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Editorial

Cretaceous in Asia: Palaeontology, Stratigraphy and Palaeoclimate — Preface

1. Introduction

The study of greenhouse Earth in deep time has become one of the main research goals for the geosciences. Aiming to find adequate past palaeoclimatic models similar to our current anthropogenically induced climate and environmental changes, we search for insights which could help us to better understand the mechanisms of sharp climatic changes and how ecosystems reacted and recovered to dramatic environmental perturbations.

The Cretaceous was one of the warmest periods in the Phanerozoic, characterized by more elevated atmospheric CO_2 levels and significantly higher global sea levels than today. The International Geoscience Programme (IGCP) Project 679 (2019–2023) (Cretaceous Earth Dynamics and Climate in Asia) aims to study the Cretaceous 'Greenhouse' Earth's oceanic and terrestrial climatic and environmental conditions and their evolution, hopefully leading to an in-depth understanding of the mechanisms of rapid climate and environmental changes, global warming and its impact on Earth's ecosystems.

The current Virtual Special Issue (VSI) presents a series of scientific articles covering case-studies of palaeoenvironmental and palaeoclimatic changes across the non-marine Cretaceous successions in mainland China, India, Korea and Russia, and in the marine Cretaceous sequences in Tibet. The volume is divided into four thematic sections, which are overlapping and closely linked: 1) new research on the taphonomy, palaeontology, palaeoecology and palaeoclimate of the Cretaceous greenhouse world, based on non-marine Lower Cretaceous deposits in Asia; 2) new fossil records in the marine Cretaceous deposits of Xizang (Tibet), which provide important palaeogeographic and palaeoecological information useful for inter-continental biostratigraphic correlations and palaeoenvironmental reconstructions; 3) studies on the geochronology, magnetostratigraphy and stratigraphic correlation of non-marine and marine deposits from southern Korea, Northeast China, and the Russian Far East; and, 4) palaeoenvironmental and palaeoclimatic reconstructions of terrestrial ecosystems in northern China and central India.

The new research contributions demonstrate the thrilling progress of the IGCP 679 project working group.

2. Non-marine fossils

Clam shrimps (Diplostraca, Crustacea) are one of the most useful macrofossil groups for the subdivision and correlation of non-marine strata (Li, 2022a, b). Early Cretaceous clam shrimp specimens of *Yanjiestheria* Chen in Zhang et al. (1976) were first discovered in the Lishugou Formation at Wudaohezi in northwestern Huanren Manchu Autonomous County of eastern Liaoning in 1930, which played an important role for understanding of the terrestrial palaeoenvironment in East Asia. A new geological investigation has reported the first discovery of the clam shrimp *Eosestheria* Chen in Zhang et al. (1976) (a common component of the Jehol Biota) from the Lishugou Formation at Xiaowenzhigou in northwestern Huanren in 2019. A detailed taxonomic study of these newly collected clam shrimp specimens revealed that their growth bands are ornamented with very fine reticulations and densely spaced radial lirae. Through comparison with the type specimen from Wudaohezi, northwestern Huanren, the newly collected clam shrimp specimens cannot be assigned to *Eosestheria*, but are conspecific with *Yanjiestheria huanjenensis* (Novozhilov, 1954) (Li and Wu, 2021).

A lower diversity Purbeck clam shrimp fauna was described based on a new collection, containing *Liograpta subquadrata* (Sowerby in Fitton, 1836) and *Carapacestheria? lulworthensis* from the Freshwater Bed, and an unidentified taxon from the Caps and Dirt Beds of the Tithonian–Valanginian Purbeck Limestone Formation of Southwest England (UK). The scanning electron micrographs clearly show that *Liograpta* has puncta on growth bands near the umbo, and between the radial lirae on the middle and ventral parts of the carapace. This newly found ornamentation feature indicates that previously described species of *Liograpta* from localities outside the UK should be moved out of *Liograpta* (Novozhilov, 1954). The only possible non-UK species of *Liograpta* was described as *Wolfestheria patagoniensis* (Tasch in Tasch and Volkheimer, 1970) from the Middle Jurassic of Argentina (Li et al., 2021).

Ostracods are microcrustaceans that have been regarded as one of the most important microfossils for paleoenvironmental reconstructions and biostratigraphic correlations. A total of seven species belonging to six genera of cypridoidean ostracods were recovered from three sections (Jeongchon, Hotan, and Tapri) of the Albian Jinju Formation from the Gyeongsang Basin, South Korea: including *Scabriculocypris yanbianensis*, *Cypridea khandae*, *Cypridea samesi*, *Mongolocypris kohi*, *Lycopterocypris*? cf. *celsa*, *Candona* sp., and *Djungarica* sp. Based on its morphology, *C. khandae* is considered to be the first record of the *Cypridea alta*-group in Korea. Although many species are endemic to the Jinju Formation, the occurrence of *Scabriculocypris yanbianensis* indicates that this fauna was linked with the contemporaneous fauna of the Lower Cretaceous Tongfosi Formation of the Yanji Basin, northeastern China. Based on previous studies and newly collected specimens, the taphonomic features of the sections indicate the presence of two distinct thanatocoenoses: a low-energy autochthonous thanatocoenosis (Jeongchon and Tapri sections) and a slightly higher energy thanatocoenosis (Hotan section). Finally, the absence of cytheroidean and darwinuloidean

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ostracods could be explained by the presence of unstable lake/temporal waterbodies and their low competitiveness (Choi et al., 2021).

Studies on early angiosperms, especially their origin, evolution and systematics, have been one of the major challenges in plant sciences. The Lower Cretaceous Yixian Formation in northeastern China has shed unique light on the evolution of diverse early angiosperms, including *Chaoyangia*, *Archaefructus*, *Sinocarpus*, *Callianthus*, *Liaoningcarpus*, *Baicarpus*, *Nothodichocarpum* and *Neofructus*. Among them, *Callianthus* was represented only by its reproductive organs, while its vegetative parts and whole plant remained unknown. This hinders our understanding of this early angiosperm in the Early Cretaceous. The newly found well-preserved materials of *Callianthus dilae* Wang and Zheng, 2009 emend., include a young plant, roots, articulated stems, leaves and reproductive organs. Based on these new materials and the specimens documented previously, *Callianthus* was reconstructed as a plant with straight, decussately branching stems, flaccid leaves with sparse meshes and an intramarginal vein, and bisexual pedicellate reproductive organs with two whorls of slightly differentiated foliar appendages. Morphological analysis indicates that *Callianthus* was an aquatic plant, as *Archaefructus*, suggesting that angiosperms might have explored aquatic habitats by the end of Barremian in the Early Cretaceous (Wang et al., 2021).

3. Marine fossils from Tibet

Diverse foraminiferal assemblages from the Weimei–Gyabula, and the Menkadun–Gucuo formations have been recorded based on the study of two Upper Jurassic to Lower Cretaceous successions, respectively located in the northern and southern parts of South Tibet. Each section contains three different foraminiferal assemblages. The identification of the *Globulina prisca* assemblage indicates a Cretaceous age for the Shale Unit of the Gucuo Formation, although the Jurassic/Cretaceous (J/K) boundary was traditionally delineated above this unit. During the Late Jurassic to Early Cretaceous, the northern part of South Tibet was located in a deep marine environment, probably at bathyal to abyssal depths, whereas the southern part of South Tibet was part of the outer neritic shelf environment (Colpaert and Li, 2021).

Well-preserved diverse radiolarian faunas have been identified in a continuous bedded chert succession in the Jiangyema section in the west segment of the Yarlung Tsangpo suture zone (YTSZ), Purang County, SW Tibet. Two radiolarian zones and two subzones are recognized and respectively named as the *Cecrops septemporatus* zone, *Aurisaturnalis carinatus* zone, *Aurisaturnalis carinatuscarinatus* subzone and *Aurisaturnalis carinatus perforates* subzone. These can be correlated with coeval Hauterivian to upper Barremian radiolarian biozones in the western Tethys and Japan. They provide a better biostratigraphical framework and reliable age constraints for parts of the Neotethyan Ocean floor that were subducted beneath supra-subduction zone (SSZ) ophiolites in the western part of the YTSZ. Geochemical data suggest that the bedded cherts were deposited in a deep oceanic basin near a continental margin. This research result and integration of available radiolarian studies from bedded cherts along the YTSZ indicate that the Neo-Tethys was a deep ocean between the Indian and Eurasian continents in which pelagic sedimentation was on-going until at least the late Barremian (Cui et al., 2021).

The upper Barremian–upper Aptian marine sedimentary successions record the profound changes in global plate configurations and the ocean-climate system. The black shales of the Lower Cretaceous Gambadongshan Formation yield well-preserved planktic foraminiferal faunas, which have been recovered for the first time. The detailed foraminiferal biostratigraphic work allowed recognition of four upper Barremian to upper Aptian planktic biozones: i.e. in ascending order the *Hedbergella excelsa* Interval Zone, the *Globigerinelloides ferreolensis* Taxon-Range Zone, the *Hedbergella infracretacea* Partial-Range Zone, and the *Paraticinella rohri* Taxon-Range Zone. Total organic carbon (TOC), the organic carbon isotope ($\delta^{13}C_{org}$) records and the planktic foraminiferal data enable the identification of Oceanic Anoxic Event 1a (OAE 1a) at the lower part of the *Globigerinelloides ferreolensis* Taxon-Range Zone. Diagenetic processes, lower sea surface temperature, and the regional hydrologic cycle were probably the main factors for the development of OAE 1a in the Chaqiela section. The relatively higher $\delta^{13}C_{org}$ values and smaller size of carbon isotopic fluctuations in the Chaqiela section may represent the local expression of OAE 1a in the Gamba area. A long-term negative $\delta^{13}C_{org}$ excursion and a decreased trend of planktic foraminiferal abundance relative to benthic foraminifera, in the upper part of the Gambadongshan Formation may suggest a lower sea-level during the late Aptian (Fang et al., 2021).

4. Geochronology, magnetostratigraphy, non-marine and marine correlations

The Dalazi Biota, mainly collected from the Dalazi Formation in Yanji and Luozigou basins, contains several key fossil taxa that document the evolution of major terrestrial plants and animals. However, its age is still controversial. Here, a SHRIMP U–Pb zircon age of 104.6 Ma for tuff sample and a SIMS U–Pb zircon age 103.3 Ma for the tuffaceous siltstone sample suggest that the age of the Dalazi Biota from Luozigou Basin may be younger than 104.6 Ma. These new data provide precise geochronological framework for the evolution of the Dalazi Biota in Luozigou Basin (J G Qin et al., 2021).

Detrital zircons of five sandstone units were analysed based on their laser ablation multi-collector inductively coupled plasma mass spectrometry U–Pb ages and their morphological features to reveal the provenance of the Lower Cretaceous Duwon Formation in Goheung, Korea. A total of 495 valid analytical points were obtained from zircon U–Pb dating, and in terms of age distribution, there were 361 Precambrian zircons (ca. 73%), nine Palaeozoic zircons (ca. 2%) and 125 Mesozoic zircons (ca. 25%). Except for 16 Cretaceous zircons, most were interpreted to be derived from the Yeongnam Massif and the southwestern Okcheon Basin located in the area to the northwest or west of the Duwon Formation. However, the Cretaceous zircons (ca. 127–118 Ma), accounting for ~3% of all zircons, were formed during the magmatic quiescence in the Korean Peninsula, making it difficult to interpret their provenance. This period coincided with active igneous activities in eastern China due to the low angle subduction of the Palaeo-Pacific plate. In addition, westerlies were dominant due to the atmospheric general circulation. From morphological analysis of the zircons, Cretaceous zircons were smaller in size than those from other ages and generally had good sphericity and a euhedral shape. The overall evidence suggests the possibility that predominant westerly winds supplied Cretaceous zircons to the Korean Peninsula during explosive volcanic eruptions in eastern China during the Early Cretaceous. However, further studies are needed to clarify this hypothesis (Chae et al., 2021).

An integrated chronology for the non-marine Upper Cretaceous Nenjiang Formation was developed based on high-resolution magnetostratigraphic results and previously published secondary ion mass spectrometry (SIMS) U–Pb zircon analyses of the eastern borehole of the Cretaceous Continental Scientific Drilling (CCSD-SK-II) borehole and two outcrop sections located in different structural provinces of the Songliao Basin, northeastern China. Detailed rock magnetic results demonstrated that pseudo-single-domain magnetite and single-domain greigite coexisted in the lacustrine black shales of the Nenjiang Formation, with the latter dominating remanence carriers. The reliable primary remanent magnetizations were isolated, which passed a class A positive reversal test and positive bootstrap reversal test, after correction for inclination shallowing, yielding a high-quality paleopole of 79.6°N/208.4°E, A95 = 2.3°. The correlation of the recognized magnetic polarity sequences to the geomagnetic polarity timescale suggests that the Nenjiang Formation from the CCSD-SK-II borehole sequence and two outcrop sections span from very late chron C34n to very early chron C33r. Furthermore, the age of the Cretaceous Normal Superchron (CNS) termination can be constrained to 82.7 ± 0.6 Ma based on magnetostratigraphy, radiometric dating, and the perfect/typical averaged sediment accumulation rate for Member 1 of the Nenjiang Formation of the borehole sequence. The estimated age obtained in this study accurately represents the age at CNS termination (Shen et al., 2022).

Upper Mesozoic (Upper Jurassic and Cretaceous) are widely distributed in Sikhote-Alin (Russian Far East) and northeastern China. In Sikhote-Alin, the Upper Jurassic and Lower Cretaceous are represented mainly by marine deposits, whereas the Upper Cretaceous is mainly volcanic and nonmarine sedimentary-volcanic rocks. In northeastern China, the upper Mesozoic rocks are, on the contrary, mainly of non-marine origin, with very rare marine fossil records, such as the Middle and Late Jurassic radiolarians (Li et al., 2019). Fully marine Upper Jurassic–Valanginian deposits are restricted to Dong'an of Rohe County, northeastern Heilongjiang Province, near the border with Russia. Barremian–Albian non-marine deposits alternating with marine ones also occur in this region. They contain marine and non-marine fauna and, therefore, represent an important object for non-marine and marine correlation. On the rest of the territory of northeastern China, upper Mesozoic rocks are represented by non-marine sedimentary and volcanogenic deposits. The complex geological structure of the region as well as different types of sedimentary basins causes difficulties in correlation between the upper Mesozoic rocks of Sikhote-Alin and northeastern China. Despite the long history of investigations, their correlation schemes are still rare. Creation of a correlation scheme between Sikhote-Alin and northeastern China should be based on revision of published stratigraphic data on both regions. The Upper Jurassic–Hauterivian deposits of Sikhote-Alin and northeastern China contain abundant *Buchia* and rarer ammonites. Based on stratigraphic distribution of buchiid assemblages, a correlation scheme for Kimmeridgian–Valanginian (possibly lowermost Hauterivian) strata of northeastern China and Sikhote-Alin was proposed. The succession of Jurassic–Cretaceous buchiid assemblages of Sikhote-Alin and northeastern China is similar to those of the other regions, e.g., Northern Siberia (Arctic Realm) and California (North Pacific Realm) (Kosenko et al., 2021a).

The Barremian–Albian stratigraphy of Sikhote-Alin and northeastern China is reviewed and a correlation scheme between these regions was proposed. Barremian–Albian rocks in Sikhote-Alin are mainly represented by marine deposits. Non-marine deposits occur in the south of Sikhote-Alin in the Partizansk and Razdolny basins. In northeastern China, in contrast, the Barremian–Albian rocks are mainly non-marine often intercalated with volcanic rocks. Non-marine deposits alternating with marine ones occur in northeastern Heilongjiang near the border with Russia, yielding fossil radiolarians (Li and Yang, 2003), foraminifera (Li and Yu, 2004) and ammonites (Li and Bengtson, 2018). A system of sedimentary basins are restricted to the Dunhua-Mishan Fault Zone and linked in the east with the Alchan Basin of Sikhote-Alin. The deposits of these basins, represented by the Jixi, Longzhaogou, Dajiashan and Huashan groups, and the Assikaevka and Alchan formations, are of high importance for non-marine and marine correlation because they contain non-marine fauna and flora assemblages together with marine molluscs. The range of the Jixi and Longzhaogou groups is clarified based on the correlation with the Assikaevka Formation containing marine index fossils and was considered as Barremian (possibly extending to Hauterivian)–middle Albian. The Jixi Group yielding elements of the Jehol Biota corresponds to the Jehol Group, and, therefore, the range of the Jehol Group was also considered as Barremian–middle Albian (Kosenko et al., 2021b).

5. Palaeoenvironmental and palaeoclimatic reconstructions

The Jehol Biota of northern China provides a new and unmatched window for the reconstruction and understanding of Early Cretaceous terrestrial ecosystems. Previous studies on the paleoenvironmental and paleoclimatic background of the Jehol Biota have mainly focused on middle–late evolutionary stages while the less diverse and more narrowly distributed early Jehol Biota remains less understood. The Lower Cretaceous (Valanginian–Hauterivian) Dabeigou Formation in the Luanping Basin (North China), preserves the early Jehol Biota and can be subdivided into three members. To reconstruct the living environment of the early Jehol Biota, a study was carried out to explore the geochemistry, bulk mineralogy, total organic carbon, sedimentology, and paleoecology of the Dabeigou Formation from the Yushuxia section of the Luanping Basin. Decreased volcanic activity during the deposition of the Dabeigou Formation resulted in changes in its source material from felsic to mafic. The Luanping palaeolake reached its deepest water depth during deposition of the Member 2, and generally exhibited low salinity, while a short time of high salinity occurred during deposition of the Member 3. Analysis on the paleoweathering indices and other evidences, indicate that the Luanping area was generally in cold and humid climate conditions during deposition of the members 1 and 2 (correlated to the Weissert Event), but changed to warm climate conditions during deposition of the Member 3, which coincides with an increasing trend of biotic diversity. Consequently, research results suggest that the increasingly warm paleoclimate and lacustrine productivity, associated with decreasingly volcanic activity in North China, have contributed to the early evolution of the Jehol Biota (Z H Qin et al., 2021).

The understanding of the low latitude terrestrial climate of the late Maastrichtian is far from satisfactory. A study has been carried out to attempt to reconstruct the late Maastrichtian vegetation and climate of the Deccan Volcanic Province (DVP), central India (Mishra et al., 2022). Palaeomagnetic results suggest that the Deccan lava flows were emplaced during the late Maastrichtian C29r magnetochron. Sedimentological studies reveal a swampy to shallow brackish lacustrine depositional setup in a warm and humid climate with low to moderate energy conditions. The floristic composition indicates an overall dominance of Arecaceae followed by Malvaceae and Ephedraceae. The vegetation prevailed under five palaeoecological associations viz., mangrove, coastal fringes, Tropical Rain Forests (TRFs), forest outliers and upland flora. The assemblage envelops taxa belonging to TRFs (54%), coastal (13%), tropical moist deciduous (13%), herbaceous (8%), mangrove (8%), and subtropical (4%) vegetation. The TRFs include taxa presently prevailing within the Western Ghats of India and in the TRFs of Africa. The Coexistence Approach (CA) analysis suggests a mean annual temperature of 24.5 °C, cold month mean temperature of 18.5 °C, warm month mean temperature of 27.5 °C, mean annual precipitation of 1890.5 mm, precipitation during the wettest month 335 mm, precipitation during the driest month 26 mm and precipitation during the warmest month 111 mm. The inferred climatic conditions were apt for sustaining the high diversity within the close canopy multi-storeyed TRFs. The palaeoclimatic data also indicates a strong seasonality, and most likely, a monsoon type of climate during the late Maastrichtian of India.

An Upper Cretaceous palaeolake near Jamsavli in the Mandla Lobe of central India has provided a unique opportunity to understand palaeoecological conditions during Deccan volcanism (Samant et al., 2022). The sedimentary deposits of this palaeolake are dominated by freshwater aquatic and semiaquatic flora, such as algae (*Pediastrum*, *Lecaniella*), dinocysts (*Pierceites deccanensis*), diatoms (*Aulacoseira*), aquatic ferns of Salviniacea (*Azolla*), Marsileaceae (*Crybelosporites*), and pollen grains of Sparganiaceae/Typhaceae (*Sparganiaceaepollenites*). Such palaeolakes, representing a few hundred years of lake history with only aquatic and semiaquatic biota, have rarely been documented from the Deccan volcanic province. An overview of aquatic and semiaquatic flora from the infratrappean and intertrappean beds associated with the Deccan volcanic province across the Cretaceous–Paleogene shows that the floral communities include algal remains of Botryococcaceae, Chlorophyceae, Chlorellaceae, Cyanophyceae, Hydrodictyaceae, Oedogoniaceae, Ulotrichaceae, Zygnemataceae, dinocysts, and diatoms. Bryophytes are scarce, whereas aquatic ferns of Salviniaceae (*Azolla*) and Marsileaceae (*Marsilea* and *Regnellidium*) are the dominating groups in the intertrappean deposits. Aquatic and semiaquatic angiosperms show less taxonomic diversity and are represented by only five families, namely Nymphaeaceae, Typhaceae, Liliaceae, Acanthaceae, and Pontederiaceae. The ubiquitous presence of macrophytes and microfloral fossil remains of Zygnemataceae (*Ovoidites*), Salviniaceae (*Azolla*), Marsileaceae (*Crybelosporites* and *Gabonisporis*), and palms, along with paleosol, indicate frost-free, warm, humid tropical to subtropical climates with intermittent dry and wet semi-arid conditions across the Late Cretaceous–early Paleocene (Samant et al., 2022).

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