

The first Pacific record of the Late Aptian warming event

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Abstract: Carbonate platforms consisting of hermatypic coral, rudists and larger foraminifers formed along the margin of the NE Japanese islands during the mid-Late Aptian. The geographical northern limit of the carbonate platforms extended to *c.* 36°N at that time, which is the highest latitude for coral and/or rudist formation in the North Pacific region. This geographical extension of the carbonate platform in the NW Pacific indicates extreme climatic warmth in the mid-latitudes and strong poleward heat transport systems. Contemporaneous warming has been detected in European and Australian regions, as represented by the migration of Tethyan fauna toward the boreal realm and the positive excursion of $\delta^{13}\text{C}$ and negative excursion of $\delta^{18}\text{O}$ in deep-sea carbonates. Our new constraint on the northern limit of 'reef' growth reinforces the view that an interval of greenhouse-like warmth punctuated the Late Aptian climate.

Superplume activities created extreme warmth in the mid-Cretaceous (Larson 1991a, b), characterized by globally averaged surface temperatures 6–14 °C higher than those of today (Barron 1983), lower Equator-to-pole thermal gradients (Bice *et al.* 2003), a lack of permanent ice sheets (Frakes 1979), the occurrence of cold-blooded reptiles in high latitudes (Tarduno *et al.* 1998), and the poleward expansion of reef lines (Johnson *et al.* 1996). Because the sessile benthic organisms that build reefs and/or shallow shelf carbonates are sensitive to environmental and climatic changes, the geographical limits of carbonate platforms can be used as a proxy for the palaeo northern and southern margins of the subtropics. The temporal distribution, faunal changes, and rhythm of growth and decline of Cretaceous carbonate platforms have been well documented in the Tethyan, Caribbean and central Pacific regions (Föllmi *et al.* 1994; Johnson *et al.* 1996; Weissert *et al.* 1998; Wilson *et al.* 1998). These studies have revealed that Cretaceous carbonate platforms latitudinally expanded during, and following, the Aptian, and were episodically drowned during several oceanic anoxic events. Based on fluctuations in the geographical development of Caribbean and Atlantic carbonate platforms, the latitudinal expansion of these platforms culminated in the late Albian and Santonian, reaching a latitude of *c.* 35° (Johnson *et al.* 1996). However, little is known about the spatiotemporal and faunal changes of carbonate platforms in the Cretaceous North Pacific Ocean. Because the North Pacific Ocean occupied huge areas throughout the Cretaceous Period (e.g. Smith *et al.* 1994; Eldridge *et al.* 1999) and is thought to have greatly influenced global ocean–climate systems, it is important to clarify the palaeogeography and fauna of the carbonate platforms in this ocean.

This paper documents carbonate platforms containing abundant hermatypic warm-water organisms, such as rudists, corals and larger foraminifers, that developed along the northwestern margin of the Pacific Ocean in the mid-Late Aptian (Fig. 1a). The northern palaeogeographical limit of the carbonate platforms at that time reached 36°N. This limit was latitudinally the highest for carbonate platforms in the North Pacific Ocean. This paper

also discusses the possible relationship between the latitudinal expansion of carbonate platforms and the formation of large igneous provinces in the mid-Late Aptian.

Geological setting of the Cretaceous Japanese islands

The Japanese islands were an eastern part of the Asian continent before the late Miocene opening of the Japan Sea. The islands are composed mainly of Late Palaeozoic to Cenozoic accretionary complexes constructed along the East Asian continental margin, which have been intruded and covered by volcanic–plutonic rocks (Fig. 1a). Structurally, the Japanese islands are divided into the NE Japan and SW Japan blocks by the Tanakura Tectonic Line (Fig. 1b). The SW Japan Block is further cut by the Median Tectonic Line. Both tectonic lines were originally a series of large-scale, left-lateral, strike-slip fault systems active since the Early Cretaceous (Fig. 1a). The SW Japan Block and fragments of continental crusts in the Japan Sea had been attached to the northeastern Korean Peninsula until the early Miocene (Fig. 1a). Although most tectonic models agree that the NE Japan Block was located just east of Sikhote–Alin during the Palaeogene to early Miocene (e.g. Otoh *et al.* 1999), there is significant discrepancy regarding the block's position during the Cretaceous period. For example, palaeo-maps by Matsukawa *et al.* (1993), Smith *et al.* (1994) and Eldridge *et al.* (2000) did not estimate the significant left-lateral strike-slip movement of the NE Japan Block along the Tanakura Tectonic Line–Median Tectonic Line, and depicted the NE Japan Block to the east of Sikhote–Alin in the Early Cretaceous, as in the Palaeogene–early Miocene. On the other hand, Otsuki (1992) and Otsuki & Ehiro (1992) located the NE Japan Block about 400 km SW of its Palaeogene–early Miocene position based on the displacement estimated by the width of the Tanakura Tectonic Line. Furthermore, the most generally accepted model places the NE Japan Block just SW of the SW Japan Block, i.e. 1000–1500 km SW of its Palaeogene–early Miocene position (e.g. Taira *et al.* 1983, 1989; Taira 2001; Tazawa 2002; Sakashima *et al.* 2003; Takashima *et al.* 2006). We followed this last model for three

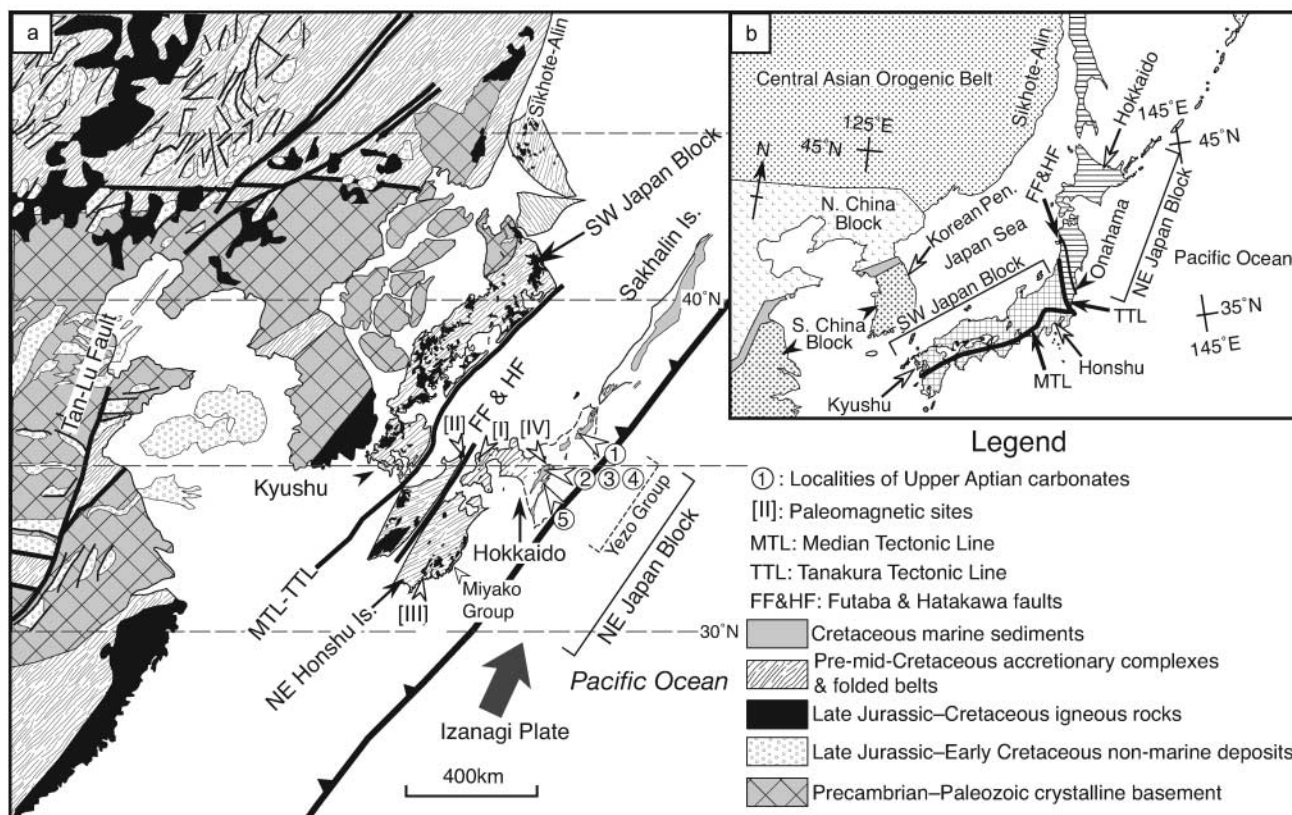


Fig. 1. (a) Tectono-stratigraphical reconstruction of mid-Cretaceous East Asia, modified from Tazawa (2002) and Takashima *et al.* (2006). The numbers in circles show the localities of middle Upper Aptian shallow marine carbonate sediments of the Yezo Group (1, Teshionakagawa; 2 and 3, Ashibetsu; 4, Oyubari; 5, Soshubetsu). The Roman numbers in brackets indicate palaeomagnetic sites of Aptian–Albian rocks studied by Sasajima (1981) (I, Oshima; II, Tsugaru; III, Kamaishi; their mid-Cretaceous palaeolatitudes are 36.2, 36.7 and 34.1°N, respectively) and palaeomagnetic sites of Valanginian rocks studied by Hoshi & Takashima (1999) (IV, central Hokkaido, 31.5°N). (b) Map of the Japanese islands and surrounding area, showing simplified tectonic domains. The major tectonic lines are shown in bold.

main reasons. (1) The Late Jurassic–Early Cretaceous plant assemblage in East Asia consists of southern and northern types, and mixtures of these types (e.g. Kimura 1987; Ohana & Kimura 1995). The southern types are distributed mainly in SE China, and the northern types are found in NE China. The southern-type Late Jurassic–Early Cretaceous plant assemblages predominate in the NE Japan Block, whereas the northern type dominates in the SW Japan Block. These lines of evidence suggest that the NE Japan Block was located south of the SW Japan Block during the Early Cretaceous and then juxtaposed to the SW Japan Block possibly during the mid-Cretaceous (e.g. Tashiro 1994). (2) According to U–Pb zircon dating of Lower Cretaceous granitic rocks, the timing and nature of these intrusions in the NE Japan Block are similar to those for the South China Block (see Fig. 1b) but differ from those for the SW Japan Block (Sakashima *et al.* 2003). (3) Palaeomagnetic data for Lower Cretaceous igneous and sedimentary rocks suggest that the palaeo-latitude of the SW Japan Block was higher than that of the NE Japan Block (e.g. Kodama & Takeda 2002; Fig. 1a).

The Late Aptian tectono-stratigraphical map shown in Figure 1a is based on an Early Cretaceous tectonic map by Tazawa (2002) and Takashima *et al.* (2006), taking into consideration mid-Cretaceous palaeomagnetic reconstructions of the South and North China blocks (Enkin *et al.* 1991; Liu & Morinaga 1999; Zorin 1999; Ren *et al.* 2002; Kirillova 2003; Meng 2003) and the

Japanese Islands (Sasajima 1981; Tosha 1982; Hoshi & Takashima 1999). Cretaceous marine sediments deposited on the NW Pacific margin are intermittently exposed along Hokkaido and northeastern Honshu (Fig. 1a). These sediments consist mainly of terrigenous sandstones and mudstones derived mainly from Mesozoic accretionary complexes and Cretaceous felsic–intermediate igneous rocks exposed immediately to the NW of each basin. Various coastal, continental shelf and slope facies are found.

Mid-Cretaceous carbonate sediments of the Japanese islands

Upper Mesozoic limestones of the Japanese Islands, including those formed by warm-water sessile benthic organisms such as hermatypic corals and rudists, occur approximately at the levels of the Tithonian, Barremian and Upper Aptian. Of these, the Upper Aptian limestones have the widest latitudinal distribution, ranging from Hokkaido to Kyushu, and are characterized by an abundance of larger foraminifers. Ujiie & Kusukawa (1968) and Matsumaru (1971) identified the larger foraminifers of the Upper Aptian Miyako and Yezo groups (Fig. 1a) as *Orbitolina lenticularis* Form-group II based on the classification of Hofker (1963). Recently, Iba *et al.* (2005) re-examined larger foraminifers of the Yezo Group based on the classification of Schroeder (1975) and

concluded that they belong to the *Orbitolina* (*Mesorbitolina*) *parva*–*O. (M.) texana* group, indicating a Late Aptian–Early Albian age.

The Upper Aptian limestones of Hokkaido, the northernmost major island of Japan, occur in the hemipelagic sequence of the lower Yezo Group as huge limestone olistoliths (localities 2–5 in Fig. 2) or carbonate pebbles in gravity-flow deposits (locality 1 in Fig. 2) (Takashima *et al.* 2004; Iba *et al.* 2005). In central Hokkaido, 60 m thick, slab-shaped limestone olistoliths (Fig. 3a) are continuously exposed for 3 km, and several tens of cubic metres of fragmented limestone blocks intermittently crop out for c. 100 km in a north–south direction. These limestones mainly consist of hermatypic massive corals (e.g. *Isastrea*, *Centrastrea*, *Thamnasteria*, *Favia*; Eguchi 1944, 1951), rudist bivalves (*Praeaprotina* and *Toucasia*; Fig. 3b and c; Yabe & Nagao 1926; Nagao 1933), larger foraminifers of *Orbitolina* (Fig. 3d; Matsu-mar 1971; Iba *et al.* 2005), the gigantic nerineacean gastropods *Adiozoptyx* (Fig. 3b; Fukada 1953; Kase 1984), and solenoporaean and coralline algae (e.g. *Nipponophycus*, *Pycnoporidium*, *Pterophyton*, *Lithothamnium*, *Archaeolithothamnium*; Nagao 1965; Kanmera & Obata 1972) with minor amounts of terrigenous detritus, and are divided into 10 facies, as shown in Figure 2. The succession within the limestone blocks generally begins with bioclastic wackestone, followed by a transition to rudist–coral-bearing wackestone and ultimately calcareous sandstone and/or packstone–grainstone with abundant *Orbitolina* (Fig. 2, localities 2–5). The facies and faunal composition suggest that limestones were deposited in a very shallow reef environment (Kanmera & Obata 1972), and the setting was reconstructed by Sano (1995) as a rimmed shelf. The terrigenous detritus in the

limestones corresponds to the Jurassic accretionary complex (Triassic–Jurassic chert and siliceous shale and greenstones), and Early Cretaceous granitic rocks (Fig. 3e) exposed in western Hokkaido (e.g. Takashima & Nishi 1999) suggest that the limestones were originally located to the west, adjacent to the Asian continental margin. According to Nishi *et al.* (2003) and Takashima *et al.* (2004), an olistostrome bed formed in the *Planomalina cheniouensis*–*Ticinella bejaouensis* planktonic foraminiferal zones. The limestone pebbles or fragments contained in turbidite or submarine debris-flow deposits of the Yezo Group occur above the olistostrome bed but are entirely absent below the bed in central Hokkaido, restricting the age of the limestone to the *P. cheniouensis*–*T. bejaouensis* biozones of the mid–Late Aptian.

Discussion

Based on the tectono-stratigraphical map, the geographical northern limit of the mid–Late Aptian carbonate platforms reached 36°N, corresponding to northern Hokkaido (Figs 1 and 4). Because this model sets Hokkaido in the southernmost position compared with other tectonic models (e.g. Otsuki 1992; Matsukawa *et al.* 1993; Smith *et al.* 1994; Eldridge *et al.* 2000), the proposed palaeo-latitude of these carbonate sediments is a minimum estimate. Therefore, there remains the possibility that these carbonate sediments formed even further north (e.g. Aptian palaeomaps by Smith *et al.* (1994) and Eldridge *et al.* (2000) place Hokkaido around 50°N). At present, coral reefs are typically distributed from 31°40'S to 32°50'N, where mean sea surface temperatures (SSTs) in winter are usually above 18 °C

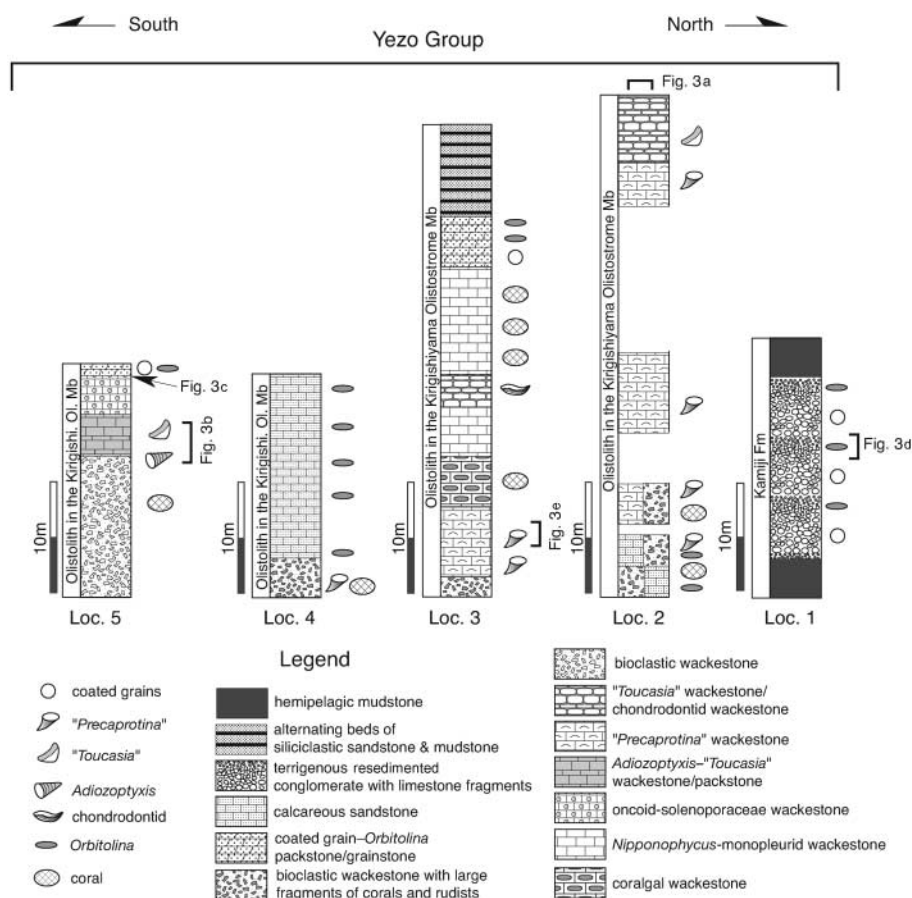


Fig. 2. Lithostratigraphical columns of the middle Upper Aptian limestone and conglomerate part containing limestone pebbles of the Yezo Group, Hokkaido. The localities of each column are shown in Figure 1a. Locality 1 is modified from Iba *et al.* (2005). Columns 2–5 represent successions within limestone olistoliths contained in the Kirigishiyama Olistostrome Member, and are modified from Sano (2000).

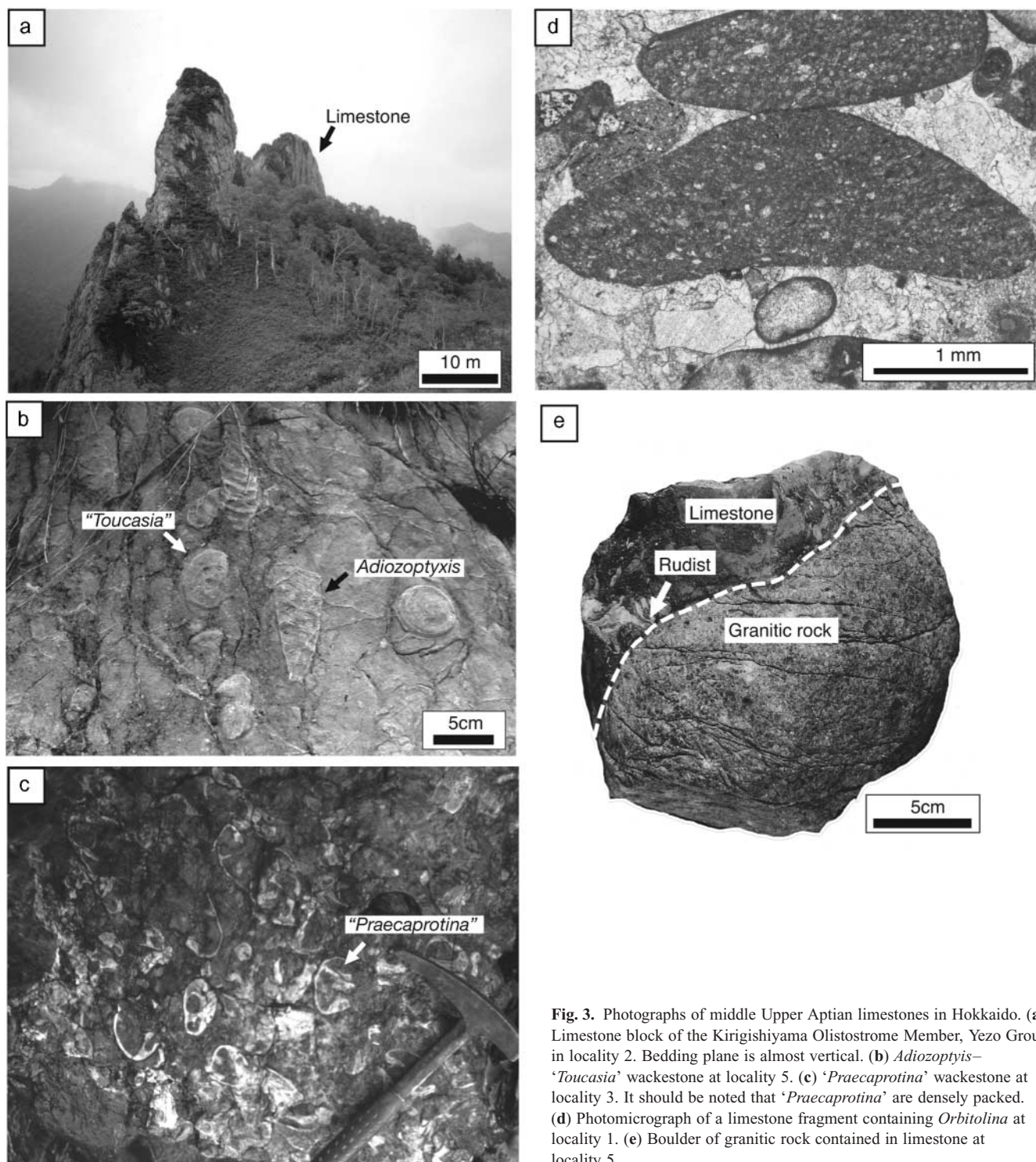


Fig. 3. Photographs of middle Upper Aptian limestones in Hokkaido. (a) Limestone block of the Kirigishiyama Olistostrome Member, Yezo Group in locality 2. Bedding plane is almost vertical. (b) *Adiozoptyxis*–*‘Toucasia’* wackestone at locality 5. (c) *‘Praecaprotina’* wackestone at locality 3. It should be noted that *‘Praecaprotina’* are densely packed. (d) Photomicrograph of a limestone fragment containing *Orbitolina* at locality 1. (e) Boulder of granitic rock contained in limestone at locality 5.

(e.g. Wells 1957). The occurrence of huge carbonate platforms in Hokkaido demonstrates that the northern geographical limit of carbonate platforms was more than 3° farther north than the limit today. For comparison, the mid-Late Aptian winter SST at 36°N would have been *c.* 8.5 °C higher than the present value (February mean SST is 9.5 °C at Onahama City, northeastern Honshu Island; Fig. 1b).

Microfossils found around the limestone horizon confirm that

these carbonates correlate with a certain horizon within *P. cheniourensis*–*T. bejaouensis* planktonic foraminiferal zones (Nishi *et al.* 2003; Takashima *et al.* 2004) of the mid-Late Aptian (*c.* 113–115 Ma; time scale of Hardenbol *et al.* 1998). Contemporaneous mid-Late Aptian warming has also been detected in European basins (Weissert & Lini 1991), as identified by two positive carbon isotope excursions found in Aptian Tethyan deep-sea carbonates. Based on fluctuations of the floral assem-

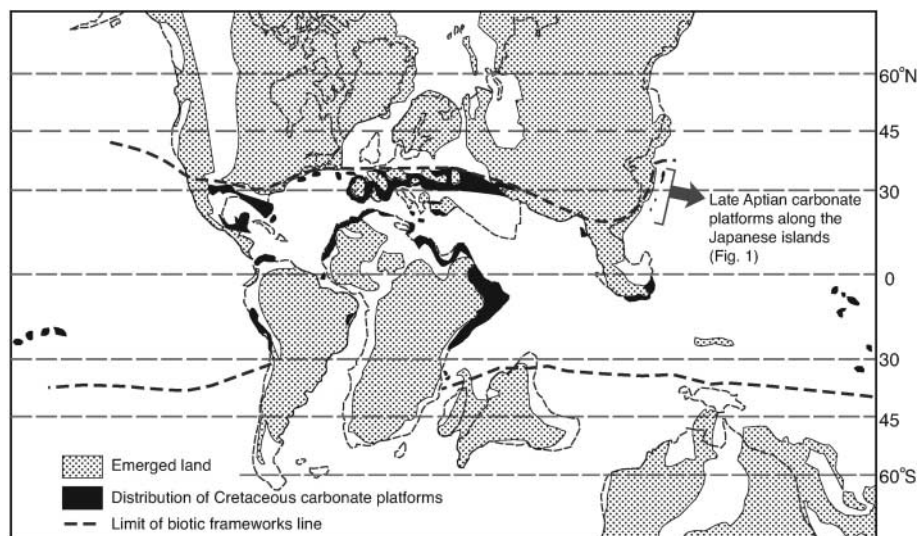


Fig. 4. Distribution of carbonate platforms of mid-Cretaceous age, modified from Simo *et al.* (1993).

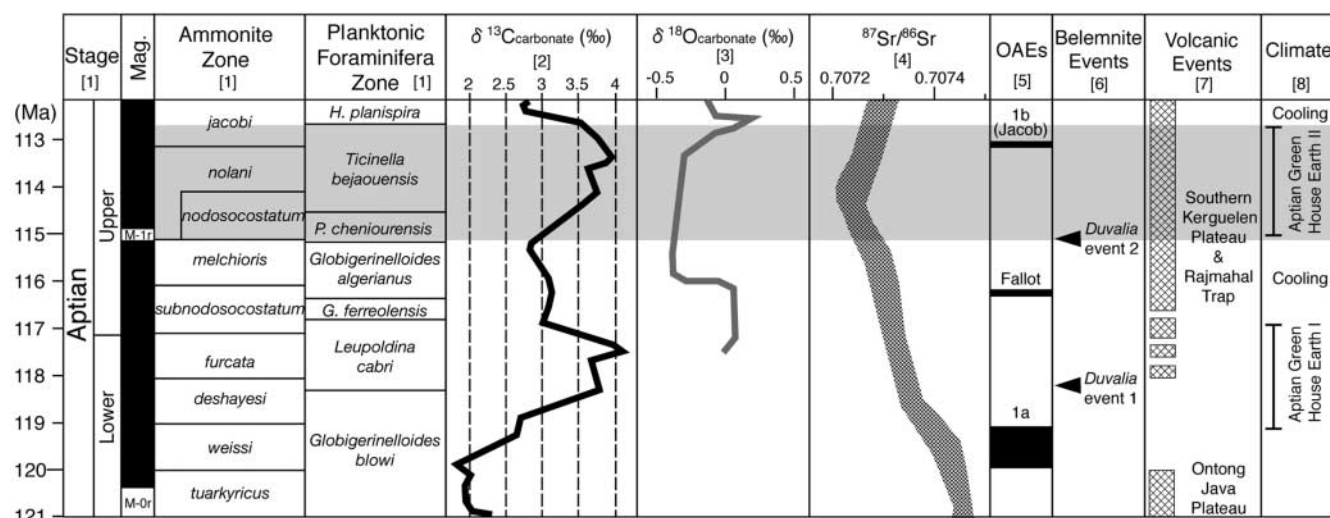


Fig. 5. Summary of faunal, tectonic and environmental events during the Aptian. Data sources: [1] Hardenbol *et al.* (1998); [2] Weissert *et al.* (1998); [3] Clarke & Jenkyns (1999); [4] Bralower *et al.* (1997); [5] Erbacher *et al.* (1996) and Larson & Erba (1999); [6] Mutterlose (1998); [7] Coffin *et al.* (2002); [8] Weissert & Lini (1991). Grey shaded part indicates the horizon of middle Upper Aptian carbonates of the Yezo Group. OAE, oceanic anoxic event.

blage, clay mineral composition, and inputs of siliciclastic material in the Aptian Tethyan sediments, Weissert & Lini (1991) concluded that both excursions represented elevated levels of atmospheric CO_2 , temperature, humidity and rainfall; they termed these excursion periods the Aptian Greenhouse Earth I and II, respectively (Fig. 5). The latter excursion is correlated with the *P. cheniourensis*–lower *T. bejaouensis* planktonic foraminiferal zones of the mid-Late Aptian. Similar conclusions on the timing of Aptian warming have been proposed by Mutterlose (1998), who recognized two migrations of the Tethyan belemnite *Duvalia* towards the boreal realm. These migration events, named *Duvalia* events 1 and 2, chronologically coincided, respectively, with the Aptian Greenhouse Earth I and II periods determined by Weissert & Lini (1991) (Fig. 5). Furthermore, a negative oxygen isotope excursion was identified from mid-Late Aptian deep-sea carbonate on the Exmouth Plateau, NW of the Australian margin (Clarke & Jenkyns 1999). Consequently, it is

plausible that global warming or strengthened heat transportation polewards occurred during the mid-Late Aptian.

The Aptian faunal, environmental and tectonic events summarized in Figure 5 clearly indicate that Aptian Greenhouse I and II synchronized with the eruption of the major large igneous provinces (e.g. Coffin *et al.* 2002), short-term magnetic abnormality, and the negative excursion of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of marine carbonates (Bralower *et al.* 1997). These findings suggest that mid-Late Aptian warming may have been related to the heightened ridge volcanism and/or eruptions of the Rajmahal Traps and South Kerguelen Plateau.

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References

- BARRON, E.J. 1983. A warm, equable Cretaceous: the nature of the problem. *Earth-Science Reviews*, **29**, 305–338.
- BICE, K.L., HUBER, B.T. & NORRIS, R.D. 2003. Extreme polar warmth during the Cretaceous greenhouse? Paradox of the late Turonian $\delta^{18}\text{O}$ record at Deep Sea Drilling Project Site 511. *Paleoceanography*, **18**, 1–11.
- BRALOWER, T.J., FULLAGAR, P.D., PAULL, C.K., DWYER, G.S. & LECKIE, R.M. 1997. Mid-Cretaceous strontium-isotope stratigraphy of deep-sea sections. *Geological Society of America Bulletin*, **109**, 1421–1442.
- CLARKE, L.J. & JENKINS, H.C. 1999. New oxygen isotope evidence for long-term Cretaceous climatic change in the southern hemisphere. *Geology*, **27**, 699–702.
- COFFIN, M.F., PRINGLE, M.S., DUNCAN, R.A., GLADCZENKO, T.P., STOREY, M., MULLER, R.D. & GAHAGAN, L.A. 2002. Kerguelen hotspot magma output since 130 Ma. *Journal of Petrology*, **43**, 1121–1139.
- EGUCHI, M. 1944. Corals from the Orbitolina Limestone of the Ishikari District, Hokkaido, Japan. *Journal of Geological Society of Japan*, **51**, 69–71 [in Japanese with English description of new species].
- EGUCHI, M. 1951. Mesozoic hexacorals from Japan. *Science Reports of Tohoku University, Second Series (Geology)*, **24**, 1–96.
- ELDRIDGE, J., WALSH, C.B. & SCOTSE, C.R. 2000. *Plate Tracker for Windows. Version 2.0*. PALEOMAP Project, Arlington, Texas.
- ENKIN, R.J., YAN, C. & COURTILLOT, V. ET AL. 1991. A Cretaceous pole from South China, and the Mesozoic hairpin turn of the Eurasian apparent polar wander path. *Journal of Geophysical Research*, **96**, 4007–4027.
- ERBACHER, J., THUROW, J. & LITKE, R. 1996. Evolution patterns of radiolaria and organic matter variations: a new approach to identify sea-level changes in mid-Cretaceous pelagic environments. *Geology*, **24**, 499–502.
- FÖLLMI, K.B., WEISSERT, H., BISPING, M. & FUNK, H. 1994. Phosphogenesis, carbon-isotope stratigraphy, and carbonate-platform evolution along the lower Cretaceous northern Tethyan margin. *Geological Society of America Bulletin*, **106**, 729–746.
- FRANKS, L.A. 1979. *Climates throughout Geologic Time*. Elsevier, Amsterdam.
- FUKADA, A. 1953. A new species of *Nerinea* from central Hokkaido. *Journal of Faculty of Science, Hokkaido University, Series 4*, **8**, 211–216.
- HARDENBOL, J., THIERRY, J., FARLEY, M.B., JACQUIN, T., DE GRACIANSKY, P.-C. & VAIL, P.R. 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: DE GRACIANSKY, P.-C., HARDENBOL, J. & VAIL, P.R. (eds) *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM Special Publications, **60**, 3–13.
- HOFKER, J. JR 1963. Studies on the genus *Orbitolina* (Foraminiferida). *Leidsche Geologische Mededelingen*, **29**, 181–254.
- HOSHI, H. & TAKASHIMA, R. 1999. Paleomagnetic analysis for some volcanic rocks of the Sorachi Group in the Furano area, central Hokkaido, Japan. *Bulletin of the Mikasa City Museum, Natural Science*, **3**, 23–30 [in Japanese with English abstract].
- IBA, Y., TAKI, S., YOSHIDA, K. & HIKIDA, Y. 2005. *Orbitolina*-bearing limestone pebbles from the lowest part of the Lower Yezo Group (Lower Cretaceous) in the Nakagawa area, northern Hokkaido, Japan and its significance. *Journal of Geological Society of Japan*, **111**, 67–73 [in Japanese with English abstract].
- JOHNSON, C.C., BARRON, E.J., KAUFFMAN, E.G., ARTHUR, M.A., FAWCETT, P.J. & YASUDA, M.K. 1996. Middle Cretaceous reef collapse linked to ocean heat transport. *Geology*, **24**, 376–380.
- KANMERA, K. & OBATA, I. 1972. A preliminary study on litho- and bio-facies of limestones of the Hidaka and Sorachi Groups in the Hidaka Mountains, Hokkaido. *Memoirs of the National Science Museum*, **5**, 203–212 [in Japanese with English summary].
- KASE, T. 1984. *Early Cretaceous Marine and Brackish-water Gastropoda from Japan*. National Science Museum, Tokyo.
- KIMURA, T. 1987. Geographical distribution of Palaeozoic and Mesozoic plants in East and Southeast Asia. In: TAIRA, A. & TASHIRO, M. (eds) *Historical Biogeography and Plate Tectonic Evolution of Japan and Eastern Asia*. Terra, Tokyo, 135–200.
- KIRILLOVA, G.L. 2003. Late Mesozoic–Cenozoic sedimentary basins of active continental margin of Southeast Russia: paleogeography, tectonics, and coal–oil–gas presence. *Marine and Petroleum Geology*, **20**, 385–397.
- KODAMA, K. & TAKEDA, T. 2002. Paleomagnetism of mid-Cretaceous red beds in west-central Kyushu Island, southwest Japan: paleoposition of Cretaceous sedimentary basins along the eastern margin of Asia. *Earth and Planetary Science Letters*, **201**, 233–246.
- LARSON, R.L. 1991a. Geological consequences of superplumes. *Geology*, **19**, 963–966.
- LARSON, R.L. 1991b. Latest pulse of Earth—evidence for a Mid Cretaceous superplume. *Geology*, **19**, 547–550.
- LARSON, R.L. & ERBA, E. 1999. Onset of the mid-Cretaceous greenhouse in the Barremian–Aptian: igneous events and the biological, sedimentary, and geochemical responses. *Paleoceanography*, **14**, 663–678.
- LIU, Y. & MORINAGA, H. 1999. Cretaceous palaeomagnetic results from Hainan Island in south China supporting the extrusion model of Southeast Asia. *Tectonophysics*, **301**, 133–144.
- MATSUKAWA, M., KALININ, J.A., FUTAKAMI, M. & PEIJI, C. 1993. Paleogeography and paleocurrents of the Barremian strata in Japan, NE China and Sikhote–Alin (Russia). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **105**, 71–81.
- MATSUMARU, K. 1971. Certain larger Foraminifera from Japan. *Journal of Saitama University, Faculty of Education*, **20**, 149–159.
- MENG, Q.R. 2003. What drove late Mesozoic extension of the northern China–Mongolia tract? *Tectonophysics*, **369**, 155–174.
- MUTTERLOSE, J. 1998. The Barremian–Aptian turnover of biota in northwestern Europe: evidence from belemnites. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **144**, 161–173.
- NAGAO, S. 1965. Regarding Jurassic–Cretaceous formation in Hokkaido with special reference to the unknown Mesozoic strata. *Report of the Geological Survey of Hokkaido*, **33**, 1–47 [in Japanese with English abstract].
- NAGAO, T. 1933. A new variety of *Toucasia carinata* (Math.) from the Lower Cretaceous of Japan. *Journal of Faculty of Science, Hokkaido Imperial University, Series 4*, **2**, 163–167.
- NISHI, H., TAKASHIMA, R., HATSUGAI, T., SAITO, T., MORIYA, K., ENNYU, A. & SAKAI, T. 2003. Planktonic foraminiferal zonation in the Cretaceous Yezo Group, Central Hokkaido, Japan. *Journal of Asian Earth Sciences*, **21**, 867–886.
- OHANA, T. & KIMURA, T. 1995. Late Mesozoic phytogeography in eastern Eurasia with special reference to the origin of angiosperms in time and site. *Journal of the Geological Society of Japan*, **101**, 54–69 [in Japanese with English abstract].
- OTOH, S., TSUKADA, K., SANO, K., NOMURA, R., JWA, Y.-J. & YANAI, S. 1999. Triassic to Jurassic dextral ductile shearing along the eastern margin of Asia: a synthesis. In: METCALFE, I., JISHUN, R., CHARVET, J. & HADA, S. (eds) *Gondwana Dispersion and Asian Accretion*. Balkema, Rotterdam, 89–113.
- OTSUKI, K. 1992. Oblique subduction, collision of microcontinents and subduction of oceanic ridge: their implications on the Cretaceous tectonics of Japan. *Island Arc*, **1**, 51–63.
- OTSUKI, K. & EHIRO, M. 1992. Cretaceous left-lateral faulting in Northeast Japan and its bearing on the origin of geologic structure of Japan. *Journal of the Geological Society of Japan*, **98**, 1097–1112 [in Japanese with English abstract].
- REN, J.Y., TAMAKI, K., LI, S.T. & JUNXIA, Z. 2002. Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas. *Tectonophysics*, **344**, 175–205.
- SAKASHIMA, T., TERADA, K., TAKESHITA, T. & SANO, Y. 2003. Large-scale displacement along the Median Tectonic Line, Japan: evidence from SHRIMP zircon U–Pb dating of granites and gneisses from the South Kitakami and paleo-Ryoke belts. *Journal of Asian Earth Sciences*, **21**, 1019–1039.
- SANO, S. 1995. Lithofacies and biofacies of Early Cretaceous rudist-bearing carbonate sediments in northeastern Japan. *Sedimentary Geology*, **99**, 179–189.
- SANO, S. 2000. Reconstruction of a carbonate platform from the evidence of olistoliths embedded in the lower part of the Yezo Group, central Hokkaido. *Gekkan Chikyū (Earth Monthly), Special Issue*, **29**, 45–59 [in Japanese].
- SASAJIMA, S. 1981. Pre-Neogene paleomagnetism of Japanese Islands (and vicinities). In: McELHINNY, M.W. & VALENCIO, D.A. (eds) *Paleoreconstruction of the Continents*. AGU Geodynamics Series, **2**, 115–128.
- SCHROEDER, R. 1975. General evolutionary trends in *Orbitolinas*. *Revista Española de Micropaleontología, Numero Especial*, 117–128.
- SIMO, J.A.T., ROBERT, S.W. & MASSE, J.P. 1993. Cretaceous carbonate platforms: an overview. In: SIMO, J.A.T., ROBERTS, S.W. & MASSE, J.P. (eds) *Cretaceous Carbonate Platforms*. American Association of Petroleum Geology, Memoirs, **56**, 1–23.
- SMITH, A.G., SMITH, D.G. & FUNNELL, B.M. 1994. *Atlas of Mesozoic and Cenozoic Coastlines*. Cambridge University Press, Cambridge.
- TAIRA, A. 2001. Tectonic evolution of the Japanese island arc system. *Annual Review of Earth and Planetary Sciences*, **29**, 109–134.
- TAIRA, A., SAITO, Y. & HASHIMOTO, M. 1983. The role of oblique subduction and strike-slip tectonics in the evolution of Japan. In: HILDE, T.W.C. & UYEDA, S. (eds) *Geodynamics of the Western Pacific–Indonesian Region*. AGU Geodynamics Series, **11**, 303–316.
- TAIRA, A., TOKUYAMA, H. & SOH, W. 1989. Accretion tectonics and evolution of Japan. In: BEN-AVRAHAM, Z. (ed.) *The Evolution of the Pacific Ocean Margins*. Oxford University Press, Oxford, 100–123.
- TAKASHIMA, R. & NISHI, H. 1999. Reevaluation of the intra-Yezo disturbance and

- the Cretaceous tectonics in Hokkaido, Japan. *Journal of the Geological Society of Japan*, **105**, 711–728 [in Japanese with English abstract].
- TAKASHIMA, R., KAWABE, F., NISHI, H., MORIYA, K., WANI, R. & ANDO, H. 2004. Geology and stratigraphy of forearc basin sediments in Hokkaido, Japan: Cretaceous environmental events on the Northwest Pacific margin. *Cretaceous Research*, **25**, 365–390.
- TAKASHIMA, R., NISHI, H. & YOSHIDA, T. 2006. Late Jurassic–Early Cretaceous intra-arc sedimentation and volcanism linked to the plate motion change, northern Japan. *Geological Magazine*, **143**, 753–770.
- TARDUNO, J.A., BRINKMAN, D.B., RENNE, P.R., COTTRELL, R.D., SCHER, H. & CASTILLO, P. 1998. Evidence for extreme climatic warmth from Late Cretaceous arctic vertebrates. *Science*, **282**, 2241–2244.
- TASHIRO, M. 1994. Cretaceous tectonic evolution of southwest Japan from the bivalve faunal view-points. *Memoirs of the Faculty of Science, Kochi University*, **43**, 43–54 [in Japanese with English abstract].
- TAZAWA, J. 2002. Late Paleozoic brachiopod faunas of the South Kitakami Belt, northeast Japan, and their paleobiogeographic and tectonic implications. *Island Arc*, **11**, 287–301.
- TOSHA, T. 1982. Paleomagnetic measurement of the Miyako Group in the Kitakami Massif, Northeast Japan. *Rock Magnetism and Geophysics*, **9**, 56–60.
- UJIIÉ, H. & KUSUKAWA, T. 1968. *Orbitolina* (Cretaceous Foraminifera) from the Miyako Group, Iwate Prefecture, Northeast Japan. *Memoirs of the National Science Museum*, **1**, 29–32 [in Japanese with English summary].
- WEISSERT, H. & LINI, A. 1991. Ice age interludes during the time of Cretaceous greenhouse climate? In: MULLER, D.W., MCKENZIE, J.A. & WEISSERT, H. (eds) *Controversies in Modern Geology*. Academic Press, San Diego, CA, 173–191.
- WEISSERT, H., LINI, A., FOLLM, K.B. & KUHN, O. 1998. Correlation of Early Cretaceous carbon isotope stratigraphy and platform drowning events: a possible link? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **137**, 189–203.
- WELLS, J.W. 1957. Coral reefs. In: HEDGEPEETH, J.W. (ed.) *Treatise on marine ecology and paleoecology*. Geological Society of America, Memoirs, **67**, 609–631.
- WILSON, P.A., JENKINS, H.C., ELDERFIELD, H. & LARSON, R.L. 1998. The paradox of drowned carbonate platforms and origin of Cretaceous Pacific guyots. *Nature*, **392**, 88–894.
- YABE, H. & NAGAO, S. 1926. *Praecaprotina*, nov. gen. from the Lower Cretaceous of Japan. *Science Reports of Tohoku Imperial University, Second Series (Geology)*, **9**, 21–24.
- ZORIN, Y.A. 1999. Geodynamics of the western part of the Mongolia–Okhotsk collisional belt, Trans-Baikal region (Russia) and Mongolia. *Tectonophysics*, **306**, 33–56.

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