Abstract—This study demonstrates that the frequency modulation of astronomically-related sedimentary rhythms can be used as a potential stratigraphic correlation tool for Mesozoic strata. For this purpose, cyclostratigraphic analyses were conducted on Upper Triassic to Lower Jurassic bedded chert sequences consisting of alternating chert-shale beds from the Kuruasu and Katsuyama sections (Inuyama area, central Japan), and the Pisenaizawa section in the Shizunai area, northern part of Japan, spanning 30 Myr, 20 Myr, and 15 Myr period, respectively. The average duration of each chert–shale couplet in each section is consistent with ca. 20 ka precession cycle. Wavelet spectral analysis of a bed number series of chert-bed thickness reveals ca. 5, 20, and 100 bed cycles, which correspond to the periodicities of the ca. 100, 400, and 2000 ka eccentricity cycles, respectively, assuming each chert–shale couplet as a ca. 20 ka precession cycle. The similar patterns of the frequency modulation of the ca. 20 bed cycles detected from these sections are interpreted as the result of the frequency modulation of ca. 20 ka precession cycle within each 405 ka eccentricity cycle of constant periodicity. The timing of frequency modulation of ca. 20 bed cycle is synchronous between Katsuyama and Kuruasu sections based on the high-resolution biostratigraphy across the Triassic-Jurassic boundary. Based on the stratigraphic variations in the frequency modulation of the ca. 20 bed cycle, the horizon of potential Triassic-Jurassic boundary is recognized in the Pisenaizawa section. This correlation is supported by the in-phase relationship of ca. 2 Myr cycle of the chert bed-thickness variation across the Triassic-Jurassic boundary among these sequences.

INTRODUCTION

The orbital cyclicity recorded in sedimentary rhythms provides a high-resolution time scale for geologic records (e.g., Fischer, 1986). The astronomically calibrated time scale is nearly complete for Cenozoic strata, and attempts have been made to extend it to Mesozoic and older strata (e.g., Hinnov and Oggi, 2008). For Triassic strata, astronomically controlled sedimentary cycles are recognized on a global scale, such as the lacustrine sequences in North America, Europe, and Africa (e.g., Olsen and Kent, 1996, 1999; Vollmer et al., 2007; Deenen et al., 2010; Olsen et al., 2011), the carbonate platforms in Europe and China (e.g., Ruhl et al., 2010; Huang et al., 2011; Wu et al., 2012), and the pelagic deep-sea sequences in Japan (Ikeda et al., 2010a, b; Ikeda and Tada, 2013). However, the Triassic astronomical time scale is under construction due to the limit of length of these records and the difficulty of the stratigraphic correlation between the different sections.

Conversely, bedded chert accumulated continuously for long-term periods in pelagic Panthalassa before the Cretaceous, and consists of rhythmic alternations of chert and shale controlled by astronomical cycles (e.g., Fischer, 1976; Hori et al., 1993; Ikeda et al., 2010a, b; Ikeda and Tada, 2013). Consequently, the bedded chert sequences are the potential template for pre-Cretaceous cyclostratigraphy (Ikeda et al., 2010a). Nevertheless, to establish a continuous cyclostratigraphy of the bedded chert sequence, the bedded chert sequences need to be correlated between the different sections with high resolution. Lithostratigraphic correlation using some key beds is a high-resolution and useful method at least at the regional scale (e.g., Sugiyama, 1997; Ikeda et al., 2010a), but it is difficult to correlate between distant localities solely by lithostratigraphy. Radiolarian and conodont biostratigraphy is used extensively for correlation of bedded chert sequences and for age constraint (e.g., Yao et al., 1980; Sugiyama, 1997). However, biostratigraphic resolution for bedded chert is generally on the order of millions of years, depending on fossil occurrence (e.g., Sugiyama, 1997). This resolution is several orders coarser than that of cyclostratigraphy, which uses the astronomical parameters, such as the ca. 20 ka precession cycle, the ca. 40 ka obliquity cycle, and the ca. 100 ka eccentricity cycle. Therefore, orbital-scale, high-resolution stratigraphy in addition to cyclostratigraphy, is necessary for cyclostratigraphic correlation between different localities (e.g., Olsen et al., 1996; Ruhl et al., 2010).

Aside from these basic orbital cycles, it is known that astronomical parameters modulate at amplitudes and frequencies on time scales longer than 100 ka (e.g., Hinnov, 2000). Although the amplitude of the astronomical cycles recorded in stratigraphic records can vary in different regions through non-linear interactions within Earth surface systems, frequency modulation should be recorded linearly in strata on a global scale (e.g. Hinnov, 2000). Thus, if the similar frequency modulations of the astronomical rhythms are detected from strata at different localities, their frequency modulations could be used as a potential stratigraphic correlation tool.

To demonstrate this possibility, this study examined the stratigraphic variations in the frequency of ca. 20 bed cycles, which are considered the result of frequency modulation of ca. 20 ka precession cycles within 405 ka eccentricity cycles of constant periodicity (e.g., Ikeda et al., 2010a). I adopted the method of Ikeda et al. (2010a) to the Upper Triassic to Lower Jurassic bedded chert sequences in Japan. Studied sections are the Katsuyama and Kuruasu section in the Inuyama area, central Japan and the Pisenaizawa section in the Shizunai area, northern part of Japan, which cover intervals of ca. 30 Myr, 20 Myr, and 15 Myr, respectively. To estimate the duration of each chert-shale couplet, this study established bed-by-bed scale high-resolution lithostratigraphy of bedded chert sequences at each section, and confirmed the ca. 20 ka precession-cycle origin of the chert-shale couplets based on the biostratigraphic age. To detect the astronomical cycle from the sedimentary rhythms of bedded chert at each section, wavelet spectral analyses were conducted on a bed-number series of chert-bed thicknesses. Based on the high-resolution biostratigraphic correlation of the end-Triassic extinction interval between Katsuyama and Kuruasu sections (Carter and Hori, 2005; Kuroda et al., 2010), I confirmed the validity of the frequency modulation of ca. 20 bed cycle as the stratigraphic correlation tool. The Pisenaizawa section, where the end-Triassic extinction interval was not well constrained, was then correlated with the Katsuyama and Kuruasu sections by using the frequency modulation of ca. 20 bed cycle. This cyclostratigraphic correlation was validated by the phase relations of ca. 100 bed (2 Myr) cycles among these sequences. These results provide a
new cyclostratigraphic method for stratigraphic correlation of the sections without high-resolution age control.

**GEOLOGIC SETTING**

*General Geology and Lithostratigraphy*

The Katsuyama section (e.g., Hori, 1990, 1997; Matsuoka et al., 1994; Carter and Hori, 2005) and Kurusu section (e.g., Hori, 1988, 1990, 1992, 1997; Kuroda et al., 2010) are located in the Inuyama area, southwestern part of the Mino Terrane, Central Japan (Fig. 1). The Mino Terrane is a Paleozoic–Mesozoic accretionary complex consisting of greenstone, limestone, bedded chert, and clastic rocks (Wakita, 1988). The accretionary complex exposed in the Inuyama area comprises Middle Triassic to Lower Jurassic bedded chert and Middle Jurassic clastic rocks, which are repeated as tectonic slices (Fig. 1; Matsuda and Isozaki, 1991; Yao et al., 1980). The Katsuyama and Kurusu sections are located in different thrust sheets, slices CH-3 and CH-4, respectively (Fig. 1; e.g., Yao et al., 1980). According to the distribution of these thrust sheets, the two sections were originally several tens of kilometer apart (e.g., Kimura and Hori, 1993).

The Pisenaizawa section is located in the Shizunai area, southern part of the Kamuikotan metamorphic complex, northern part of Japan, a distance of ca. 1000 km from the Inuyama area (Fig. 1). The Kamuikotan complex is a Mesozoic accretionary complex consisting of greenstone, limestone, bedded chert, and clastic rocks (e.g., Suzuki et al., 1961; Hori and Sakakibara, 1994), which were formed in Early Cretaceous time. The bedded chert sequence from this area spans from the Upper Triassic to Lower Cretaceous, and is well exposed along the Pisenaizawa River, Hokkaido, Japan (Hori and Sakakibara, 1994).

The bedded chert sequence was generally deposited on the pelagic deep-sea floor of Panthalassa below the carbonate compensation depth (CCD), whereas the clastic rocks are considered to have been deposited within a trench in a subduction zone (e.g., Matsuda and Isozaki, 1991). Paleomagnetic studies of the bedded chert sequence in the study area suggest that the site of deposition moved from low latitudes during the Middle Triassic to middle latitudes during the Lower Jurassic as a course of plate motion (Fig. 1; Shibuya and Sasaki, 1986; Oda and Suzuki, 2000; Ando et al., 2001).

The bedding of these pelagic deep-sea sequences consists of alternating thick chert and thin shale beds, the so-called chert-shale couplet. The alternation of chert-shale couplets was considered the result of the cyclical accumulation of biogenic SiO2 in environments with extremely slow accumulation of shale with probable eolian dust (Hori et al., 1993). Hori et al. (1993) also proposed that the individual chert–shale couplets of the Upper Triassic to Lower Jurassic bedded chert at the Katsuyama and Kurusu sections in the Inuyama area may represent astronomical cycles, as the average duration represented by each couplet is 10–70 ka, with median durations of 20 ka for the Upper Triassic and 40 ka for the Lower Jurassic; these values roughly agree with the periodicities of the precession and obliquity cycles, respectively. The sedimentary rhythms of the Middle Triassic bedded chert sequence in the Inuyama area have been proven to be of astronomical origin based on the hierarchical cyclicity of ca. 100 ka, 405 ka, 1800 ka, and 3600 ka from chert-bed thickness variation (Ikeda et al., 2010a).

The studied Katsuyama section consists of Norian to Toarcian bedded chert, 36 m thick, which is red, green-gray, purple, and black in color (Fig. 2; e.g., Hori, 1990; Matsuoka et al., 1994; Sugiyama, 1997; Ikeda and Tada, 2013). The lower and middle parts of this section contain ca. 30 mm-thick red shale beds, which correlate to the shale beds named CS-2 and CS-3 of Sugiyama (1997), in ascending order (Fig. 2). The lower limit of this section consists of a white chert bed, which is ca. 200 mm thick, about 0.5 m below the CS-2 bed. The upper limit of this section consists of a green-gray chert bed just below a white chert bed ca. 500 mm thick, which correlates to the massive Toarcian white chert of Hori (1990). The bed number of this section is defined such that the red chert bed just above a white chert bed, which is the lower limit of our columnar section, is assigned as number 1, and the bed number increases up section until bed number 1596.

The Kurusu section consists of Rhaetian to Toarcian bedded cherts, ca. 22 m thick, which are mostly greenish-gray in color (Fig. 2; Hori, 1988, 1990, 1992). There are no remarkable thick shale beds in the lower to middle part of this section (Fig. 2; Hori, 1988, 1990). The bed number is referenced after Hori et al. (2007), and increases up section. The lower limit of this section is cut by a fault just below a green-gray chert (bed number KU – 125 of Hori et al., 2007). The upper limit of the Kurusu section consists of a green-gray chert (bed number KU + 625 of this study), just below a red shale bed ca. 100 mm thick. The bottom of this red shale bed is deformed by a fault. The Pisenaizawa section studied consists of Norian red siliceous shale, ca. 5 m thick, Norian to the Valanginian red bedded chert, ca. 90 m thick, Valanginian to Hauterivian varicolored shale, ca. 6 m thick, and Hauterivian to Barremian black shale, ca. 5 m thick with frequent intercalation of acidic tuff, in ascending order (Hori and Sakakibara, 1994). The purple bedded chert, ca. 0.5 m thick, is intercalated within the lower part of this section (Fig. 2). The lowest purple chert bed of this purple bedded chert is assigned as bed number PS + 1, and the bed number increases up section and decrease down section. The bedded chert sequence of bed number PS + 438 to PS + 240 is discussed below to establish the cyclostratigraphy across the Triassic-Jurassic boundary.

*Biostratigraphy*

The age for the Upper Triassic to Lower Jurassic bedded chert sequences is established based on the radiolarian-conodont-ammonoid biostratigraphic correlation to reference sections where numerical ages have been estimated. The ages of the stage boundaries are after Ogg (2012) and Ogg and Hinnov (2012). The Norian/Rhaetian boundary in...
FIGURE 2. The estimated average sedimentation rates and the average durations of individual chert-shale couplets for the Upper Triassic to Lower Jurassic bedded chert sequences at A, Katsuyama section; B, Kurusu section in the Inuyama area, Central Japan; and C, Pisenaizawa section in the Shizunai area, northern part of Japan. The average durations of the couplets were estimated from the duration of the intervals of interest divided by the number of beds (see the text for details). The ranges of the estimated durations are based on errors in the ages of geological stage boundaries (Ogg, 2012; Mundil et al., 2010, Häring et al., 2011) and uncertainties in the stratigraphic positions of the geological boundaries described by radiolarian zones are based on Hori (1988, 1990, 1992, 1997), Hori and Sakakibara (1999), Sugiyama (1997), Carter and Hori (2005), Hori et al. (2007), and Kuroda et al. (2010). The lithologic types of bedded chert are modified after Sugiyama (1997); B-, F- and A-types are predominated by > 1 mm thick shale beds, < 1 mm thick shale beds, and the alternation of B- and F-types within 1 m. Nor, Rht, Het, Sin, Plb, and Toa = Norian, Rhaetian, Hettangian, Sinemurian, Pliensbachian and Toarcian stages.
the Katsuyama section is correlated to the last occurrence of the radiolarian *Betracclum deweveri* within the interval between beds 400 and 430 in the Katsuyama section (Sugiyama, 1997), based on the radiolarian biostratigraphic correlation with the Queen Charlotte Islands, Canada, where the Norian/Rhaetian boundary is identified as the *Gromohalorites cordilleranus*/Paracochloceras *amoenus* ammonoid ammonoid zone boundary (Carter, 1993; Carter and Orchard, 2007). This ammonoid zone boundary is correlated with Paracochloceras *asuesii*/Vandaites *stuemenbaumi* ammonoid zone in the Steinbergkogel section, Austria, where the Norian/Rhaetian boundary was estimated as 209.5 ± 1.0 Ma by magnetostratigraphic correlation with the astronomically tuned geomagnetic polarity time scale of the Newark Supergroup (Hüsing et al., 2011; Olsen et al., 2010). These radiolarian zones equate to the radiolarian zones in the Pucara section (Schoene et al., 2010; Ruhl et al., 2010). Based on these chronostratigraphic constraints, the end-Triassic extinction in the Katsuyama, Kurusu, and Pisenaizawa sections, respectively, by ammonite biostratigraphy of Queen Charlotte Islands and other areas from North America (Carter et al., 2010). Thus, the uppermost part of the *P. simpium* IV Subzone of Hori (1990, 1997) is equivalent to the *Emaciatricaeras emaciatum/Dactyliloceras teniucostatum* ammonite Zone boundary of Europe, where the Pliensbachian/Toarcian boundary was assigned as 182.7 ± 0.5 Ma (Ogg and Hinov, 2012). This correlation is supported by the negative excursion of organic carbon isotope (Grocke et al., 2010). In the Pisenaizawa section, the Norian radiolarian fossils were obtained ca. 20 m below the PS – 1 (Hori and Sakakibara, 1994). The duration of the Norian was assigned as the interval between 228.4 ± 2.0 Ma and 209.5 ± 1.0 Ma (Ogg, 2012). The lower Toarcian radiolarian fossils *Tricolocapsa* sp. and *Bagotum* sp. were obtained ca. 10 m above PS – 1 (Hori and Sakakibara, 1994).

**METHOD**

The method of Ikeda et al. (2010a) was used to detect astronomical cycles from the sedimentary rhythms of the Upper Triassic to Lower Jurassic bedded chert sequences in the Katsuyama, Kurusu, and Pisenaizawa sections. For this purpose, I established high-resolution lithostratigraphy by measuring the thicknesses of individual chert and shale beds in each outcrop with a precision of one mm. At each outcrop, some transects were selected with minimal lateral change in bed thickness caused by tectonic deformation and diagenesis. I constructed continuous columnar sections ca. 36 m, 22 m and 15 m thick based on bed by bed thickness measurements of 1565, 751, and 679 chert and shale beds at the Katsuyama, Kurusu, and Pisenaizawa sections, respectively (Fig. 3). The thickness of the shale beds is generally less than 10 mm and the estimation errors are large for cyclostratigraphy (Ikeda et al., 2010a); consequently, this study did not examine the cyclicities of shale-bed thickness variation.

The average durations of chert–shale couplets for each interval were estimated from the average thickness of the couplets divided by the median sedimentation rate (Fig. 2). This study also performed wavelet analyses on bed-number series of chert-bed thickness in order to assess the dominant cyclicities and their modulations in the amplitude and frequency of the stratigraphic variations in chert-bed thickness. The wavelet analyses were conducted by using a series of Matlab algorithms modified from those developed by Torrence and Compo (1998). This program can identify whether peaks in the spectrum of the time series are significant against the red-noise (autoregressive lag1) background spectrum. The analysis was carried out in the bed number domain rather than in the depth domain, because the sedimentation rates are considered to have changed significantly between chert beds and intercalated shale beds (e.g., Hori et al., 1993).

**RESULTS**

**Chert-bed Thickness Variations of the Upper Triassic to Lower Jurassic Bedded Chert Sequences in Japan**

The stratigraphic variation in chert-bed thickness and its 5-point moving average in the Katsuyama, Kurusu, and Pisenaizawa sections is shown in Figure 3. In the Katsuyama section, chert-bed thickness ranges from 5 to 92 mm, with an average of 24 mm and standard deviation of 10 mm. The smoothed stratigraphic variations in chert-bed thickness show ca. 100 bed cyclicity with the amplitude of ca. 10 mm (Fig. 3). In the Kurusu section, chert-bed thickness ranges from 8 to 80 mm with an average of 28 mm and standard deviation of 11 mm. The smoothed stratigraphic variations in chert-bed thickness show ca. 100 bed cyclicity with an amplitude of ~7 mm (Fig. 3). In the Pisenaizawa section, chert-bed thickness ranges from 5 to 49 mm with an average of 17 mm and standard deviation of 7 mm. The smoothed stratigraphic variations in chert-bed thickness show ca. 100 bed cyclicity with the amplitude of ~5 mm (Fig. 3).
FIGURE 3. Stratigraphic variations in the chert-bed thickness, 5-point moving average, and dominant frequency of ~ 20 bed cycle of the chert-bed thickness, and Wavelet power spectrum and bandpass filter of a bed number series of chert-bed thickness in Upper Triassic to Lower Jurassic bedded chert sequences at A, Katsuyama section; B, Kurusu section in the Inuyama area, Central Japan; and C, Pisenaizawa section in the Shizunai area, northern part of Japan. The shaded region is the cone of influence, where zero padding has reduced the variance. Black contour is the 90 % confidence level, using a red-noise (autoregressive lag1) background spectrum (Torrence and Compo, 1998). Radiolarian zones are based on Hori (1988, 1990, 1992, 1997), Hori and Sakakibara (1994), Sugiyama (1997), Carter and Hori (2005), Hori et al. (2007) and Kuroda et al. (2010).
Comparison Between the Average Duration of Individual Chert–Shale Couplets and Precession Cycle

The sedimentation rate of each interval was estimated based on the age models of studied sections (Fig. 2). In the Katsuyama section, the rate during the Rhaetian to Pliensbachian was 0.6–1.0 m/Myr, with a median rate of 0.8 m/Myr; in the Kurusu section, the rate during the Hettangian–Sinemurian was 0.6–0.9 m/Myr, with a median rate of 0.7 m/Myr; in the Pisenaizawa section, the rate during the Norian to Pliensbachian was 0.6–1.0 m/Myr, with a median rate of 0.8 m/Myr (Fig. 2). The estimated ranges in the sedimentation rates include age estimation errors for the geological boundaries (Ogg, 2012; Ogg and Hinnov, 2012) and the uncertainties in the stratigraphic positions of the boundaries (Fig. 2).

The average durations of chert–shale couplets for each interval were estimated based on the above sedimentation rates (Fig. 2). In the Katsuyama section, the average duration of an individual chert–shale couplet is between 17 and 28 ka (median value, 22 ka) for the Rhaetian, 18 and 27 ka (median value, 21 ka) for the Hettangian to Pliensbachian, and 19 and 25 ka (median value, 22 ka) for the Rhaetian to Pliensbachian, respectively (Fig. 2a). In the Kurusu section, the duration is between 15 and 25 ka (median value, 21 ka) for the Hettangian–Sinemurian (Fig. 2b). In the Pisenaizawa section, the duration is 17 and 28 ka (median value, 20 ka) for the Norian to Pliensbachian (Fig. 2c). These estimated average durations for an individual chert–shale couplet are consistent with the 17 to 21 ka duration of the precession cycle during Late Triassic to Early Jurassic time (Berger et al., 1989).

Cyclostratigraphic Analysis of Chert-bed Thickness Variation

The results of wavelet analyses of the bed number series of chert-bed thickness in the Katsuyama, Kurusu, and Pisenaizawa sections are shown in Figure 3. In the Katsuyama section, the global wavelet power spectrum of the bed number series of chert-bed thickness variations shows cyclicities of ca. 3 to 5 beds, ca. 100 beds, and ca. 500 beds above the 90% confidence level, and a secondary peak at ca. 20 bed (Fig. 3a). The wavelet spectrum of the bed number series of chert-bed thickness variations revealed occurrences of the ca. 20 bed cycle in intervals between bed number PS – 70 and + 20 above the 10% significant level (Fig. 3b). The ca. 20 bed cycle modulates its frequency at 25 beds between bed number PS – 400 and – 220, at 16 beds between bed number PS – 220 and – 150, at 20 beds between PS – 160 and – 80, at 16 beds between PS – 60 and + 0, and at 20 beds between PS + 20 and + 180 (Fig. 3b). The wavelet spectrum of the bed number series of chert-bed thickness variations revealed occurrences of the ca. 100 bed cycle within the intervals between PS – 300 and + 0 (Fig. 3).

The end-Triassic extinction interval in the Katsuyama section is located at the maximum of the ca. 5 bed cycle, ca. 15 beds below the maximum of the ca. 20 bed cycle, and ca. 60 beds below the maximum of the ca. 100 bed cycle (Fig. 3a). In the Kurusu section, the end-Triassic extinction interval is also located in the interval from the maximum of the ca. 5 bed cycle, ca. 7 beds below the maximum of the ca. 20 bed cycle, and ca. 60 beds below the maximum of the ca. 100 bed cycle, to the minimum of the ca. 5 bed cycle, the maximum of the ca. 20 bed cycle, and ca. 53 beds below the maximum of the ca. 100 bed cycle in the Katsuyama section (Fig. 3b).

DISCUSSION

Frequency Modulation of the Astronomical Rhythms of the Bedded Chert Sequences across the Triassic-Jurassic Boundary

To establish the cyclostratigraphy of the Upper Triassic to Lower Jurassic bedded chert sequences in the Katsuyama, Kurusu, and Pisenaizawa sections, the cyclostratigraphic method of Ikeda et al. (2010a) was adapted to these sequences. The estimated durations of a chert-shale couplet agree with the 17–21 ka duration of the precession cycle during the Late Triassic to Early Jurassic (Berger et al., 1989). Therefore, it is reasonable to assume that each chert–shale couplet corresponds to a single precession cycle. Based on this, the significant spectral peaks at ca. 5 bed, 20 bed, and 100 beds of the wavelet spectrum of the bed number series of the chert-bed thickness are consistent with the duration of ca. 100 ka, 405 ka, and 2000 ka eccentricity cycles (Fig. 3; e.g., Berger et al., 1989, Laskar et al., 2004). Collectively, the similarities in the periodicities of the dominant cycles and their hierarchy of chert-bed thickness variations with those of the astronomical cycles supports the hypothesis that the cyclicities of chert-bed thickness variations in bedded chert are paced by the astronomical cycles (e.g., Ikeda et al., 2010a).

On the basis of this cyclostratigraphy, we tried to demonstrate the frequency modulation of the astronomical rhythms as a stratigraphic correlation tool. To test this possibility, we correlated the bedded chert between the Katsuyama section and the Kurusu section by high-resolution biostratigraphy. In the Katsuyama and Kurusu sections, the end-Triassic extinction intervals are well constrained by the radiolarian and conodont biostratigraphy with resolutions of ~ 19 ka and ~ 133 Ka, respectively (Carter and Hori, 2005; Kuroda et al., 2010), assuming a chert–shale couplet represents ~ 19 ka precession cycle. Based on this correlation, the frequency change of ~ 20 bed cycles in the Katsuyama section between ~ 16 beds and ~ 20 beds is well correlated with those in the Kurusu section (Fig. 3).

The frequency modulation of ~ 20 bed cycles detected in this study are caused by the frequency modulation of the ~ 20 ka precession cycle by each 405-ka eccentricity cycle (e.g., Ikeda et al., 2010a). The frequency modulations of the precession cycles are the result of the complex gravitational interactions among the planets (e.g., Hinnov et al., 2000; Huybers and Aharamon, 2010), and mainly related with the chaotic behavior of Earth-Mars secular resonance (e.g., Laskar, 1990; Laskar et al., 2004). Because this frequency modulation is not a simple cycle, but chaotic, the frequency modulation of ~ 20 bed cycles can be regarded as a fingerprint time, suggesting a possible stratigraphic tool. This idea is supported by the results showing the same patterns of the frequency modulation at the Katsuyama and Kurusu sections (Fig. 3). Therefore, it is certain that the frequency modulations of the astronomical rhythms can be used as a potential stratigraphic correlation tool independent from other methods.
Recognition of the Potential Triassic-Jurassic Boundary by the
Frequency Modulation of the Astronomical Rhythms

On the basis of the frequency modulation of the astronomical rhythms, the potential Triassic-Jurassic boundary was recognized in the bedded chert sequence in the Pisenaizawa section by correlation of the frequency modulation of ca. 20 bed cycle with those in the Katsuyama and Kurusu sections (Fig. 3). The cyclostratigraphy of the Pisenaizawa bedded chert shows the frequency modulation of ca. 20 bed cycle, similar to those in the Katsuyama and Kurusu sections (Fig. 3). According to the timing of the frequency modulation of ca. 20 bed cycles from 16 beds to 20 beds, and then back to 16 beds at the interval from Ps – 200 to – 120 in the Pisenaizawa section, we tentatively correlate this interval with the end-Triassic extinction interval in the Katsuyama and Kurusu sections (Fig. 3). To support this correlation, the phase of the ca. 2 Myr (ca. 100 bed) cycle at this interval in the Pisenaizawa section was compared with those of the Katsuyama and Kurusu sections (Fig. 3). According to high-resolution biostratigraphy, the end-Triassic extinction interval at Katsuyama section corresponds to 100 ka before the 405 ka cycle maximum and 500 ka before the ca. 2 Myr cycle maximum (Fig. 3). These timings are consistent with the base of the extinction interval in the Kurusu section (Fig. 3). In the Pisenaizawa section, the timing of these astronomical cycles is correlated with PS – 116 within the tentative end-Triassic mass extinction interval (Fig. 3). This result supports the conclusion that the end-Triassic extinction interval at the Kurusu section can be correlated by the frequency modulation of the ca. 20 bed cycle (Fig. 3). The timing of the astronomical cycles at the end-Triassic are consistent with the cyclostratigraphic results of the shallow marine Tethyan sequence at the St. Audrie’s section in the U.K. (Ruhl et al., 2010) and the lacustrine sequences of the Newark Supergroup (e.g., Whiteside et al., 2007, 2010). These similarities further support our cyclostratigraphic results and the possibility of coincidence of the end-Triassic extinction among terrestrial, shallow marine Tethys, and pelagic Panthalassa realms. Because the paleoclimatic and paleoceanographic implications are beyond the focus of this study, a more detailed discussion of this topic will be presented elsewhere (Ikeda et al., in prep). The in-phase relationship of the ca. 2 Myr cycle among these bedded-chert sequences, in addition to the similar pattern of the frequency modulation of ca. 20 bed cycle supports the stratigraphic correlation using the Ps – 105 to Ps – 122 chert beds as the end-Triassic extinction interval. Further geochronologic studies in the Pisenaizawa section will test this hypothesis, and provide the basis for a pre-Cretaceous astronomical time scale, because the Inuyama and Sizunai bedded chert sequences range from the Lower Triassic to Lower Jurassic and the Upper Triassic to Lower Cretaceous, respectively.

CONCLUSION

Cyclostratigraphic analyses of Upper Triassic to Lower Jurassic bedded chert sequences were conducted at the Katsuyama and Kurusu sections, in the Inuyama area, central Japan, and Pisenaizawa section in the Shizunai area, northern part of Japan. The average duration of chert–shale couplets estimated by the age model based on biostratigraphy is consistent with the length of the precession cycle during the Triassic to Jurassic (Berger et al., 1989). Spectral analysis of a bed number series of thickness variations in chert beds reveals ca. 100 ka, 400 ka, and 2000 ka eccentricity cycles, assuming that each chert–shale couplet represents the ca. 20 ka precession cycle. The periodicity of one sedimentary cycle and the hierarchy of the dominant cycles supports the idea that the sedimentary rhythm of bedded chert is paced by the astronomical cycles. The similar patterns of the frequency modulation of ca. 20 bed cycle were detected from these sections. The high-resolution biostratigraphic constraints of the end-Triassic mass extinction in the Katsuyama and Kurusu sections reveal the synchronous frequency modulation of ca. 20 bed cycles with each other. This result suggests that these frequency modulations of ca. 20 bed cycles could be used as a potential independent cyclostratigraphic correlation tool without other age constraints.

Based on this, we tentatively estimated the age of the Kamuikotan section by using the patterns of the frequency modulation of ca. 20 bed cycles similar to those in the Katsuyama and Kurusu sections. This correlation is consistent with the phase of the ca. 2 Myr cycle in the end-Triassic extinction interval in the Katsuyama and Kurusu sections, St. Audrie’s Bay section, and Newark Supergroup. The frequency modulations of the astronomical rhythms could be used as the new stratigraphic correlation tool and provide the basis for the astronomical time scale before the Cretaceous and the understanding of global environmental changes, such as the Triassic-Jurassic boundary event.

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