown, coarse-crystalline calcite of "microcodium" replacement (M). Probably middle Kasimovian.

yoshi Limestone Group were grouped into six major lithofacies (Table 1, Fig. 6). They are oolite-oolitic grainstone (Fig. 7A), skeletal grainstone, skeletal packstone/wackestone/mudstone (Figs. 7B–D and 8B–C), lime-mudstone with low biotic diversity, metazoan reefal facies with stromatolitic boundstone (Figs. 5C–D and 7E), and microbialite facies (Figs. 7F and 8A). The Akiyoshi Limestone Group is also characterized by the prolific occurrence of diverse shallow-marine benthic organisms (Fig. 6, Table 1). They include, fusulinids and smaller foraminifers, crinoids, corals, chaetetid screlosponges, bryozoans, brachiopods, mollusks, calcareous algae chiefly of dasycladaceans and codiaceans, and cyanobacteria, with subordinate sphinctozoan sponges, solenoporacean algae, and ostracodes.

3.3. Diagenetic facies and its stratigraphic distribution

Most of the carbonate rocks of the Akiyoshi Limestone Group experienced early diagenetic alteration in the marine phreatic zone (Sano et al., 2004). Though occasionally obliterated by later modification, the marine-phreatic diagenetic alteration is best represented by isopachous rim cements of fibrous calcite (e.g., Fig. 8C).

Table 1
Summary of stratigraphic distribution, microscopic properties, and biotic components of major lithofacies of the Akiyoshi Limestone Group

Lithofacies	Stratigraphic distribution	Microscopic properties	Biotic composition	Interpretation	References
Oolite-oolitic grainstone	Predominant in upper Viséan to lower Bashkirian; intermittent in middle Moscovian to lower Artinskian	Tangential ooids and abundant basaltic debris in Mississippian oolite; superficial oolitic cortices in Pennsylvanian-Permian; marine cements dominant	Crinoids in Mississippian; fusulines and smaller foraminifers, crinoids, *Tubiphytes*, and dasyclads in Pennsylvanian-Permian	Shallow subtidal zone with high water-energy, active water circulation, and warm water temperature	Ota, 1968; Yanagida et al., 1971; Igo, 1973; Nagai, 1978; Nagai and Ota, 1980; Haikawa, 1986, 1988; Matsusue, 1995; Kajiwara, 1996
Skeletal grainstone	Most dominant in upper Viséan to Bashkirian; common in Gzhelian to lower Artinskian and Wordian to Capitanian	Dominant marine cements; often with oolite-oolitic grainstone; basaltic debris in Mississippian	Highly diverse; fusulinids and smaller foraminifers, calcareous algae, *Tubiphytes*, corals, bryozoans, brachiopods, echinoderms, mollusks	High water-energy with open marine circulation in shallow subtidal zone	Ota, 1968; Yanagida et al., 1971; Nagai, 1978; Nagai and Ota, 1980; Ueno, 1989; Kajiwara, 1996; Igawa, 2003; Nakazawa and Ueno, 2004; Sano et al., 2004
Skeletal packstone/ wackestone/mudstone	Widespread in middle Moscovian to Capitanian	Matrix of poorly sorted lime-mud with peloids, minute skeletal debris, and calcimicrobial debris	Highly diverse; fusulinids and smaller foraminifers, crinoids, dasyclads, phylloid algae, cyanobacteria; subordinate mollusks, corals, *Chaetetes*, bryozoans, brachiopods	Shallow subtidal zone in relatively quiet lagoonal setting	Yanagida, 1962; Ota, 1968; Nagai, 1978; Nagai and Ota, 1980; Ueno, 1989; Kajiwara, 1996; Igawa, 2003; Sano et al., 2004
Lime-mudstone with low biotic diversity	Limited levels in Moscovian, Kasimovian, Artinskian, and Wordian	Homogenous-looking lime-mud; skeletal debris poor, or absent; containing crystal silts-filled fenestral voids, flat pebble breccias, and black pebbles	Low diversity; ostracode shells, sessile foraminifers, calcispheres	Relatively quiet, intertidal to supratidal zone	Ota, 1968; Igawa, 2003; Nakazawa and Ueno, 2004: Sano et al., 2004
Metazoan reefal facies	Upper Viséan to upper Moscovian; flourished in upper Serpukhovian to middle Bashkirian	Framestone and bindstone mainly formed by corals and *Chaetetes*; with stromatolitic boundstone and oolitic grainstone	Corals, *Chaetetes*, and bryozoans with encrusting foraminifers and calcimicrobes	Reef zones with high water-energy and warm water-temperature conditions	Ota, 1968; Sugimura and Ota, 1971, 1979; Haikawa and Ota, 1978; Nagai, 1978, 1985; Nagai and Ota, 1980; Sugiyama and Nagai, 1994; West et al., 2001
Microbialite facies	Predominant in Lower Permian; upward-increasing abundance above the Moscovian	Bindstone with syndepositional cements; related organosedimentary fabrics including cyanolith, micritic crusts and envelops, micritic mats	*Tubiphytes*, filamentous cyanobacteria (e.g., *Ortonella, Girvanella*), encrusting foraminifers	Shallow subtidal to intertidal zones	Sano and Kanmera, 1996; Igawa, 2003

Table 2
Summary of stratigraphic distribution and facies interpretation of major biotas of the Akiyoshi Limestone Group

	Stratigraphic distribution	Facies interpretation	References
Crinoids	Widespread; most flourished in upper Viséan to Bashkirian	Shallow subtidal; open marine circulation	Ota, 1968; Yanagida et al., 1971; Igo, 1973; Nagai and Ota, 1980; Kajiwara, 1996
Corals and *Chaetetes*	Upper Viséan to upper Moscovian; corals predominant in upper Viséan to lower Bashkirian; *Chaetetes* flourished in Serpukhovian to lower Bashkirian	Shallow subtidal; open marine circulation; warm water	Ota, 1968; Nagai, 1978, 1985; Sugimura and Ota, 1979; Nagai and Ota, 1980; Sugiyama, 1984; Haikawa, 1986, 1988; Sugiyama and Nagai, 1994; West et al., 2001
Bryozoans	Predominant and highly diverse in upper Viséan; common in Kungurian and upper Capitanian; decline in upper Moscovian–Kasimovian; increase in diversity in Gzhelian	Shallow subtidal; presumably warm water	Sakagami, 1964a,b; Sakagami and Sugimura, 1979, 1981; Sugimura and Ota, 1979
Calcareous algae	Widespread; dasyclads predominant in Lower Permian with upward-increasing abundance; phylloid forms abundant in Gzhelian; solenoporaceans dominant in Capitanian	Shallow subtidal; warm water	Endo, 1961; Ota, 1968; Nagai, 1978, 1985; Igawa, 2003; Nakazawa and Ueno, 2004; Sano et al., 2004
Calcimicrobes	Widespread and upward-increasing abundance; *Tubiphytes* most abundant in upper Kasimovian to Artinskian; filamentous cyanobacteria dominant in Sakmarian	Shallow-subtidal to intertidal; warm water	Sano and Kanmera, 1996; Igawa, 2003; Sano et al., 2004
Fusulinids	Widespread; marked hiatus in upper Kasimovian; mid-Kasimovian decline	Shallow subtidal; open marine circulation	Ota, 1968; Ota and Ota, 1993; Matsusue, 1995; Ueno, 1989, 1995; Ozawa and Kobayashi, 1990; Watanabe, 1991; Igawa, 2003; Nakazawa and Ueno, 2004

Microscopic examination also revealed that freshwater diagenetic alteration features occur at many levels in the Akiyoshi Limestone Group (Fig. 6). Freshwater-alteration features include "microcodium" structure (Figs. 5E–F and 8D; Klappa, 1978; Esteban and Klappa, 1983; Kosir, 2004), pendant (dripstone) and related meniscus cements (see Figs. 9C–D and 10C of Sano et al., 2004; Tucker and Wright, 1990), replacement of primary aragonite by calcite (see Fig. 10A–B of Sano et al., 2004; Chafetz and Rush, 1995), equant calcite cements (Quinn, 1991), bladed, prismatic, and dogtooth cements often with crystal silts (see Fig. 10D of Sano et al., 2004; Steinhauff and Walker, 1995), black pebbles and grains (Platt, 1992), and dolomitization. All these diagenetic alteration features, termed emergence-indicative facies, often occur in close association with one another and are significant as a proxy for a sea-level lowering, which resulted in emergence of the carbonate buildup (Sano et al., 2004). Approximate stratigraphic levels of prominent freshwater alteration are shown in Fig. 6 on the basis of literature review (Ota, 1968; Ozawa and Kobayashi, 1990; Sano and Kanmera, 1991b; Ota and Ota, 1993; Machiyama, 1994; Kajiwara, 1996; Igawa, 2003; Nakazawa and Ueno, 2004; Sano et al., 2004).

Sano et al. (2004) recognized several stratigraphic intervals in which emergence-indicative facies occur concentrated in the Moscovian to Asselian succession of the Akiyoshi Limestone Group. Each of these stratigraphic intervals with frequent intercalations of emergence-indicative facies, less than 70-m-thick, represents a general period of low sea-level stands, when the Akiyoshi buildup experienced prominent emergence events. Stratigraphic examination shows that each of the prominent emergence events correspond to the highest parts of each of the fusuline zones, and are estimated to have lasted for ca. 1 Ma, or less, controlled by sea-level fluctuations well correlated with the fusulinid zones of the duration of ca. 2 Ma (Fig. 12 of Sano et al., 2004). These authors consider that these prominent emergence events are comparable with the Late Paleozoic transgressive–regressive sequences of Ross and Ross (1994). Detailed examination revealed the frequent intercalation of less or non-altered limestone in each of these stratigraphic intervals of the prominent emergence events (Fig. 11 of Sano et al., 2004). These authors suggest the possibility that the frequent intercalation of less or non-altered limestone represent shorter-lived emergence–resubmergence episodes due to high-frequency sea-level fluctuations, comparable with gla-

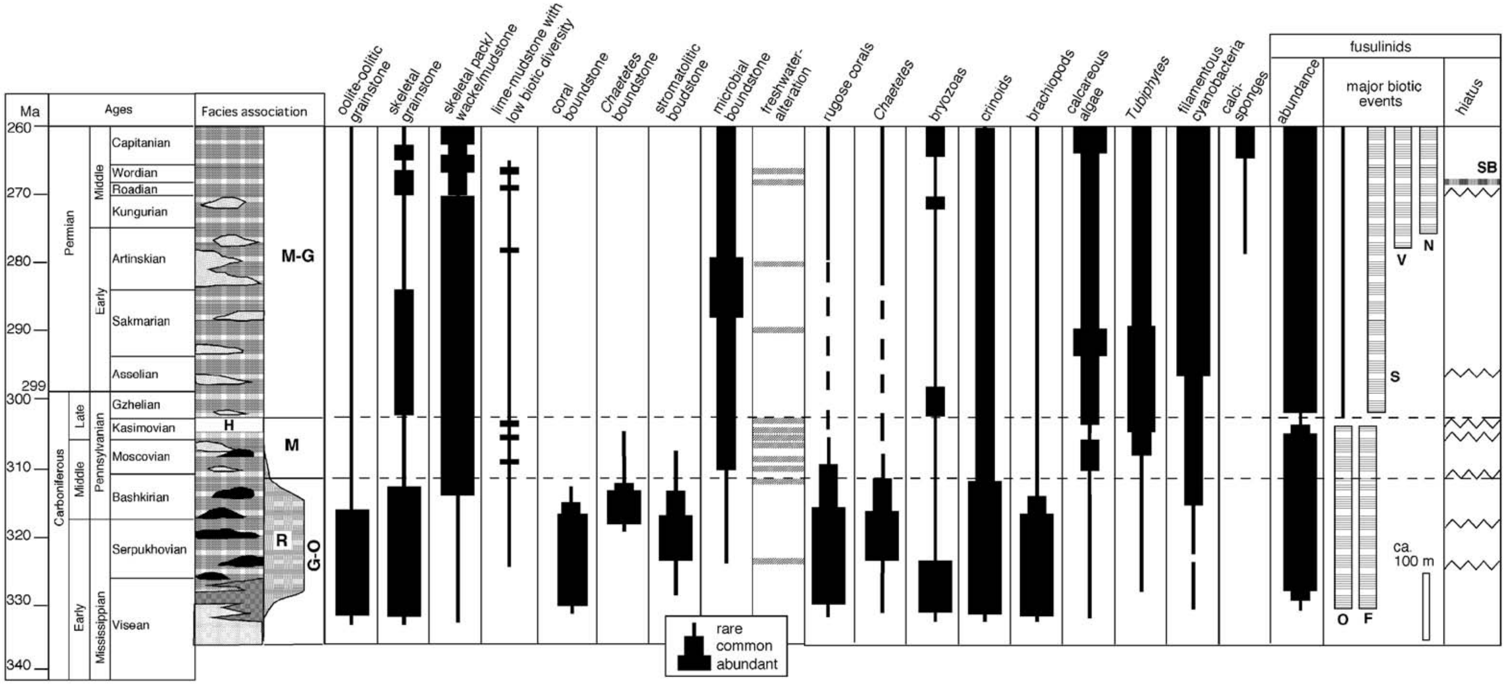

Fig. 6. Stratigraphic changes of relative abundance of major limestone facies and biotic components, and approximate levels of freshwater alteration and fusulinid biostratigraphic discontinuities of Akiyoshi Limestone Group, compiled from references cited in Tables 1 and 2, and text. Abbreviations: O, F, S, V, and N stand for the Ozawainellidae, Fusulinidae, Schwagerinidae, Verbeekinidae, and Neoschwagerinidae, respectively. SB in column at right margin denotes approximated stratigraphic level of sequence boundary shown by Nakazawa and Ueno (2004).

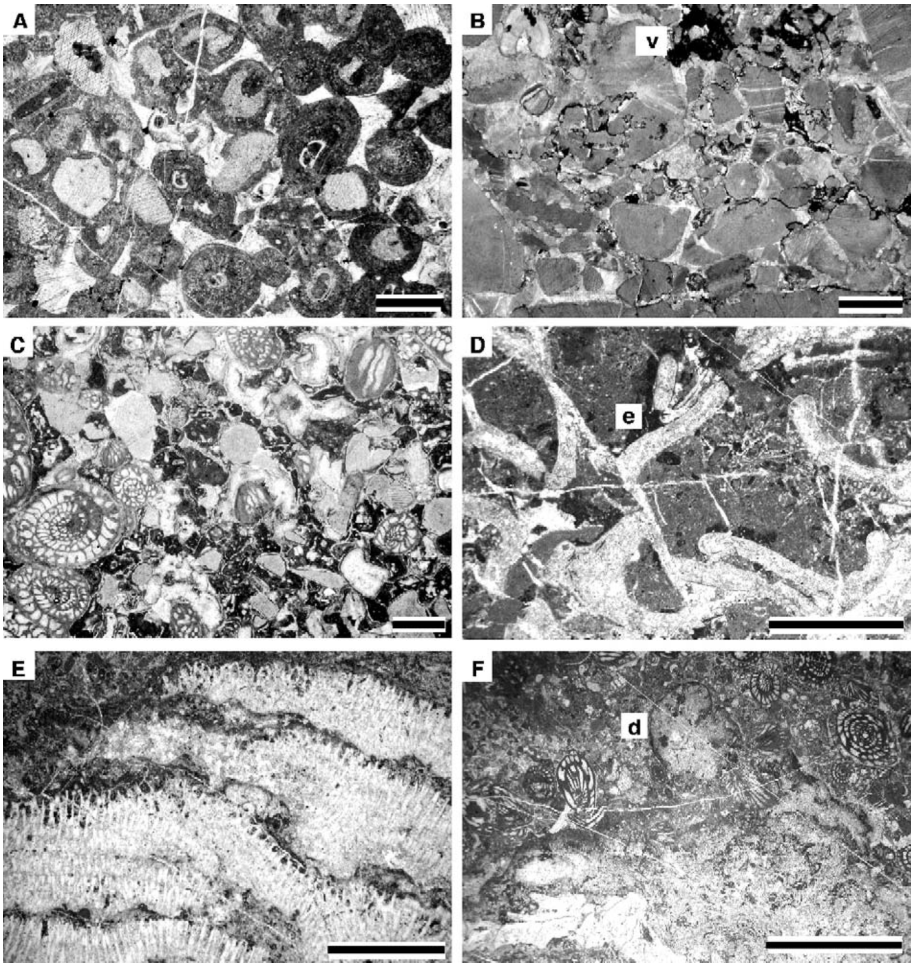

Fig. 7. Thin-section photomicrographs of representative microfacies of Akiyoshi Limestone Group. Localities of samples are shown in Fig. 3. (A) Oolite. Ooids often contain crinoidal and basaltic rock debris as nuclei. TB 1. Upper Viséan. *Nagatophyllum satoi* Zone. Scale bar = 1 mm. (B) Crinoidal packstone with great admixture of volcaniclastic debris (v) and minor bryozoan debris. GB 1. Upper Viséan. *Endothyra* Zone. Scale bar = 2 mm. (C) *Tubiphytes*-crinoid-fusulinid packstone. GP 1. Upper Asselian. *Pseudofusulina vulgaris* Zone. Scale bar = 2 mm. (D) Phylloid algal limestone. e=Local encrustation of presumable *Tubiphytes* and related cyanobacteria on phylloid algal fragments. FM 8-1. Asselian. "*Alpinoschwagerina*" *fusiformis* Zone. Scale bar = 2 mm. (E) *Chaetetes* boundstone characterized by domal, vertical stacking of in situ grown, lenticular- to laminar-formed *Chaetetes*. MB 124-1. Lower Moscovian. *Fusulinella biconica* Zone. Scale bar = 5 mm. (F) Microbial boundstone characterized by domal structure (d) constructed by stacking of upward-grown microbial lobes. MB 124-3. Lower Moscovian. *Fusulinella biconica* Zone. Scale bar = 5 mm.

cio-eustatic sea-level changes at the scale of fourth-order cycles of Vail et al. (1977).

It is noted that the emergence events occurred most frequently during Moscovian to Kasimovian time (Fig. 6). Sano et al. (2004) showed that the Akiyoshi buildup experienced at least seven emergence events during this interval of approximately 15 Ma. Among the series of the Moscovian to Kasimovian emergence events, the late Kasimovian event most seriously affected the shallow-marine sedimentation of the Akiyoshi buildup (Fig. 6; Sano et al., 2004). The hiatus between the middle Kasimovian and Gzhelian (Ueno, 1989; Ota and Ota, 1993) is considered to have resulted from a marked dissolution unconformity due to prolonged emergence in late Kasimovian, at approximately 305 to 303 Ma.

Other stratigraphic levels of the Akiyoshi Limestone Group also record emergence events (Fig. 6). For example, Nakazawa and Ueno (2004) described a sequence boundary formed by a sea-level lowering in late Wordian, which resulted in a biotic turnover of fusulinids and karstification. Kajiwara (1996) reported an exposure surface in the Serpukhovian, which includes a 20-m-thick stratigraphic interval of freshwater diagenesis-related recrystallization along the discordant, unconformable contact between two fusulinid

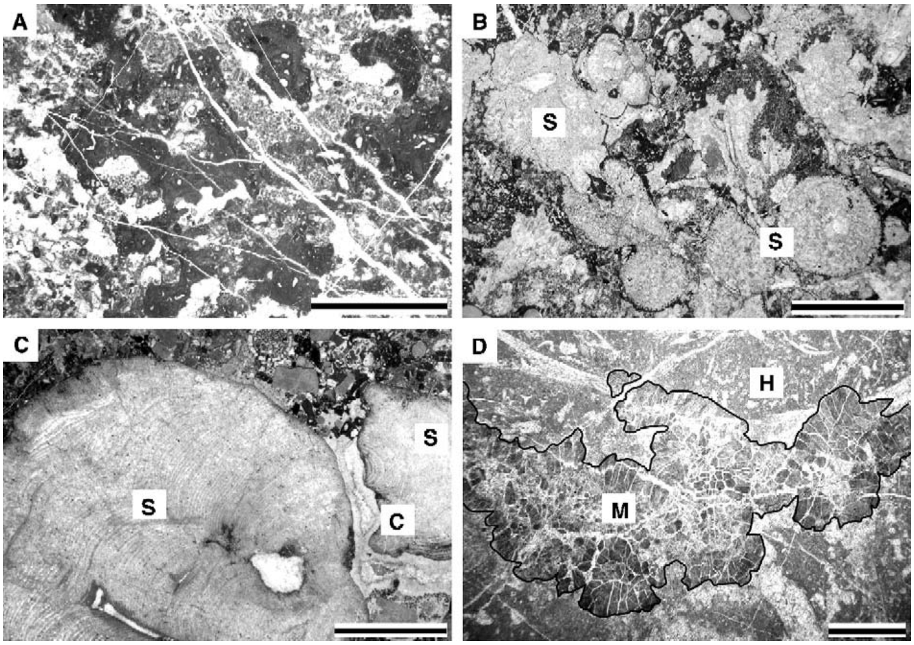

Fig. 8. Representative microfacies of the Akiyoshi Limestone Group. Localities of samples are shown in Fig. 3. (A) *Tubiphytes* boundstone formed by complicated framework of in situ grown *Tubiphytes*. FM 9-2. Asselian. "*Alpinoschwagerina*" *fusiformis* Zone. Scale bar = 2 mm. (B) Calcisponge limestone. Spaces among presumably in situ grown sphinctozoan calcisponges (S) are filled with peloidal sediment. ProbablyWordian. SM 311-9. Scale bar = 5 mm. (C) Solenoporacean algal debris-rich limestone. Note isopachous rim cements of fibrous calcite (c) between algal debris (S). ProbablyWordian. SM 309-9. Scale bar = 5 mm. (D) Microcodium structure (M), characterized by irregular-shaped aggregate of radially grown, blade-shaped, brown sparry calcite, outlined by solid line, in host rock of fossil debris-poor lime-mudstone (H). Upper Moscovian. *Fusulinella taishakuensis* Zone. MB 196-1. Scale bar = 1 mm.

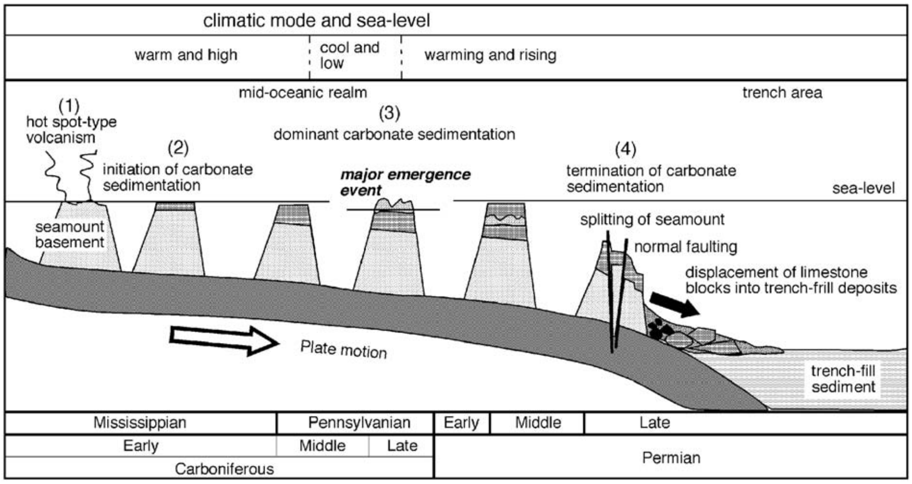

Fig. 9. Schematic illustration depicting sedimentary history of Akiyoshi buildup ranging from Early Mississippian birth in mid-oceanic realm, through the most critical turning point of the Late Carboniferous cooling and prominent emergence, to late Middle Permian death at convergent margin. Climatic modes and sea-level changes inferred from depositional and biotic events on Akiyoshi buildup are shown. (1) Formation of Akiyoshi seamount by Early Mississippian submarine volcanic activity of hot spot-type presumably in equatorial zone of mid-oceanic realm of Panthalassa Ocean, (2) initiation of shallow-marine carbonate sedimentation soon after cessation of hot spot-type volcanic activity. (3) accumulation of shallow-marine carbonates, including metazoan reef accretion in late Mississippian to Pennsylvanian, and prominent emergence events in middle to late Pennsylvanian, and (4) termination of carbonate sedimentation in Middle Permian, soon after which encroachment of Akiyoshi seamount into trench area, normal faulting-induced tectonic collapse of seamount at outer bulge, and formation of limestone blocks and debris and their displacement down into a trench-fill sediment took place in Middle to Late Permian.

zones. Occurrence of exposure surfaces is infrequent, however, outside the Moscovian and Kasimovian.

4. Facies associations and their paleoenvironmental interpretation

On the basis of the stratigraphic summaries of the major lithofacies, biotic components, diagenetic facies, and hiatuses, four facies associations were recognized in the entire Akiyoshi Limestone Group; skeletal-oolitic grainstone, reefal limestone, muddy limestone, and muddy limestone–skeletal grainstone associations (Figs. 4 and 6). Skeletal-oolitic grainstone, muddy limestone, and muddy limestone–skeletal grainstone associations are stratigraphically succeeded in ascending order, and reefal limestone association is nearly coeval with skeletal-oolitic grainstone association.

4.1. Skeletal-oolitic grainstone association

Skeletal-oolitic grainstone association is best characterized by the dominance of oolite-oolitic grainstone facies and skeletal grainstone facies in close association with each other (Fig. 6, Table 1). Both of these facies are indicative of deposition under high water-energy conditions.

Rocks of this facies association occupy the lower part (upper Viséan to Bashkirian) of the Akiyoshi Limestone Group, (Figs. 4 and 6). Conformably overlying the volcaniclastic rocks, the basal part of this facies association is marked by reddish, oolitic and crinoidal limestones containing a great admixture of basaltic detritus (Fig. 7A–B). The upper boundary of this facies association is put approximately at the stratigraphic level characterized by the replacement of skeletal grainstone by skeletal pack/wacke/mudstone, coupled with the marked decline of *Chaetetes* and its boundstone facies near the Bashkirian–Moscovian boundary (ca. 311 Ma; Fig. 6). More significantly, the upper boundary approximately corresponds to the hiatus at the top of Bashkirian. It is noted that this hiatus marks the beginning of the series of frequent emergence–resubmergence events in Moscovian through Kasimovian time (Fig. 6).

Though often obliterated by a later diagenetic modification, the ooids are tangential and therefore probably were originally aragonitic (Fig. 7A). An oolitic cortex having concentric laminae encrusts nuclei of basaltic and crinoid debris in the upper Viséan to lower Serpukhovian reddish oolitic grainstone. Isopachous rim cements of fibrous calcite are common in this facies association. Microscopic characteristics of the cements indicate their precipitation in a high-energy, well agitated and circulated water condition at shallow subtidal depths. The dominance of oolite indicates deposition under high water-temperature and elevated sea-level conditions (e.g., Schlanger, 1987; Opdyke and Wilkinson, 1990).

Crinoids, bryozoans, brachiopods, corals, and *Chaetetes* characterize the biotic assemblage of this facies association (Fig. 6). Crinoids appeared and flourished along with bryozoans as early as the initiation of basaltic volcaniclastic sedimentation on the Akiyoshi seamount. Bryozoans were most prolific and diverse in the upper Viséan, which yields 24 bryozoan genera among a total of 31 Carboniferous genera, including *Penniretepora*, *Fenestella*, *Pseudobatostomella*, and *Fistulipora*. Corals and *Chaetetes* occur dominantly also as major reef-builders of the time-equivalent reefal limestone association. These biotas occasionally form fossil-crowded beds. Most prominent are crinoids, often forming exclusively encrinitic limestones in the upper Serpukhovian to Bashkirian (Fig. 7B). The Serpukhovian to lower Bashkirian succession contains coarse packstone–rudstone crowded with large brachiopods, including *Gigantoproductus*.

The biotic assemblage of skeletal-oolitic grainstone association is similar to that of ancient and modern warm-water carbonates (e.g., Chloroforam–Chlorosponge carbonates, Sverdrup Basin, Permian: Beauchamp, 1994; modern high-energy coralgal reef carbonates of Tahiti: Camoin and Montaggioni, 1994). Of the organisms in skeletal-oolitic grainstone association, rugose corals and *Chaetetes* are representative warm-adapted biotas, most commonly distributed in tropical to subtropical zone during Paleozoic time (Kiessling, 2001). Whereas bryozoans are the significant component of the Cenozoic and modern non-tropical carbonate in temperate latitudes (e.g., Hayton et al., 1995), Taylor and Allison (1998) showed that most Paleozoic bryozoan-rich deposits accumulated in low palaeolatitudinal zones. According to the dominance of Permo-Carboniferous bryozoan-rich deposits in the tropics (within 20° in Early Mississippian: Taylor and Allison, 1998), it is inferred that bryozoans-rich sediments in skeletal-oolitic grainstone association accumulated in a low latitudinal zone. This inference is consistent with the dominance of other warm-adapted metazoan reef-builders.

4.2. Reefal limestone association

Reefal limestone association R is characterized by metazoan reefal facies including several types of boundstone constructed mainly by in situ growth of warm-adapted hermatypic corals and *Chaetete*s, with encrustation of bryozoans, foraminifers, and cyanobacteria (Fig. 5C). Stromatolitic boundstone of unidentified, problematic encrusting biotas crops out often with the metazoan reefal limestone (Fig. 5D). Careful mapping shows that the metazoan reefal facies occur as thin, laterally discrete and patchy masses, ranging in thickness from several to a few tens of meters and in extent from a few tens to 100 m, intercalated in skeletal-oolitic grainstone association. The sediments of the reefal limestone association are interpreted as having formed narrow reef zones under conditions of high water-energy.

The lowest occurrence of the metazoan reefal facies is recorded by the upper Viséan bryozoan boundstone facies dominated by the genus *Sulcoreptepora* in association with crinoids and corals (Fig. 6). The upper Viséan bryozoan reefal facies is immediately followed by the first appearance of coral-dominated reefal facies including *Nagatophyllum satoi*, *Carcinophyllum enorme*, and *Echigophyllum atetsuense*. The first appearance of *Chaetetes* reefal facies is recorded near the Mississippian–Pennsylvanian boundary. These coral-*Chaetetes* reefal facies flourished most prominently in the upper Serpukhovian to middle Bashkirian together with stromatolitic boundstone (Fig. 6). Careful examination reveals, however, that the stratigraphic distribution of these two warm-adapted reef-builders differs slightly from each other. Corals flourished mostly from the upper Viséan to lower Bashkirian, while *Chaetetes* peaked in the Serpukhovian to lower Bashkirian and rapidly declined in the upper Bashkirian, earlier than the corals (Fig. 6).

Paleozoic reefs formed by corals and coralline sponges including chaetetids occur most dominantly in the tropical to subtropical zone (Kiessling, 2001). The metazoan reefal limestones of reefal limestone association accumulated under a warm climatic condition in low latitudes, and best characterize atoll carbonate sedimentation on the Akiyoshi seamount. Predominance of the oolitic facies and marine cements in coeval skeletal-oolitic grainstone association supports the accumulation of the reefal limestone under a warm water-temperature and high water-energy condition. The rapid decline of the metazoan reefal facies implies a transition from the end of the warm climatic mode in late Bashkirian time.

4.3. Muddy limestone association II

Muddy limestone association occupies the middle part of the Akiyoshi Limestone Group (Figs. 4 and 6). The rocks range approximately from Moscovian to Kasimovian in age.

In stark contrast with skeletal-oolitic grainstone association, muddy limestone association is dominated by skeletal wackestone, packstone, and lime-mudstone facies, and lacks metazoan reef facies (Fig. 6). Lime-mudstone with low biotic diversity and having peritidal facies occurs intercalated intermittently in this facies association. The sediments of this facies association are interpreted to have accumulated in the shallow subtidal to intertidal zone in a relatively quiet lagoonal setting.

The biotic assemblage of muddy limestone association is dominated by crinoids and fusulinids (Fig. 6). Crinoids prevail throughout the succession, but fusulinids exhibit a marked taxonomic turnover and decline in the middle to upper Kasimovian. Corals and *Chaetetes* are present, but are actually rare and occur as scattered debris. These two warm-adapted organisms significantly diminished in the middle to upper Moscovian. Additionally, bryozoans exhibit an upward-decrease in diversity and markedly declined in the upper Moscovian to Kasimovian time, while the Gzhelian section of muddy limestone–skeletal grainstone association records an increase in their diversity (Fig. 6). These features indicate that the prominent turnover of Carboniferous bryozoans took place in Moscovian through Kasimovian time. Exhibiting an upward-increasing significance, calcimicrobes played an important role in the accumulation of post-Moscovian carbonates on Akiyoshi buildup. It is noted that the skeletal debris of muddy limestone association is less diverse than that of skeletal-oolitic grainstone association (Fig. 6).

The Akiyoshi Limestone Group records fusulinid biostratigraphic discontinuities at several levels (column at right margin of Fig. 6). The most distinct discontinuity is between the middle Kasimovian and overlying Gzhelian rocks of muddy limestone association. The late Kasimovian hiatus is recognized not only in the entire extent of the Akiyoshi Limestone Group, but also in other equivalent units of the seamount-top facies of the Akiyoshi terrane (e.g., Taishaku Limestone Group: Ueno and Mizuno, 1993).

The late Kasimovian hiatus took place immediately after the mid-Kasimovian decline of fusulinids, best represented by their major taxonomic turnover at the family level (Fig. 6). Most genera of the Ozawainellidae largely declined and disappeared, and the Fusulinidae became extinct in the middle Kasimovian. This taxonomic turnover was, in turn, followed by the appearance of the Schwagerinidae, as shown by a marked diversification of the genus *Triticites* in the Gzhelian of muddy limestone–skeletal grainstone association.

Markedly frequent intercalation of freshwater-altered limestone characterizes muddy limestone–skeletal grainstone association (Fig. 6). Sano et al. (2004) showed seven emergence events in the approximately eight million-year-long interval from Moscovian through Kasimovian, which had a serious impact on the carbonate sedimentation of muddy limestone association. The hiatus and distinct taxonomic turnover of fusulinids in middle to late Kasimovian are considered to have resulted from the prolonged emergence event in late Kasimovian time (ca. 305 to 303 Ma: Sano et al., 2004). This is the most prominent emergence event in the series of Moscovian to Kasimovian emergence events, each of which represents a general period of the low sea-level stand.

The rapid decline and demise of tropical metazoan organisms in late Bashkirian through Kasimovian suggest that climatic cooling took place during Mascovian to Kasimovian. The decrease of fossil diversity among other groups in muddy limestone associations may reflect an inhospitable, repeated subaerial exposure of their living space on the Akiyoshi buildup during Moscovian to Kasimovian.

4.4. Muddy limestone–skeletal grainstone association

Muddy limestone–skeletal grainstone association occupies the upper half of the Akiyoshi Limestone Group (Gzhelian to Capitanian: Figs. 4 and 6). The lower boundary nearly corresponds to the termination of the series of prominent emergence events in Moscovian through Kasimovian, coupled with the appearance of the Schwagerinidae (Fig. 6).

Skeletal packstone and wackestone facies are dominant in muddy limestone–skeletal grainstone association (Fig. 6). Skeletal grainstone facies is common in the Gzhelian to lower Artinskian and in the Roadian to Capitanian. Oolitic-skeletal grainstone facies characterized by superficial ooids is intermittently intercalated. All these facies are rich in diverse shallow-marine skeletal debris (Fig. 7C–D).

Often dolomitized lime-mudstone with low biotic diversity occurs at a few levels of this facies association (Fig. 6). For example, weakly dolomitized, skeletal debris-poor lime-mudstone is reported immediately above the sequence boundary in the Wordian, and is interpreted as peritidal mud during the slow transgression (SB in Fig. 6; Nakazawa and Ueno, 2004). These rocks contain fenestral voids often filled with crystal silts, flat pebble breccias, characteristic of inter- to supratidal facies, and black pebbles implying subaerial emergence.

Frequent intercalation of microbial boundstone of various types and related microscopic organosedimentary structures characterize this facies association (Fig. 6). Major rock-forming calcimicrobes are cyanobacteria, including *Tubiphytes* (Fig. 8A), mainly *T. obscurus*, and filamentous forms of *Ortonella* and *Girvanella*. They form microbial bindstone often with encrusting foraminifers and other enigmatic microproblematica (Fig. 7F). Besides the microbial boundstone, various types of microbial particles and microscopic organosedimentary structures are recognized at many levels. These include an oncoid-like nodular aggregate, better described as “cyanolith”, in which filamentous cyanobacteria are complexly interwoven, micritic crusts and envelopes that connect and aggregate skeletal grains, and micritic mats having a palisade structure of vertically grown filamentous cyanobacteria.

Previous studies show the upward-increasing abundance of microbialite facies above the Moscovian, the level at which the metazoan reefal facies disappeared (Figs. 4 and 6). Careful stratigraphic examination revealed that the Upper Pennsylvanian to Lower Permian rocks record the most frequent intercalations of microbialite facies (Fig. 6). *Tubiphytes* and related forms predominantly occur in the upper Kasimovian to Artinskian, and filamentous forms are widespread above the Sakmarian.

The diversity of shallow-marine skeletal debris is markedly higher in this facies association than in muddy limestone association (Fig. 6). Fusulinids, crinoids, calcimicrobes, and calcareous algae occur prevail in muddy limestone–skeletal grainstone association, where a marked diversification of the fusulinids is recorded. It is noted that few corals and *Chaetetes* are recognized in the Artinskian and Kungurian (Fig. 6). They occur as isolated debris in skeletal limestone, but no metazoan boundstone facies thus far has been reported from this facies association. Permian bryozoans generally have low diversity in the Akiyoshi Limestone Group: 17 Permian genera including 13 genera of holdovers from the Carboniferous. Nevertheless, the bryozoans exhibit an upward-increase in abundance in the Kungurian and upper Midian (Fig. 6). Dasycladacean algae exhibit a marked upward-increase in abundance, and their most prolific occurrence is recorded in the Lower Permian (Fig. 6). Also characteristic is the marked abundance of phylloid algae in the Gzhelian, where their crowded accumulation of phylloid algae resulted in the formation of possible algal mounds in the Gzhelian to Sakmarian succession (Fig. 7D). Capitanian limestones locally contain abundant sphinctozoan calcisponges and solenoporaceans (Fig. 8B, C).

Riding (1992) inferred a positive correlation of Phanerozoic cyanobacterial calcification episodes with elevation of global temperatures. Furthermore, Kiessling (2001) showed that Paleozoic microbial reefs occur dominantly in low latitudes, along with calcareous algae. Dasycladacean algae are biotic elements characteristic of low latitude, warm-water environments (e.g., Beauchamp, 1994). The prevalence of warm-adapted calcareous algae and calcimicrobes in this facies association is interpreted to reflect its accumulation under a warm climatic condition. This interpretation is consistent with the occurrence of calcisponges and bryozoans in this facies association. Upward-increasing abundance of calcareous algae, calcimicrobes, and calcisponges indicates a general trend of climatic warming in Gzhelian through Permian.

Muddy limestone–skeletal grainstone association records emergence events at only a few levels (Fig. 6), compared to muddy limestone association. In further contrast with the muddy limestone association, surfaces with evidence of prolonged exposure (dissolution, karst, etc.) are absent from muddy limestone–skeletal grainstone association. These features indicate an overall sea-level rise during Gzhelian through Capitanian.

5. Discussion

5.1. Records of climate episodes and sea-level changes in Akiyoshi buildup

Paleoenvironmental interpretation of the four facies associations reveals that climatic change and sea-level fluctuation significantly affected the Akiyoshi atoll sedimentation. The time-distribution of the four facies associations shows the warm climate with generally high sea-level during late Viséan to Bashkirian, cool-climate mode and generally low sea-levels with a series of prominent emergence events during Moscovian to Kasimovian, and climatic warming and sea-level rise during Gzhelian to Capitanian (Fig. 4). Akiyoshi atoll stratigraphy records two climatic transition events; transition from a warm mode in late Bashkirian and transition from a cool mode back to warm in Gzhelian.

All the lithologic and biotic properties of skeletal-oolitic grainstone and reefal limestone associations support a late Viséan to mid-Bashkirian warm climate and generally high sea-level in the Akiyoshi buildup (Fig. 4). The warm climatic condition presumably in an equatorial zone resulted in the flourishing of warm-adapted metazoan reef-builders and accumulation of their reefal facies (Fig. 6). The upper Viséan to lower Bashkirian dominant deposition of oolitic facies also indicates high-elevated sea-levels and high sea-surface temperatures. Emergence events occurred much less frequently during Viséan to Bashkirian than during Moscovian to Kasimovian.

Rapid decline of the warm-adapted metazoan reef-builders and their reefal facies in the upper part of skeletal-oolitic grainstone and reefal limestone associations mark the rapid onset of climatic cooling in late Bashkirian (Figs. 4 and 6). The upward-decreasing significance of oolite in the Bashkirian also reflects the late Bashkirian climatic shift from the late Viséan–Bashkirian warm mode to the Moscovian–Kasimovian cool mode.

Late Bashkirian climatic transition was followed by the major cool climate interval, which lasted for ca. 8 Ma during Moscovian through Kasimovian (Fig. 4). The Akiyoshi buildup experienced at least seven times of major subaerial exposure events during the Moscovian through Kasimovian cool climate period (Fig. 6; Sano et al., 2004). The significant decline of the tropical metazoan reef-builders took place nearly synchronously with the series of Moscovian to Kasimovian emergence events (Sano et al., 2004). The most prolonged emergence event in late Kasimovian resulted in the prominent dissolution unconformity and consequently a marked hiatus (Fig. 4; ca. 305 to 303 Ma). The late Kasimovian emergence had the most critical impact on the sedimentary evolution of the Akiyoshi buildup (Figs. 4 and 9).

Litho- and bio-facies of muddy limestone–skeletal grainstone association indicate the climatic transition to the warming mode in Gzhelian through Capitanian (Figs. 4 and 6). The restoration of the bryozoans and diversification of *Tubiphytes* and calcareous algae in the Gzhelian possibly mark the onset of warming (Fig. 6; ca. 300 Ma). The upward-increasing significance of calcimicrobes and calcareous algae in the Upper Pennsylvanian to Lower Permian also shows climatic warming. The sea-level rise in Gzhelian through Capitanian is inferred from more frequent intercalation of oolitic grainstone and less frequent emergence events in muddy limestone–skeletal grainstone association than in muddy limestone association (Figs. 4 and 6).

The stratigraphic records of the palaeoclimatic episodes and sea-level fluctuation in the Akiyoshi buildup permit the author to hypothesize its entire sedimentary evolution in a mid-oceanic setting and in context of global icehouse–greenhouse climate changes (Figs. 4 and 9). Akiyoshi atoll sedimentation was initiated under the late Viséan–Bashkirian warm-climate condition with generally elevated sea-level. The hospitable conditions favored by warm-adapted metazoan animals diminished by the rapid onset of cooling in late Bashkirian and a series of Moscovian to Kasimovian emergence events. The Moscovian–Kasimovian cooling and associated prominent emergence events, most seriously affected the Akiyoshi atoll sedimentation and biotic assemblage. After the transition from the cool mode in the Gzhelian, dominant atoll sedimentation recovered in the warming climatic condition with generally high and rising sea-level, and lasted until the tectonic collapse of the buildup at a convergent margin approximately in late Capitanian.

5.2. Comparison with Pangean climatic episodes and sea-level changes

Climatic episodes and sea-level changes recorded in the Akiyoshi Limestone Group generally correspond to the Mississippian to Permian climate evolution and sea-level changes studied mainly in equatorial regions of the supercontinent Pangea (Fig. 4). Akiyoshi atoll stratigraphy reflects the global climate change and associated sea-level fluctuation related to the major glacial episodes of Gondwana glaciation.

5.2.1. Pre-glacial warm climate

Late Viséan to mid-Bashkirian warm climate and high sea-level recorded in the Akiyoshi buildup are analogous to the Tournaisian to Viséan warm climate and highstands in Pangean epicontinental seas (Fig. 4). Akiyoshi atoll sedimentation began under the warm, hospitable condition in an equatorial zone of a mid-oceanic setting (Fig. 9).

Many studies show that the global climate of this period is generally characterized by the pre-glacial warm climate, indicated by the minor volume and limited distribution of ice-sheets (e.g., Veevers and Powell, 1987; Frakes and Francis, 1988). A high, but decreasing content of atmospheric CO_2 shows the early to middle Mississippian warm climatic condition during Tournaisian to Viséan, though punctuated by short-lived glaciation events (Crowley and Baum, 1992; Crowley and Berner, 2001). High sea surface temperatures during this period are estimated by oxygen isotopic analyses (e.g., 26 to 31 °C: Stanton et al., 2002) and predicted by the numerical modeling (25 to 30 °C: Crowley et al., 1996). The paleobotanical data also show the high atmospheric CO_2 concentration above the threshold CO_2 level for deglaciation in Late Devonian to Mississippian (Lycopsid flora: Beerling, 2002). The warm, frost-free floral belt is reported to have occurred during late Viséan to earliest Serpukhovian on the Gondwana continent (Parana flora: Iannuzzi and Pfefferkorn, 2002). The dominance of filter-feeders in all benthic ostracodes indicates a high seawater temperature in the Viséan (Lethiers and Whatley, 1994).

Pre-glacial sea-levels in Tournaisian to Viséan are considered to have been generally high (Veevers and Powell, 1987; Wright and Vanstone, 2001), and relatively stable, with the punctuation of only minor emergence events (e.g., Wright and Vanstone, 2001).

5.2.2. Mid-glacial cool mode

Moscovian to Kasimovian cool climate and frequent emergence events recorded in the Akiyoshi buildup nearly correspond to the cool climate and associated glacio-eustatic sea-level fluctuations related to the major glacial episode of the Permo-Carboniferous Gondwana glaciation (Fig. 4; Sano et al., 2004). Akiyoshi atoll sedimentation in a mid-oceanic realm experienced glacio-eustatic sea-level lowering events and was possibly affected by prolonged and severe cooling during the icehouse period (Fig. 9). The demise of the warm-adapted metazoan reef-builders in late Moscovian and the marked hiatus in late Kasimovian happened nearly synchronously with the maximum growth of the ice sheets approximately at 306 to 300 Ma (Figs. 4 and 9: Crowley and Baum, 1992; Otto-Bliesner, 1996).

The Permo-Carboniferous is accepted as a period of one of the most prolonged and extensive glaciation in the Earth's history (e.g., Frakes and Francis, 1988; Crowley and Baum, 1991; Veizer et al., 2000). The onset of the major glaciation is marked by the beginning of the high-frequency glacio-eustatic sea-level oscillation (Smith and Reed, 2000; Wright and Vanstone, 2001; Bernett et al., 2002) and also by sharp drop of biotic diversity (e.g., Namurian brachiopods: Powell and Veevers, 1987), northward shift of the tropical reef zone (Kiessling, 2001), and rapid increase in $\partial^{18}O$ values (Bruckschen et al., 1999; Mii et al., 2001). Extensive ice-sheets persisted on the Gondwana continent for several tens of million years during this icehouse period (e.g., over 60 My: Otto-Bliesner, 1996; extent up to ca. 35° paleolatitude: Crowley and Baum, 1992). Geochemical studies and numerical modeling estimate the severe global cooling, characterized by the minimum atmospheric content of CO_2 (Berner, 1997; Crowley and Baum, 1992; Crowley and Berner, 2001; Beerling, 2002), low tropical sea surface temperature (20 ± 5 °C: Bruckschen et al., 1999) at the peak time of glaciation. The Permo-Carboniferous ice age was also characterized by high seasonality, which enhanced the continentality of the Pangean climate (Mii and Grossman, 1994).

High amplitude, high-frequency glacio-eustatic sea-level fluctuation also characterizes the Permo-Carboniferous ice age (e.g., Veevers and Powell, 1987; Heckel, 1994; Ross and Ross, 1994). Many sedimentological studies show sea-level fluctuation with a high frequency (ca. 120 ka: Maynard and Leeder, 1992; ca. 100 ka: Wright and Vanstone, 2001) and high amplitude (60 ± 15 m: Crowley and Baum, 1991; 42 m: Maynard and Leeder, 1992; 80 m and probably exceeding 100 m: Soregham and Giles, 1999). Sano et al. (2004) postulate the possibility that glacio-eustatic sea-level fluctuation, most likely at the scale of fourth-order cycles of Vail et al. (1977), is recorded in the series of the Moscovian to Kasimovian prominent emergence events of the Akiyoshi buildup.

The exact timing of the onset of the Permo-Carboniferous Gondwana glaciation still remains controversial. Nevertheless, it is widely accepted as a general consensus that the major glaciation episode began around 335 to 330 Ma (Fig. 4: mid-Viséan: Frakes and Francis, 1988; late Viséan: Veevers and Powell, 1987; Bernett et al., 2002; Smith and Read, 2000; Viséan to Serpukhovian: Garzanti and Schiunnach, 1997; late Serpukhovian: Bruckschen et al., 1999; Saltzman, 2003). It is noted that the transition to the cooling mode in the Akiyoshi buildup was delayed, approximately 10 Ma after the onset of the high frequency, high amplitude glacio-eustatic sea-level fluctuation on the Pangean shelves (e.g., late Viséan: Smith and Reed, 2000). The pre-glacial warm mode and highstand survived longer in the mid-oceanic realm of the Panthalassa Ocean than in Pangean epicontinental seas.

5.2.3. Post-glacial warming mode

Gzhelian through Capitanian climatic warming and sea-level rise in the Akiyoshi buildup nearly corresponds to the post-glacial global warming and sea-level rise documented in Pangean shelf sediments, related to the deglaciation episode (Fig. 4). The warming mode in the Akiyoshi buildup is considered to have started most presumably in the Gzhelian (Fig. 4). The dominant carbonate sedimentation on the Akiyoshi buildup occurred during the warming mode with generally high and rising sea-level, and lasted until late Capitanian (Figs. 4 and 9). Nevertheless, no reefal facies of warm-adapted metazoan animals reappeared in the post-glacial warming period after their late Moscovian demise.

The demise of the ice age is coupled with the retreat of ice sheets (Frakes and Francis, 1988; Crowley and Baum, 1992), increasing RCO_2 (Crowley and Baum, 1992), revival of warm-adapted biotas (Rees et al., 1999; Angiolini et al., 2003; Jasper et al., 2003), and major transgression (Angiolini et al., 2003). Many geological, geochemical, and paleontological studies as well as model simulation show the collapse of the prolonged icehouse climate occurred around Early to early Middle Permian (Fig. 4: early to mid-Sakmarian: Veevers and Powell, 1987; ca. 270 Ma: Crowley and Baum, 1992; 280 Ma: Wordian: Rees et al., 1999; Artinskian: Mei and Henderson, 2001; Sakmarian-Artinskian boundary: Beauchamp and Baud, 2002; Gibbs et al., 2002; late Early Sakmarian: Angiolini et al., 2003; Kungrian: Jasper et al., 2003). It is noted that the post-glacial climatic warming took place at least ca. 5 to 6 My earlier in the Akiyoshi buildup than on the Pangean shelves (Fig. 4). The severe impact of the mid-glacial cooling on the Akiyoshi atoll sedimentation persisted as little as approximately ten million years from Moscovian through Kasimovian.

The causes for the delayed onset and earlier termination of the mid-glacial cool mode in the Akiyoshi buildup remain unresolved. The most likely explanation is that the Pennsylvanian paleoposition of the Akiyoshi buildup in an equatorial zone of a mid-oceanic realm of the Panthalassa Ocean, which was less subject to the serious impact of Pennsylvanian cool climate than the Pangean shelf sediments. Also unresolved is the question of whether Akiyoshi atoll sedimentation was visibly affected by the high-frequency glacio-eustatic sea-level oscillation recorded in the Pennsylvanian to Lower Permian North American Midcontinent cyclothemic succession (e.g., Heckel, 1994). More detailed sedimentological and biostratigraphic examinations of complete successions of drilled samples would be required to resolve this question.

5.3. Termination of Akiyoshi atoll sedimentation

Akiyoshi atoll sedimentation ended in late Capitanian, nearly synchronously with the encroachment of the Akiyoshi seamount into a trench area and its normal fault-induced tectonic collapse (Fig. 9: Sano and Kanmera, 1991c). The termination of atoll sedimentation and subsequent tectonic events took place in a short interval from late Capitanian to earliest Wuchiapingian.

The youngest-dated limestone of the Akiyoshi Limestone Group is the upper Capitanian limestone, characterized by several species of *Yabeina* and *Lepidolina*, and highly advanced forms of *Neoschwagerina* (Fig. 4). The upper Capitanian limestone occurs as the most dominant clasts of limestone conglomerate and also as scattered debris embedded in mudstone with scaly cleavage of the tectonically underlying Tsunemori Formation interpreted as a trench-fill sediment (Fig. 3;

Sano and Kanmera, 1991a). The minimum age of the limestone conglomerate is nearly coeval with the age of the Tsunemori mudstone, which best approximates the timing of its mixing with the limestone clasts (late Middle to earliest Late Permian: Sano and Kanmera, 1991a). Sano and Kanmera (1991c) interpreted the limestone conglomerate as having been formed by mixing of the polymictic limestone clasts produced by a normal faulting-induced tectonic collapse of the Akiyoshi buildup, and the trench-fill argillaceous sediment in late Middle to earliest Late Permian (Fig. 9).

Microscopic data support the synchroneity of the upper Capitanian limestone clasts and Tsunemori mudstone. Inter- and intra-particle voids of the upper Capitanian limestone clasts are filled with land-derived argillaceous sediment, instead of calcareous sediment, or sparry cements. That is, the mixing of the upper Capitanian limestone clasts with the Tsunemori trench-fill argillaceous sediment took place prior to the completion of the cementation of the upper Capitanian limestone. The timing of the tectonic events implies that the normal faulting-induced tectonic collapse of the buildup at an outer bulge to trench slope is the major cause for the termination of atoll sedimentation most likely in late Middle Permian to earliest Late Permian time (Fig. 9).

6. Summary

The review and interpretation of the stratigraphic changes of the litho- and bio-facies, diagenetic alteration, and hiatuses of the Akiyoshi Limestone Group (upper Viséan to upper Capitanian) resulted in better understanding of the impact of the long-term climate change and sea-level fluctuation on the sedimentation of a mid-oceanic atoll. On the basis of the time-distribution and interpretation of the litho- and bio-facies, the entire sedimentary evolution of the Akiyoshi atoll is inferred as follows; (1) Initiation of atoll sedimentation and the following flourishing of metazoan reefal facies during the late Viséan through mid-Bashkirian warm climate with sea-level highstand, (2) Demise of the conditions favorable for the warm-adapted metazoan animals by the rapid onset of cooling in late Bashkirian and frequent emergence events at the beginning of the Moscovian. Akiyoshi atoll sedimentation and biotic assemblages were most seriously affected by the Moscovian to Kasimovian cooling and associated prominent emergence events, (3) Revival of the dominant atoll sedimentation under climatic warming with rising sea-levels during Gzhelian to Capitanian.

The late Viséan to Bashkirian warm mode, Moscovian–Kasimovian cool climate, and Gzhelian to Capitanian warming in the Akiyoshi buildup generally corresponds to the pre-glacial warm climate, mid-glacial cooling at the peak time of the Gondwana ice age, and post-glacial warming of the Permo-Carboniferous Pangean climate evolution. A series of the Moscovian to Kasimovian prominent emergence events in the Akiyoshi buildup is analogous most probably to the general sea-level lowering and high-frequency glacio-eustatic sea-level changes recorded in Pangean epicontinental seas at the culmination of glaciation. The late Viséan to middle Bashkirian highstands in the Akiyoshi buildup also corresponds to the Tournaisian to Viséan highstand in Pangean shelf areas.

The Akiyoshi buildup was significantly affected by Pennsylvanian global cooling and related sea-level change, but their impacts on atoll sedimentation was short-lived. The onset of the cooling and frequent emergence events was delayed in the Akiyoshi buildup approximately 10 Ma later than on the Pangean shelves. The post-glacial warming occurred much earlier in the Akiyoshi buildup than in Pangean epicontinental seas. The delayed onset and early termination of the mid-glacial cooler climatic episodes in the Akiyoshi buildup may be the result of its palaeoposition in a mid-oceanic realm of the Panthalassa Ocean.

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