The Capitanian (Permian) minimum of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the mid-Panthalassan paleo-atoll carbonates and its demise by the deglaciation and continental doming

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A B S T R A C T

The Capitanian minimum in the Permian represents one of the most significant features in the Phanerozoic seawater $^{87}\text{Sr}/^{86}\text{Sr}$ history. In order to establish the detailed Sr chemostratigraphy around the Guadalupian minimum, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured for the Capitanian (upper Middle Permian) paleo-atoll limestones at Akasaka in Japan. The limestone was primarily deposited on a paleo-seamount in the low-latitude mid-Panthalassa, and was secondarily accreted to Japan (South China block) margin in the Jurassic. As being free from local continental influences, the Akasaka limestone recorded well-mixed seawater isotope composition of the Permian low-latitude mid-superocean. We detected extremely low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (ca. 0.7068–0.7069) in the 70 m-thick Capitanian interval, immediately below the Guadalupian–Lopingian (Middle-Late Permian) boundary (G–LB), of the Akasaka limestone. This Sr isotopic profile at Akasaka suggests that the global seawater was least affected by radiogenic continental flux throughout the Capitanian. As these values correspond to the lowest in the Paleozoic, this interval with low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, lasted for at least some million years, represents the Capitanian minimum, which marks the significant turning point from the Late Paleozoic decrease to Early Mesozoic increase in seawater $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. The geological lines of evidence indicate that the Capitanian minimum was caused likely by the mid-Permian cooling that may have driven extensive ice-cover over continental crusts to suppress continental flux enriched in radiogenic Sr into the superocean. The rapid increase in $^{87}\text{Sr}/^{86}\text{Sr}$ values after the minimum can be explained either by the deglaciation or by the Pangean rifting.

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1. Introduction

As Sr isotopic composition ($^{87}\text{Sr}/^{86}\text{Sr}$) of seawater has changed over geologic time, the high-resolution Sr isotope curve appears useful in chemostratigraphic correlation/dating for the Phanerozoic. Significant changes in global balance between the radiogenic continental flux and the less radiogenic mantle flux have left several remarkable Sr events in the Phanerozoic. One of such outstanding features is the “Capitanian minimum” that occurred during the Middle-Late Guadalupian (Middle Permian) to mark the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, ca. 0.7068, in the Phanerozoic (Fig. 1; e.g., Veizer et al., 1999; McArthur and Howarth, 2004). Ever since the Cambrian, although with minor fluctuations, the long-term decrease of seawater Sr isotope ratio continued basically throughout the Paleozoic until the Capitanian minimum. In turn, immediately after the Capitanian minimum, $^{87}\text{Sr}/^{86}\text{Sr}$ ratio started to rise abruptly, in the most rapid rate in the Phanerozoic (Korte et al., 2006). The cause of this long-term trend change has not yet been identified, although some possible causal links were proposed, such as changes in global tectonics, sea-level, climate, weathering rate, and diageneric processes (e.g., Veizer, 1989; Derry and France-Lanord, 1997; Korte et al., 2003; Banner, 2004).

Most of the previous studies on the Permian record of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were performed for biostratigraphically well-constrained shallow marine carbonates and/or well-preserved brachiopod shells from western North America (Denison et al., 1994; Denison and Koepnick, 1995) and the Tethyan domain (Korte et al., 2006). On the other hand, mid-oceanic carbonates in general may have good advantage in recording the world average Sr isotope ratio of well-mixed seawater due to the absence of local influences from continents. Nishioka et al. (1991) first reported the Early-Middle Permian Sr-isotope record of the superocean Panthalassa from the paleo-atoll carbonates at Akiyoshi in Japan. With more intense focus on the Middle-Late Permian (Guadalupian–Lopingian) boundary (G–LB; 260 Ma), Kani et al. (2008) detected the Capitanian minimum for the first time in the Middle-Upper Permian paleo-atoll carbonates at Kamura, Japan. Brand et al. (2009) also added more data from the Lower to lower Middle Permian paleo-atoll carbonates in Japan. These paleo-atoll data confirmed the Capitanian minimum in the low-latitude mid-superocean. This major chemostratigraphic signal of global context is significant as it might be related with the contemporary G–LB extinction (e.g., Isozaki, 2009a, 2009b). Nonetheless, the onset timing and total duration of the Capitanian minimum were not yet strictly...
Fig. 1. The Phanerozoic secular change of Sr isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) and the Capitanian minimum (modified from McArthur and Howarth, 2004).

Constrained. In a continuous section without any missing interval, therefore, we need to identify precise horizons of the onset and end of the Capitanian minimum.

In order to check the unique Sr event in mid-Panthalassa, this study analyzed a continuous single section of the Guadalupian–Lopingian carbonates of the Akasaka limestone in central Japan. This limestone body was deposited likewise as a paleo-atoll complex in mid-Panthalassa but was formed on a separate paleo-seamount from those of Akiyoshi and Kamura mentioned above. This article reports the high-resolution Sr isotope chemostatigraphy of the continuous Guadalupian–Lopingian rocks at Akasaka and discusses their geological significance.

2. Geologic setting

Numerous blocks/lenses of Permian limestone occur as allochthonous units in the Jurassic accretionary complex in SW Japan, including the ones at Akasaka and Kamura (Fig. 2A). These limestones were primarily deposited as paleo-atoll complexes developed on the top of Permian seamounts in low-latitude domains of the superocean Panthalassa (Fig. 2B; C; Sano and Kammera, 1988; Sano and Nakashima, 1997; Isozaki, 1997; Ota and Isozaki, 2006; Kasuya et al., 2012). During the Triassic and the earlier half of the Jurassic, these paleo-atoll limestones were transported horizontally across Panthalassa to the subduction zone along the Mesozoic Asian margin. Through the subduction/accretion processes at trench, these rocks were eventually dismembered in detail and the barren interval of the Upper Member). Section 2, previously described by Ota and Isozaki (2006), displays the transitional interval from the Upper Member to the Ichihashi Formation across the G–LB.

3. Methods

3.1. Material

Fine-grained micritic limestone (or lime mudstone) is suitable for measuring primary $^{87}\text{Sr}/^{86}\text{Sr}$ signature rather than sparry bioclastic limestones, as demonstrated in a good agreement among the coeval conodonts, brachiopods, and limestones of the Permian age (Popp et al., 1986; Denison et al., 1994; Denison and Koepnick, 1995; Martin and Macdougall, 1995). Owing to the facies-related scarcity of brachiopods and conodonts in the Permian limestone of Akasaka, we specifically chose fine-grained limestone (micritic part composed of pure carbonates with scarce terrigenous components) for analysis.

Out of over 50 samples of fine-grained limestone collected from the above-described two sections in Akasaka (Sections 1 and 2), 29 samples of vein-free fresh limestone were analyzed for Sr-isotope ratio. At Section 1, we newly collected 23 samples from the Yabeina Zone and the barren interval. The sample numbers from the barren interval of Section 2 are common with those used in Ota and Isozaki (2006). The stratigraphic horizons of these are shown in Fig. 4.

3.2. Sr isotope analysis

For Sr-isotope measurements, 40–50 mg of handpicked specimens from each sample was dissolved in 5 ml of 1 M suprapure acetic acid. Sr was extracted in 1 ml micro-columns filled with 100 μl Sr Spec resin (Elchrom Industries). The column was rinsed with 3 ml of 3 M HNO₃, and Sr was eluted with 1 ml of H₂O. Separated Sr was loaded on single W filaments with Ta activator. Samples were analyzed by thermal ionization mass spectrometer (TIMS; Finnigan MAT 262) at the Faculty of Science, Kumamoto University, with a reproducibility of $1 \times 10^{-5}$. All data were corrected for internal mass bias using $^{87}\text{Sr}/^{86}\text{Sr}=0.1194$. Recent average value of standard NIST SRM 987 are $^{87}\text{Sr}/^{86}\text{Sr}=0.710267 \pm 14$ (2SD; n = 24). Our laboratory blanks were <500 pg.

In the Carboniferous and Permian carbonates in Japan, strontium concentrations are varied from 300 to 3400 ppm, and Rb/Sr ratios are always very low ($<0.01$). In this study, the very low Rb/Sr ratios make the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of carbonates close to the initial ratios of Permian with negligible age effect.

4. Results

Table 1 shows the measurements of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the 29 carbonate samples collected from two studied sections at Akasaka. Fig. 4 displays their stratigraphic change. The $^{87}\text{Sr}/^{86}\text{Sr}$ values from the Upper Member range in 0.7068 to 0.7072. The residence time of Sr in seawater is estimated ca. 3 m.y. in modern oceans. When we discuss past records on the resolution of several tens of million years,
Fig. 2. Index map and geologic setting of the studied Permian paleo-atoll complexes in Japan. A: index map of the paleo-atoll carbonates at Akasaka, Kamura, and Akiyoshi in SW Japan. The Akasaka and Kamura sections occur in the Jurassic accretionary complex (the Mino-Tanba and Chichibu belts), whereas the Akiyoshi section in the Permian accretionary complex (the Akiyoshi belt). B: a simplified diagram of a ridge-subduction system showing the tectono-sedimentary setting of the Permian paleo-atoll complex; from the primary deposition on a mid-oceanic seamount to the secondary accretion at a trench (from Isozaki, 2007). C: The Permian paleogeographic map showing the primary location of the paleo-seamounts (Akasaka, Kamura, and Akiyoshi seamounts) and the reference section in S. China (modified from Scotese, 2008 based on Maruyama et al., 1989 and Kasuya et al., 2012).
therefore, all the ancient seawaters were regarded to have been well mixed isotopically in general.

The Capitanian interval, i.e., the lower half of the barren interval (8 m-thick) and the Yabeina Zone (65 m-thick), is characterized by extremely low values of 0.7068–0.7070. Extremely low values ~0.70690 are detected also from 2 samples of the barren interval and 16 samples of the Yabeina Zone in Sections 2 and 1, respectively. The lowest value 0.706808 (sample 07AKA258) was detected within the Capitanian Yabeina Zone. These extremely low values continued upward to the middle of the barren interval, ca. 6 m below the G–LB, whereas the value started to increase in the upper part of the barren interval up to 0.70723 at the G–LB.

Ancient marine carbonates were often altered secondarily by syn-depositional and post-depositional diagenetic processes, and the primary Sr isotopes values were modified either (Gröcke et al., 2007). We cannot totally neglect the possibility of secondary diageneric overprint to the measured samples from the Permian accreted limestones in Japan, as they often suffered from subduction-related multiple deformations. Nonetheless, as diagenetic alteration by meteoric water generally brings Sr isotope values to the higher side. As long as the measured values from the Akasaka limestone are relatively low with respect to the reported values of the Phanerozoic carbonates (Fig. 1), they likely represent the primary signatures. Even in some interval with relatively scattered data, the lower envelop of the measured values likely approximates the primary signal.

5. Discussion

5.1. $^{87}\text{Sr}/^{86}\text{Sr}$ record of the Panthalassan seawater

This study confirms that the Capitanian Yabeina Zone and barren interval of the Akasaka Formation are characterized isotopically by the extremely low $^{87}\text{Sr}/^{86}\text{Sr}$ values, lower than 0.70690 (Fig. 4), with respect to the fluctuation range of Sr isotope ratio throughout the Phanerozoic (Fig. 1). Such extremely low Sr isotope ratio were detected for the first time from a 70 m-thick continuous Capitanian section (i.e., the Yabeina Zone and barren interval) that ranges for at least some million years immediately before the G–LB.
The present data indicate that the most of the Capitanian limestone at Akasaka was deposited under a unique seawater extremely depleted in radiogenic $^{87}$Sr, and that the low-latitude mid-Panthalassan surface water around the Akasaka paleo-seamount was least affected by the terrestrial flux from weathered continental crusts and/or more influenced by the hydrothermal flux from mid-oceanic ridges. This unique condition persisted consistently for at least some million years but ended abruptly around the G–LB, ca. 260 Ma, since which the Panthalassan seawater had received more continental flux.

The $^{87}$Sr/$^{86}$Sr profile of the Akasaka Formation agrees concordantly with that of the coeval Iwato Formation at Kamura in Kyushu (Kani et al., 2008). Fig. 5 illustrates the bio- and chemostratigraphical correlation between the Akasaka and Iwato formations. The Iwato Fm at Kamura shares more or less the same tectono-sedimentary history as the Akasaka Fm, as it experienced the primary deposition as a paleo-atoll complex on the top of a mid-oceanic seamount and the secondary accretion to the Jurassic Japan (South China) margin after the long journey across Panthassla (Sano and Nakashima, 1997; Ota and Isozaki, 2006; Kasuya et al., 2012).

The data from Kamura (Kani et al., 2008) show the sporadic occurrence of relatively higher values within the Capitanian, which is not observed in Akasaka. As to the Iwato Fm, the stratigraphical continuity is less clear with respect to the Akasaka Fm, owing to the severer structural disturbances relevant to the subduction–accretion processes. Judging from the more tectonized conditions of the Iwato Fm, we currently regard these spikes of high values in Kamura are of secondary diagenetic origin, thus they should be disregarded in further discussion on the primary signature.

As the Akasaka and Iwato formations are separated from each other for ca. 500 km at present, the two limestones were likely derived from independent paleo-seamounts from the same domain in Panthalassa, in particular in the low-latitude domain of the southern hemisphere (ca. 12°S; Kirschvink and Isozaki, 2007). The identical $^{87}$Sr/$^{86}$Sr records from the two independent paleo-atoll complexes indicate that the

Fig. 4. The secular change in $^{87}$Sr/$^{86}$Sr ratio of bulk carbonates in the two studied sections in the Akasaka area.
low-latitude mid-superoscean surface seawater was extremely depleted in radiogenic Sr throughout the Capitanian, at least for some million years. The rapid increase of $^{87}\text{Sr}/^{86}\text{Sr}$ in surface seawater, from ~0.7068 to ~0.7072, likely started commonly in the low-latitude Panthalassa, but also to the rest extensive low-latitude tropical domains of Panthalassa.

Due to the lesser influence from local terrigenous sources with radiogenic $^{87}\text{Sr}$, mid-oceanic rocks likely record the global average of seawater Sr isotopic composition better than the contemporary continental shelf deposits (e.g., Brand et al., 2009). Thus the Sr isotopic record of the unique Capitanian interval of the studied paleo-atoll carbonates likely represents the global signature. Furthermore, the rapid increase at the end of the Capitanian probably suggests the appearance of a particular event of global context, probably of tectonic origin, which induced the larger flux of high $^{87}\text{Sr}/^{86}\text{Sr}$ from continental crusts, i.e., the Pangean crust at that time, into the superocean.

5.2. The Guadalupian minimum and its possible cause

The Guadalupian marine Sr record from mid-Panthalassan (Kani et al., 2008; this study) is compared concordantly with those from coeval continental margin carbonates around Pangea (Fig. 2C). From the biostratigraphically well-defined shallow marine carbonates in east Pangean margin, extremely low $^{87}\text{Sr}/^{86}\text{Sr}$ values, lower than 0.7070, were reported; e.g., 15 samples of the Wordian to Capitanian in southwestern USA (Martin and Macdougall, 1995; Denison and Koepnick, 1995; Jones et al., 1995; Korte et al., 2006; see table 2 of Kani et al., 2008).

Also from the uppermost Capitanian in South China off the western margin of Pangea (Fig. 2C), relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ values were reported (Wang et al., 2004; Korte et al., 2006; fig. 6). In particular, Korte et al. (2006) documented $^{87}\text{Sr}/^{86}\text{Sr}$ values of brachiopod shell; 4 samples from the Capitanian at Shangsi, South China (0.706965, 0.706949, 0.706948 and 0.706920), and one sample from Penglaitan (0.706897). In addition, the extremely low value of 0.70671 was detected from the horizon 1 m below the G–LB at CSSP of G–LB at Penglaitan (Wang et al., 2004). In contrast, Wignall et al. (2009) reported relatively higher values of 0.7072–0.7073 from the same section across the G–LB with only one sample with 0.7069 (although the corresponding plot in their figure contradictorily shows much higher value, and details of this measurement were not described). Judging from the ambiguity, we eliminate the data by Wignall et al. (2009) in the following discussion.

The above data confirm that the unique surface seawater depleted in radiogenic Sr has appeared during the Wordian and Capitanian on both sides of Pangea (Fig. 2C), whereas the seawater immediately around the G–LB might have relatively higher values over 0.7070. In other words, these validated the global context of the Capitanian minimum of seawater Sr isotope ratio, which was recognized merely on the basis of sporadic data from N. America and Tethys (Veizer et al., 1999; McArthur and Howarth, 2004). The present data confirm that the Capitanian minimum ended around the G–LB (Fig. 6), and further highlight that the geological significance of the G–LB event as a major turning point in the Phanerozoic seawater Sr isotope history; i.e., from the Pernian decrease to the Triassic increase via the Capitanian minimum. In contrast, the onset timing of the Capitanian minimum has not yet been sufficiently constrained, thus needs to be checked.

The cause of the Capitanian minimum has not yet been fully explained. In order to drive such extremely low $^{87}\text{Sr}/^{86}\text{Sr}$ values (down to 0.7068) in global seawater, the suppression of the continental flux is inevitable because the continental flux into oceans increases when the surface erosion/weathering of continental crust increases. In contrast, it is generally difficult to increase dramatically the flux from mid-oceanic ridge hydrothermal systems, because the plate tectonic processes are rather constant through time; e.g., even in the mid-Cretaceous with faster-spreading ridges, the seawater $^{87}\text{Sr}/^{86}\text{Sr}$ did not drastically decreased.

The classic explanation for low Sr isotope ratios is the shortening of total length of continental coastlines with respect to the assembly of the supercontinent Pangaea (e.g., Korte et al., 2006). According to the widely-used paleogeographic maps by Scotese (2008), Pangaea reached its maximum size with the minimum total length of coastline.

### Table 1: Analytical results of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Guadalupian (Middle Permian) limestones in Akasaka, Japan

<table>
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<tr>
<th>Sample</th>
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<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
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<td>Barren interval</td>
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<td>Barren interval</td>
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<td>Barren interval</td>
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<td>Yabeina</td>
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</table>
in the Permian; however, the precise timing of each continental collisional event was not properly constrained in his reconstruction. For example, as more than 7 individual continental blocks of Asia were not yet amalgamated in the Middle Permian (e.g., Maruyama et al., 1989); i.e. Asia was not yet in shape prior to the final closure of the Uralian seaway to form Laurasia (northern half of Pangea) in the Late Permian (Fig. 2C). During the Middle Permian, therefore, the total length of continental coastlines was not at the minimum as previously imagined (e.g., Korte et al., 2006).

Another possible explanation for limiting continental flux is the sea-level rise that may decrease continental erosion rate. This was not the case, however, as the Capitanian witnessed the lowest sea-level of the Phanerozoic (Haq and Schutter, 2008). The sea-level of the world oceans falls considerably when a large amount of seawater is stabilized on land in the form of glacier ice. The Capitanian appears to have been the time for the greatest continental erosion probably with the largest flux of radiogenic Sr into the oceans but this contradicts with the Sr isotopic record. Nonetheless, by considering the ice-driven suppression of continental erosion under a cold/cool climate, a completely different scenario becomes possible.

Under a cold climate during which glacial ice sheets extensively conceal continental crusts, the surface erosion/weathering can be significantly suppressed regardless the global sea-level drop (Figs. 7–1A). The Late Paleozoic (Gondwana) glaciation started in the Late Devonian, and recorded multiple episodes of major glaciation in the Carboniferous and Early Permian (e.g., Crowell, 1999; López-Gamundi and Buatois, 2010). After the peak in the earliest Permian, it was generally regarded as if the Gondwana ice sheets waned away during the Permian. Nonetheless, the development of higher latitude alpine glaciers in the Capitanian was recently recognized (Fielding et al., 2008), and this proved that a cool/cold episode remained or re-appeared still in the Late Guadalupian. Although the timing and duration of the glacial event during the Late Permian have not been yet fully constrained (e.g., Fielding et al., 2008; López-Gamundi and Buatois, 2010; Chen et al., 2013), a cool/cold episode likely appeared by and large simultaneously during the interval of the Capitanian minimum. In addition to the lowest sea-level in the Phanerozoic (Haq and Schutter, 2008), the appearance of a cool/cold episode still in the Capitanian is supported by other lines of paleontological and geochemical evidence; e.g., the selective extinction of photosymbiotic community in tropical fauna (Isozaki and Aljinović, 2009), the migration of mid-latitude brachiopods toward the equator (Shen and Shi, 2002), and the high positive values of δ13Ccarb (Isozaki et al., 2007). The claimed development of glacier in the Guadalupian world needs to be further tested.

In short, we speculate that the main cause of the Capitanian minimum was likely the persistence/resurgence of the cold/cool climate in the Late Guadalupian. Regardless the lowest sea-level of the Phanerozoic, the potential coverage of extensive glacial ice over major continental crusts (Figs. 7–1A) could drive the continental flux to the lowest Sr isotopic ratio in the Panthalassan seawater.

5.3. Post-Guadalupian regime change

The above data and discussion confirm that the Sr isotope composition of the mid-Panthalassan seawater changed its overall trend around the G–LB (Fig. 6). After the Capitanian minimum, the seawater 87Sr/86Sr values increased for 0.0014 during ca. 15 m.y. (Fig. 1) during the Late Permian–Early Triassic interval; i.e., in the most rapid way and in the largest magnitude in the entire Phanerozoic. This unusually rapid increase in Sr isotope ratio essentially indicates that an extraordinarily large amount of terrigenous clastics (replete with radiogenic Sr) was transported abruptly from Pangea to...
Panthalassa (Kani et al., 2008), and that non-ordinary processes likely have functioned on a global scale since the G–LB timing.

Immediately after the G–LB, the Late Permian experienced the sea-level rise (Haq and Schutter, 2008) likely under a warmer climate. This appears contradictory with the rapid increase in seawater Sr isotope ratios, because the total land surface became shrink under the higher sea-level. In accordance with the above-explained cause of the Capitanian minimum, however, the ultimate termination of the long-lasting Gondwana glaciation is a possible and promising explanation. By removing ice covers from the major continents, the erosion/weathering rate of continental crusts might be enhanced to increase the continental flux to Panthalassan seawater (Figs. 7–1B).

In a mirror image of the condition of the Capitanian minimum, the post-G–LB global warming and deglaciation started to trigger the rapid increase of the seawater Sr isotope ratio. As to the extraordinary increase in Sr isotope ratio, the global tectonics should be also taken into consideration. During the Late Permian, Laurasia was under the final construction, generating multiple collision-related orogenic belts in the northern hemisphere (e.g., Maruyama et al., 1989). On the other hand in the southern hemisphere, Gondwanaland already started to break up already in the Permian (e.g., Veevers, 1990). All of these Permian tectonic episodes of major continents might function not for suppressing but for accelerating the continental flux with radiogenic Sr into the Panthalassan seawater.

The breakup of Gondwanaland, in particular along its northern margin, was initiated by the impingement of plural mantle plumes, as evidenced by the occurrence of several large igneous provinces (LIPs) in Oman and Western Australia (e.g., Veevers, 1990). Continental breakup generally proceeds in the following series of tectonic events; i.e., 1) regional uplift of pre-existing continental crusts, 2) continental
rifting under extensional tectonic regime, 3) widening of the rift valley, and 4) appearance of a new ocean between the separated two continental margins. The first event often results in additional elevation of continental surface for ca. 2–3 km, and this enables to intensify considerably the surface erosion/weathering of continental crust (Figs. 7–2), as observed in Cenozoic Africa. In the second and third stages, normal faulting exposes deeper parts of continental crusts to accelerate the continental flux of radiogenic Sr to the surrounding oceans (Figs. 7–3).

During the Permian, intra-supercontinental basins, e.g., in Africa (Veevers, 1990; Wopfner and Jin, 2009) and in North America/Greenland (e.g., Surlyk, 1990; Vigran, et al., 1999), might accumulate large amounts of terrigenous clastics enriched in radiogenic $^{87}$Sr. Further acceleration of increase becomes possible by the rift-related development of new drainage systems that opened new leaking passages from the intracontinental basins to the surrounding superocean (Isozaki, 2007; Kani et al., 2008; figs. 7–3). We need to check actual regions and timing of rifting with high-resolution chronology to test the above interpretation.

After all, the rapid increase in Sr isotope ratio across the G–LB was likely accelerated by the continental breakup of Gondwanaland. One of the Permian LIPs in South China (Emeishan trap) was emplaced immediately after the G–LB (e.g., Shellmut et al., 2012). Prior to the ca. 259–256 Ma (Early Wuchiapiangian) flood basalt volcanism, the pre-eruption doming/uptilt likely occurred in South China. This alone might not contribute much to the increase of seawater Sr isotope ratio; however, because the size of the LIP was too small, and also because the uplifted/eroded surface crust of South China was occupied mostly by thick shallow marine carbonates (e.g., He et al., 2003) that were not enriched in radiogenic $^{87}$Sr. More regional effects by multiple LIPs are likely needed to explain the total change in Sr record.

On the basis of the distribution of the contemporary plume-related large igneous provinces, Isozaki (2007, 2009b) explained that the entire Phanerzoic secular change of $^{87}$Sr/$^{86}$Sr values (Fig. 1) likely recorded the two-phased breakup history of Pangea; i.e., first in the Guadalupian in the eastern half Pangea, and second in the mid-Jurassic in the western half. The first breakup/rifting of Gondwanaland was the main trigger of the post-Guadalupian regime change in seawater Sr isotope composition, whereas the second major rifting associated with the initial opening of the Atlantic Ocean drove the mid-Jurassic minimum. The rapid increase in $^{87}$Sr/$^{86}$Sr ratio during the Neoproterozoic, more or less the same in magnitude as the mid-Permian case, was also explained likewise in terms of the break-up of the supercontinent Rodinia (Halverson et al., 2007; Maruyama and Santosh, 2008).

As to the extinction scenarios for the G–LB event, the appearance of cool climatic conditions during the Capitanian (Isozaki et al., 2007) can explain many geological phenomena in harmony. The present work documented that the Middle-Late Permian seawater Sr isotope record can be also explained concordantly with the Kamura cooling event in the Guadalupian.

6. Conclusions

The present study analyzed $^{87}$Sr/$^{86}$Sr stratigraphy of the Capitanian (upper Middle Permian) Akasaka paleo-atoll limestone deposited in the low-latitude mid-Panthalassa. The new facts of the present study led the following conclusions:

1. The Capitanian interval consistently records extremely low $^{87}$Sr/$^{86}$Sr values, lower than 0.7069, confirming the remarkable chemostratigraphical episode called the “Capitanian minimum” in the low-latitude mid-Panthalassa.
2. The likely cause of the Capitanian minimum was the appearance of a cold/cool climate that prohibited the continental flux into Panthalassa by ice covering on continents.
3. The rapid increase in $^{87}$Sr/$^{86}$Sr values immediately after the Capitanian minimum can be explained by the deglaciation and the continental rifting. In the Early Wuchiapiangian after the Kamura cooling event, the ice-free extensive exposure of the continental crust, as well as the plume-induced continental rifting with new
drainage systems, likely increased the continental flux enriched in radiogenic Sr to Panthalassa.

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