

## 非海相白垩系年代学 and 对比<sup>①</sup>

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**摘 要:** 从1800年代初最早确定的白垩系定义起, 白垩系就包括了海相和非海相白垩纪的地层和化石。白垩纪是一个全球性气候温暖、海平面高、构造和火山活动强烈的世界。此时, 多块大陆分解, 几乎所有海洋都已打开, 形成了与现代相近的海陆分布的地理图案。这一变革导致了全球生物群的区域化, 给全球对比带来了困难。白垩纪的全球年代地层表是主要依据菊石和微体生物(有孔虫和钙质超微浮游生物)化石, 并与已完整建立的全极性倒转年表和很多放射性同位素年龄相结合的产物。从孢粉到恐龙等各类非海相化石均已用于白垩纪生物地层学。此期专刊的特色是聚焦于区域或全球的孢粉(包括沟鞭藻、大植物、甲壳类(包括叶肢介和介形类)、软体动物(包括腹足类和双壳类)和脊椎动物(包括硬躯体和足印)非海相白垩纪生物地层学和生物年代学。这些研究大大扩展了非海相白垩系对比的内容, 并强调了将能取得更多进展的研究方向。非海相地层和化石群中直接夹有海相地层和化石的剖面/地区的非海相生物地层学更精确的研究, 高分辨率的微体化石, 特别是既出现于非海相又见于海相地层中的微体化石的微体生物地层学的进展, 更多的直接与非海相生物地层学相关的放射性同位素和古地磁年龄的测试, 非海相地层的高分辨率层序和旋回地层学分析及与非海相生物地层学对比的化学地层学的发展等, 均将促进全球非海相白垩纪地层时代和对比, 甚至以国际地质时标为准绳的全球非海相白垩纪地层对比框架表的建立。

**关 键 词:** 非海相生物地层学和生物年代学, 孢粉, 植物, 叶肢介, 介形类, 软体动物, 脊椎动物, 白垩纪

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## NON-MARINE CRETACEOUS CHRONOLOGY AND CORRELATION

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**Abstract** From the first definition of the Cretaceous System in the early 1800s, the Cretaceous has included both marine and non-marine Cretaceous strata and fossils. The Cretaceous was a world of global greenhouse, high sea level, and intensive tectonic and volcanic activity, during which the remaining world oceans opened and the continents diverged to attain relatively modern configurations. This produced a provincialization of the global biota that makes global correlations challenging. The Cretaceous standard global chronostratigraphic scale is based primarily on ammonoids and microfossils (foraminiferans and calcareous nannoplankton) integrated with a well-established global polarity timescale and a relative abundance of radioisotopic ages. All groups of Cretaceous non-marine fossils have been used in Cretaceous biostratigraphy, from spore-pollen to dinosaurs. This special issue features regional and global studies of Cretaceous non-marine biostratigraphy and biochronology that focus on spore-pollen, including dinoflagellates, megafossil plants, crustaceans (conchostracans and ostracods), molluscs (gastropods and bivalves) and vertebrates (both hard-part

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body fossils and footprints). These studies substantially augment non-marine Cretaceous correlations and underscore the ways in which further progress can be made. Better establishing non-marine biostratigraphy where non-marine strata and fossils are directly intercalated with marine strata and fossils; advances in high-resolution microfossil biostratigraphy, especially of microfossils that co-occur in non-marine and marine strata; more radioisotopic ages and palaeomagnetic dating that can be directly related to non-marine biostratigraphy; analysis of high resolution sequence and cycle stratigraphy in non-marine strata; and further development of chemostratigraphy correlated to non-marine biostratigraphy—will all promote the establishment of non-marine Cretaceous stratigraphic ages and correlation and even promote establishing a non-marine Cretaceous stratigraphic framework chart in the global timescale.

**Key words** non-marine biostratigraphy and biochronology, correlation, spore-pollen, plants, conchostracans, ostracods, molluscs, vertebrates, Cretaceous

## 1 Introduction

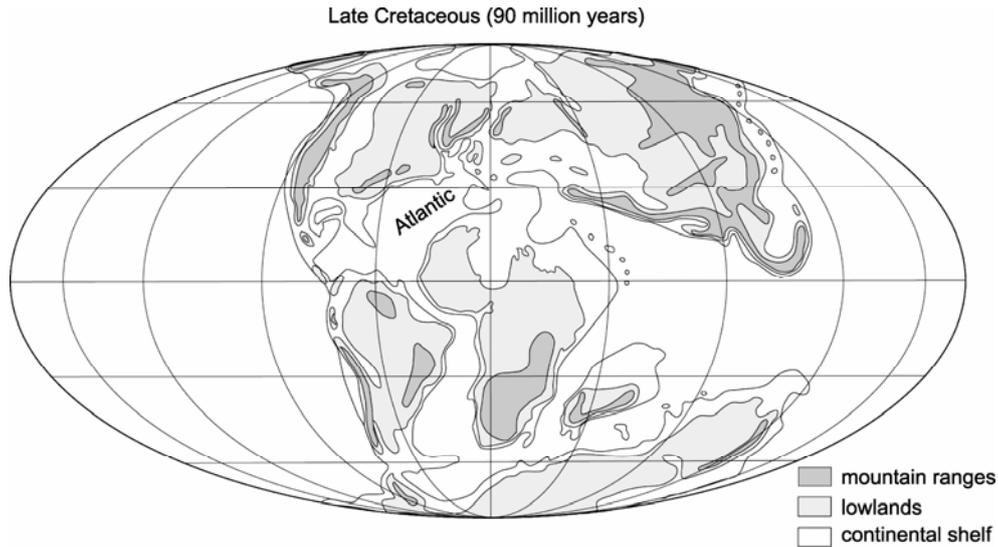
In 1822, working on a geological map of France, Belgian geologist Jean Baptiste Julien d'Omalius d'Halloy (1783~1875) coined the term *Terrain Crétacé* to refer to rocks in Western Europe that had already been grouped together under the terms "chalk" (England), "craie" (France) and "Kreide" or "Kreidegebirge" (German). Omalius d'Halloy (1822) derived the term "*Crétacé*" from the Latin word for chalk, *krete*, and the Cretaceous as originally conceived mostly encompassed the well known marine strata in Western Europe that contain conspicuous beds of chalk. However, from its inception, the Cretaceous System (English equivalent of *Terrain Crétacé*) included more than just chalk, namely it included non-marine strata, notably the fossil plant- and dinosaur-bearing "Wealden beds" of southeastern England (Conybeare & Phillips, 1822; Mantell, 1822). Today, non-marine Cretaceous strata are known from all of the world's continents. Their chronology and correlation thus is an extensive field of research that is essential to ordering the history of geological and biological events during the Cretaceous, a time interval of about 80 million years of Earth history. This special issue brings together state-of-the art reviews and new local or regional contributions to the data used to correlate the non-marine Cretaceous. Here, we provide some context within which to view these contributions.

## 2 The Cretaceous World

In brief, the Cretaceous world can be described as one of global greenhouse, high sea-level and continental areas that had already well diverged signifi-

cantly from the unity of Pangea that had existed earlier during the Mesozoic, principally during the Triassic (Fig. 1). In geological history, the Cretaceous was a time of violent tectonic movements, great paleogeographic, paleoclimatic and biotic changes, and the formation of vast quantities of endogenic and sedimentary (particularly coal and oil) deposits of economic value.

The earlier Mesozoic world had one ocean: Panthalassa (Pacific and Tethys joined together) and one supercontinent—Pangea—but all of the oceans of the modern world had become distinct by Cretaceous time (Fig. 1). The second ocean—a nascent Atlantic Ocean—developed as both the Gondwanan and Laurussian parts of Pangea began to separate. It opened as early as the beginning of Jurassic, perhaps even earlier (Late Triassic) (e.g., Smith, 1999; Damborenea, 2000; Aberhan, 2002; Sha, 2002a; Sha et al., 2002a) when Pangea rifted along the area between North America and South America and Africa. This separation, along the southern margin of the Laurussian continent, formed the Hispanic Corridor, which linked the western Tethys to the eastern Pacific, and then extended northwards as far as Greenland with the rifting of Laurussia, and southwards to Argentina with the breakup of Gondwana. The North American and South American continents drifted northwest and west, respectively, narrowing the Pacific. Some of the former continents of Pangea began to drift north and south, into more boreal and austral latitudes, and the Indo-Pakistani subcontinent was already well on its way toward southern Asia. The "super-Tethys" seaway developed in the Equatorial and tropical zones was to



**Fig. 1 The Cretaceous world** (base map after Wing & Sues, 1992)

ultimately become separated into the Caribbean and Mediterranean basins by the opening of the Atlantic Basin. With the Early Cretaceous drift of the Indian Block together with Madagascar from Antarctica eastward and then northward, the Indian Ocean was extended but the Tethys narrowed. Other blocks had rifted off of the northeastern margin of Gondwana to form a Tethyan archipelago, much of which was accreting to form southeastern Asia. Other blocks (terranes) of the Panthalassan realm were accreting to the Pacific margin of the Americas. Meanwhile, the North Alaska-Chukotka block rifted from the Canadian Arctic islands, opening the Arctic Ocean (e.g., Hallam, 1994).

Indeed, the Cretaceous was a time of relatively high levels of tectonic activity driven by increased rates of sea-floor spreading that led to more subduction and plate collisions than had taken place earlier in the Mesozoic. This made the Cretaceous a more volcanologically active world as well, especially in the circum-Pacific (including the Yanshan tectonic belts), which is ringed by subduction zones, with associated earthquake belts and volcanic chains constituting what is the popularly referred to as the "Pacific ring of fire" (e.g., Skelton, 2006).

These factors, together with the variations in the angle between the Earth's axis and Equator, and the strength of the sun's radiation, resulted in a high atmospheric CO<sub>2</sub> concentration, and created a global greenhouse during the Cretaceous. Climates were almost pervasively tropical or sub-tropical worldwide,

and there were no long-lived or extensive ice caps. Although it was unstable (e.g., Huber & Norris, 2002; Forster et al., 2007; Zakharov et al., 2009), the climate during the cold periods could be compared with that of the Quaternary (Kemper, 1987; Sha, 1991a), and there even probably existed local glaciers at the poles (Frakes & Francis, 1988). There was snow and ice during the winter seasons during the Early Cretaceous (a mild "ice house" world), and cool temperate forests covered the polar regions (e.g., Kemper, 1987; Crowley & North, 1991; <http://geoknow.net>), forming large quantities of coal and oil, even in high latitude areas. During the Late Cretaceous, no ice existed at the Poles. Dinosaurs freely migrated between the warm temperate and cool temperate zones as the seasons changed. In particular, the latitudinal temperature gradients were so pronounced after the Late Jurassic that the animal world was segregated into the Tethyan, Boreal and other faunal realms, a provincialization of the global biota that creates difficulties in establishing global GSSPs (global stratotype sections and points) for most of the Cretaceous stages (e.g., Ogg et al., 2004; <http://www.stratigraphy.org>). Sea level was undergoing global, eustatic oscillations superimposed on an overall significant sea-level rise from the Berriasian to the Maastrichtian (e.g., Haq et al., 1987; Hallam, 1992; Smith et al., 1994), particularly in western North America, western Europe, North Africa and southern Asia, while great regressions took place in Middle and East Asia, and parts of North America.

All the geological, geographical and climatic events

above led to significant changes in the distribution of land and sea, and in environmental parameters, providing a new environmental background for biotic evolution and resulting in the mass evolutionary diversification of terrestrial organisms. Life on land was prolific, and major biological events of the Cretaceous include the origin and rise to dominance of the flowering plants, the proliferation of social insects, the diversification of trigonioidid bivalves, the radiation of birds, the appearance of true crocodylians and of therian (marsupial and placental) mammals and the evolutionary diversification of the last dinosaur clades, notably the hadrosaurids, ceratopsids and tyrannosaurids. The impact of an asteroid with the Earth at the end of the Cretaceous underlies one of the largest mass extinctions of the Phanerozoic. On land it decimated the dinosaurs and numerous taxa of plants and invertebrates, including the trigonioidid bivalves, which were completely killed, and ushered in the Tertiary, the age of mammals, angiosperms, and new forms/associations of invertebrates.

### 3 Cretaceous timescale

The Cretaceous Standard Global Chronostratigraphic Scale (SGCS) (Fig. 2) is primarily based on ammonite biostratigraphy integrated with microfossil biostratigraphies provided by planktonic foraminiferans and calcareous nannoplankton (e.g., Ogg et al., 2004). However, there is a serious argument about the correlation of the Jurassic-Cretaceous boundary between the Boreal and Tethyan biostratigraphic realms. According to Ogg et al. (2004), Sha et al. (2006a) and Sha (2007), the boreal upper Volgian approximately corresponds to the Tethyan lower Berriasian stage, and the boreal middle and lower Volgian to the Tethyan Tithonian stage, which was accepted by the authors herein (Fig. 2). The non-marine strata must be integrated into a chronostratigraphic scheme, as Yin (1980) and Gu (1982) emphasized that "non-marine formations should be correlated with marine ones", but how to integrate the non-marine strata distributed in separated basins/areas? Primarily by relying on the integration of correlations of fossil-based biostratigraphy and radiometric ages (Sha, 2005). While reviewing the Cretaceous stratigraphy of northeast China in 2007, Sha concluded that "through correct taxonomic identi-

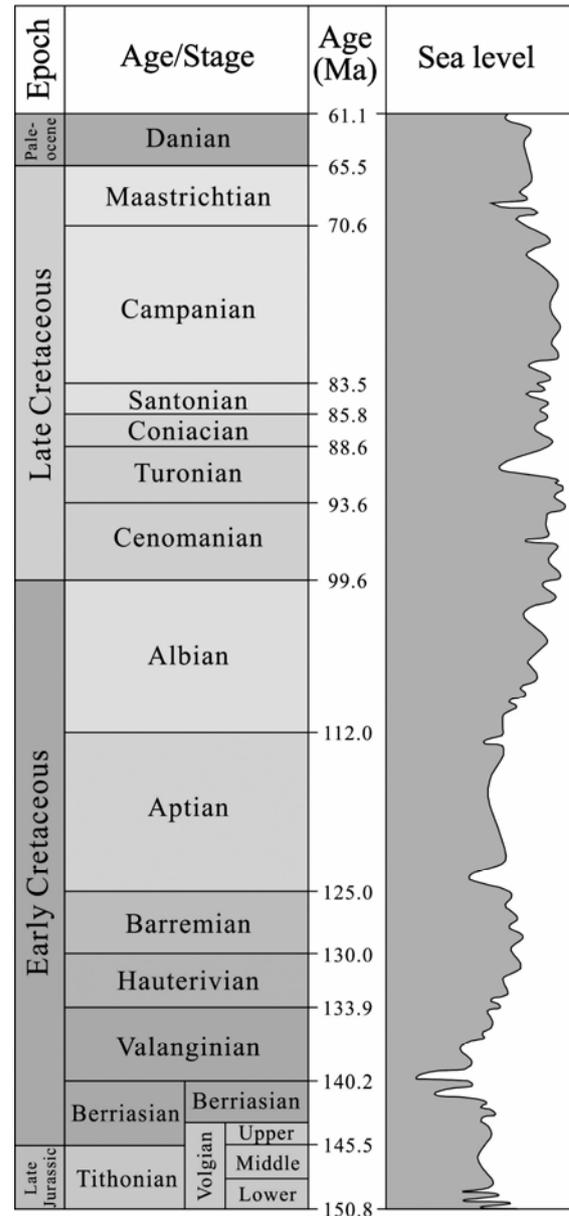


Fig. 2 The Cretaceous standard global chronostratigraphic scale (based on Ogg et al., 2004, 2008; Sha et al., 2006a, 2009; Sha, 2007)

fication of both marine and non-marine fossils in alternating marine and non-marine strata, it should be possible to correlate both marine and non-marine strata with the international chronostratigraphic chart (e.g., Gradstein et al., 2004a, b; Ogg, 2004; Ogg et al., 2004; <http://www.stratigraphy.org>) and, therefore, to determine or constrain the age of the non-marine strata (chronostratigraphy). The intervening tuffs, tuffaceous rocks and lavas can also be radiometrically dated (geochronology), hence providing a basis for accurate age determinations of the associated sedimentary rocks and the fossils they contain".

The magnetic polarity timescale for the Cretaceous

is relatively well understood and stable. A wealth of material is present in Cretaceous rocks (e.g., many volcanic ash beds, lava intercalations) for radioisotopic dating, so the Cretaceous numerical timescale is much more precise and better established than are those of the Triassic and Jurassic. This is not to say there are not gaps or problems with the Cretaceous sgcs. However, the precision and stability of the Cretaceous timescale is more like that of the Tertiary timescale than it is like the less precise and less stable older Mesozoic timescales of the Triassic and Jurassic. Furthermore, the ash beds and volcanoclastic and volcanic rocks (including lavas), together with the finely-laminated strata, which are common in the Cretaceous, are superb records precisely establishing the Cretaceous timescale (Sha et al., 2011).

High Cretaceous sea levels drowned vast continental areas, so epicontinental seas covered many regions, especially in western North America, western Europe, North Africa and southern Asia. The result is the extensive intercalation of non-marine and marine Cretaceous strata in many areas. This makes possible a direct correlation of the non-marine strata and their fossils with the marine strata and thereby to the sgcs. However, not all non-marine Cretaceous strata can be correlated this way, so there is a need to determine their ages with other data and methods. For instance, the famous Jehol Group yielding the Jehol Biota, which is widely distributed in northern and eastern China and environs, and the important coal-bearing measures, the Longzhaogou and Jixi groups in eastern Heilongjiang, northeast China, either have ever been seen as Jurassic or Jurassic-earliest Cretaceous for dozens of years by many authors. However, they were proved to be Hauterivian/Barremian–Aptian by non-marine and marine correlation (e.g., Sha, 1990, 1991b, 2002b, 2007; Sha & Fürsich, 1993, 1994; Sha et al., 1994, 2000, 2002b, 2003, 2007, 2008, 2009; Lucas & Estep, 1998; Lucas, 2001; Smith et al., 2001), which has been confirmed by radioisotopic dating (see in Sha, 2007; Sha et al., 2012b).

In some cases, radioisotopic ages have been determined directly from ash beds and lava intercalations in Cretaceous non-marine strata (e.g., Swisher III et al., 2002; He et al., 2004; Roberts et al., 2005; Yang et al., 2007; Yang & Li, 2008; Chang et al., 2009). In more

cases, magnetostratigraphy is very available for non-marine Cretaceous strata and can be tied to a radioisotopic age or biostratigraphy that calibrates the magnetostratigraphy so it can be used in correlation (e.g., Zhu et al., 2001, 2002, 2003, 2004a, 2004b; Lerbekmo & Braman, 2002). But, in the majority of cases, the chronology and correlation of non-marine Cretaceous strata relies on biostratigraphy developed for non-marine fossil groups. Indeed, it is fair to say that all the major groups of non-marine Cretaceous fossils, from palynomorphs to dinosaurs, have been used for biostratigraphy and biochronology. All of the articles in this volume are about Cretaceous non-marine biostratigraphy. Such non-marine biostratigraphy provides a temporal framework within which to understand evolutionary events at the level of assemblages ("floras" and "faunas"). In effect, a viable non-marine biochronology of the Cretaceous serves as an independent temporal framework within which to interpret the Cretaceous evolution of the non-marine biota.

In understanding Cretaceous non-marine biostratigraphy, it is important to realize that the non-marine Cretaceous biota was provincialized. Thus, the divergence of the Cretaceous continents and the numerous sea barriers to overland dispersal had broken down the terrestrial cosmopolitanism that existed during the Triassic and during at least the earlier part of the Jurassic. This means that correlations using Cretaceous non-marine fossils are often limited to a province and not globally applicable. Non-marine Cretaceous chronology and correlation thus begins with provincial biostratigraphy, which is correlated to and integrated with available radioisotopic ages and magnetostratigraphy. It then moves forward to correlation between provinces and culminates with correlation to the SGCS.

#### 4 Non-marine Cretaceous biostratigraphy and biochronology

This volume consists of 22 articles devoted to diverse aspects of non-marine Cretaceous chronology and correlation, involved in almost all the continents of the world. Here, we provide an overview of these articles and place them in a broader context.

##### 4.1 Sporo-pollen

Fossils of sporo-pollen play an important role in studying the ages, subdivision, correlation and bounda-

ries of non-marine strata because the grains of spores and pollen can have a very wide distribution in both non-marine and marine deposits, even though the distributions of mega- (macro) plants are controlled by geography (latitudes and continents). In this volume, six articles deal with spore-pollen (including dinoflagellates) biostratigraphy, including the Cretaceous-Paleogene mass-extinction event.

Vajda & Berocovici (2012) and Berocovici et al. (2012), respectively, reviewed the pollen and spore stratigraphy of the Cretaceous-Paleogene mass-extinction (K-Pg impact event) interval, and summarized the palynostratigraphical biozones of the Santonian-Paleocene (thus spanning the K-Pg boundary), in both the Southern and the Northern hemispheres. According to their studies, in the Southern Hemisphere, Maastrichtian key-species that go extinct at the Cretaceous-Paleogene boundary within the tropical to subtropical *Palmae* Province include *Aquilapollenites magnus*, *Buttinia andreevi*, *Crassitricolporites brasiliensis*, *Proteacidites dehaani* and *Gabonispuris vigourouxii*. In the high-latitude *Nothofagidites/Proteacidites* Province, taxa such as *Tricolporites lilliei*, *Triporopollenites sectilis*, *Quadruplanus brossus*, *Nothofagidites kaitangata*, and *Grapnelispora evansii* have their last appearances at the boundary. In the United States of America of the Northern Hemisphere *Aquilapollenites* paleophytogeographic province, Late Cretaceous assemblages are marked by the appearance of a series of key taxa, the Santonian-Campanian transition is characterized by the appearance of *Aquilapollenites* and associated with triprojectate genera, while the base of the Maastrichtian is marked by the appearance of the oculate genus *Wodehouseia* as well as *Kurtzipites* sp. The K-Pg extinction event remains easily identifiable in the palynological record with the disappearance of a series of angiospermous taxa that are part of the *Wodehouseia spinata* Assemblage Zone, which are characterized by their relatively large size and complex wall structure. The recovery palynoflora in the Paleocene is represented by assemblages dominated by porate grains, with key-species from the genera *Momipites* and *Caryapollenites*.

Based on a revision of published data on the geological units with palynomorphs, Prámparo (2012) evaluates the Cretaceous palynostratigraphy, compiles

a Cretaceous stratigraphic correlation chart and establishes the Cretaceous non-marine palynozones of the basins from north to south of Argentina, South America. He concludes that in Argentina, the Valanginian-Aptian palynofloras are dominated by the association of coniferous gymnosperm pollen grains, with conifer affinity, *Cyclusphaera-Balmeiopsis-Classopollis*. *Celyphus rallus* (filamentous cyanobacteria) appears together with *Cyclusphaera* but disappears in the Barremian in all of the Patagonian basins. Angiosperm pollen grains are important markers of Aptian and younger strata. *Peninsulapollis gillii*, the first record of the Proteaceae family in Argentina, is one of the few species occurring in all of the late Campanian-Maastrichtian associations, sometimes together with *Grapnelispora loncochensis*. Their presence could be indicative of a provisional palynozone.

Lebedeva & Pestchevitskaya (2012) establish a reference succession of Cretaceous pollen and spores in western Siberia. They use palynomorphs from marine sections to calibrate the palynomorph succession to ammonite zones, and they define spore-pollen zones at some levels in the Lower and Upper Cretaceous. The succession of spore-pollen assemblages reflects the evolutionary stages of Cretaceous palynofloras. They conclude that considerable lateral variation of spore-pollen assemblages related to facies and palaeogeographic features preclude accurate interregional correlations using spore-pollen data, but some general tendencies in the evolutionary development of spore-pollen assemblages can be defined.

Pestchevitskaya et al. (2012) well calibrated the palynological zones to the ammonite, foraminiferal and dinocyst zones in the northern Siberian marine section, review the early Valanginian palaeoenvironments and vegetation of coastal and innerland areas in southeastern West Siberia, and compare the distribution of Valanginian spore-pollen assemblages of central to eastern regions of Eurasia. They conclude that the short-term fluctuations of Early Valanginian vegetation and landscape are related to climatic changes and the dynamics of the neighboring paleobasin, and the transitional character of the vegetation in the south-eastern region of Western Siberia has the typical features of both the Indo-European and the Siberian-Canadian palaeofloristic provinces.

Dinoflagellate fossils range through marine, brackish- and freshwater environments. Cretaceous non-marine dinoflagellates have been recovered since the 1980's from a number of depositional basins in England, Australia and China. These non-marine dinoflagellate assemblages could hardly be correlated with each other or with coeval marine assemblages at the species level, nor could they be used for precise age determination because most of the non-marine species are endemic. Cheng & He (2012), in this volume, summarize the Cretaceous non-marine dinoflagellates assemblages and their features from a dozen of basins of eastern China, the Wessex-Weald Basin of southern England and the Perth Basin of southwestern Australia. They find that the non-marine dinoflagellates greatly varied within these basins at the specific level, but some non-marine dinoflagellate genera such as *Nyctericysta* and *Vesperopsis* can be regarded as index fossils of the Early Cretaceous. The non-marine dinoflagellate assemblages have some common features that differentiate them from marine assemblages; for example, in non-marine dinocyst assemblages, the diversity is low in general, but the abundance of some species is high, and their forms and ornaments are usually simpler than those of marine ones. The non-marine dinoflagellate assemblages show a close relationship to the palaeosalinity of each basin, when ceratoid cysts such as *Nyctericysta* and *Vesperopsis* dominate, and the palaeosalinity is close to freshwater. In contrast, where gonyaulacoid cysts such as *Kiokansium*, *Tetrachacysta* and *Dinogymniopsis* dominate, the palaeosalinity increases to slightly brackish to brackish water, so the non-marine dinoflagellates can be used as indicators of paleoenvironment.

#### 4.2 Megafossil plants

In this volume, Deng et al. (2012) review the biostratigraphy of Chinese Cretaceous megafossil plants. In the Early Cretaceous, three phytogeographical regions (North China, South China and southern Tibet) can be identified in China. The North China phytogeographical region (=Vakhrameev's Siberian-Canadian phytogeographical region) includes three floras: Jehol, Fuxin and Dalazi: in ascending order. The Jehol flora, which occurs in the Yixian Formation and the Jiufotang Formation of western Liaoning and contemporaneous strata in other areas, is dominated by Cycadopsida and

Coniferopsida. It is regarded as early Early Cretaceous in age. The Fuxin flora, characterized by the boom of Filicopsida, Ginkgopsida and Coniferopsida, with quite abundant Cycadopsida and Equisetales, was found in the Shahai Formation and the Fuxin Formation of western Liaoning and other relevant strata. Filicopsida are marked by the abundance of Dicksoniaceae, Osmundaceae, Schizaeaceae and monolete spore elements in the flora. This flora can be subdivided (ascending) into three assemblages: *Acanthopteris-Ginkgocoriacea* assemblage, *Ruffordia goeperti-Dryopterites* assemblage and *Ctenislyrata-Chilinia* assemblage, which are, respectively, represented by fossils from the Shahai Formation, and the lower-middle and upper parts of the Fuxin Formation in western Liaoning Province. The Dalazi flora from the Dalazi Formation of the Yanji basin of Jilin Province and the Quantou Formation of the Songliao basin, Northeast China, is characterized by the dominance of angiosperms and abundant scale-like or awl-shaped leaf conifers, including *Pseudofrenelopsis*, *Frenelopsis* and *Suturovagina* of Cheirolepidiaceae and the form genera *Brachyphyllum* and *Pagiophyllum*.

The South phytogeographical region belongs to Vakhrameev's Euro-Sinian phytogeographical region, with the dominance of Cycadopsida, scale-like or awl-shaped leaf conifers, small and thick pinnule ferns (mainly *Cladophlebis*), and the absence of Ginkgopsida, dicksoniaceae and monolete spore ferns. It represents tropical-subtropical floras, and can be divided into three sub-regions, namely the Eastern sub-region, the North Tibet sub-region and the Center sub-region. The Eastern sub-region, near the ancient Pacific Ocean, is typically represented by plants from Zhejiang and Fujian Provinces and the Laiyang basin of Shandong Province, where the scale-like or awl-shaped leaf conifers and *Ptilophyllum* of Bennettiales dominate, and the schizaeaceous fern *Ruffordia* is common. The schizaeaceous fern *Klukia* and gleicheniaceae fern *Gleichenites* appear but are not very abundant in the flora. The Early Cretaceous flora of this sub-region can be divided into 3~4 assemblages (ascending): *Cupressinocladus-Pagiophyllum* assemblage, *Cladophlebis-Ptilophyllum* assemblage, *Ruffordia-Zamiophyllum* assemblage and *Suturovagina-Frenelopsis* assemblage. The flora of the Tibet sub-region shares its main characteristics with

the Eastern sub-region, but the ferns are more abundant; particularly rich are *Klukia* and *Gleichenites*, as well as the occurrence of *Scleropteris* (a schizaeaceous fern) and some matoniaceous ferns; gymnosperms are rich in Cycadopsida, whereas relatively less in Coniferopsida. The flora of the North Tibet sub-region could be further subdivided into two assemblages. The Center sub-region between the two discussed sub-regions above is characterized by poorly-developed floras in arid environments. The flora consists of a low diversity of species and low abundance of fossils, and is dominated by scaly or awl-shaped leaf conifers. The southern Tibet phytogeographical region, where fossils, including the araucariaceous conifers and seed fern *Pachypteris specifica*, have just been reported in the Himalaya area, belongs to the Austral phytogeographical region of Vakhrameev (1991). The Late Cretaceous flora hitherto has only been found from a few horizons of some localities scattered in Northeast China, South China and Tibet. It can be divided neither into phytogeographical regions nor into assemblages due to the limited studies thus far. Principally based on plant fossils, and by integrating other biostratigraphical evidence with non-biostratigraphical data, the correlations of the Cretaceous plant fossil-bearing strata and the relevant strata in different phytogeographical regions of China have been established.

### 4.3 Ostracods

Cretaceous non-marine ostracod biostratigraphy has a long tradition, especially in the United Kingdom through the work of F. W. Anderson, who, from the 1930s until his death in 1982, developed a non-marine ostracod biostratigraphy for the Jurassic-Cretaceous transition ("Purbeck-Wealden interval") there.

In this volume, Sames & Horne (2012) review that biostratigraphy and note that studies of late Mesozoic non-marine ostracods in different parts of the world have produced an extensive literature that is often confusing and contradictory. This not only applies to the taxonomy of the ostracods but also to their interpretation with regard to paleoenvironments and phylogeny. According to Sames & Horne, regional and intra-basinal ostracod biostratigraphy has potential for local high-resolution correlations, but the utility of ostracods for inter-basinal to global correlations has

been questioned. A uniformitarian palaeobiological approach to revise and rejuvenate the biostratigraphic and palaeoenvironmental applications of late Mesozoic non-marine ostracods has promoted the supraregional biostratigraphical approach. Essential to this is an appreciation of the fact that many non-marine ostracod groups are not restricted to individual waterbodies or small geographical regions. As is true today, whole living specimens or eggs of Late Jurassic and Early Cretaceous non-marine ostracods are considered to have been able to be transported passively by larger animals or wind over long distances, crossing migration barriers. Nevertheless, supraregional correlations face two major issues: the application of taxonomy and the paleoenvironmental context. A major obstacle to success is the absence of a stable, consistent ostracod taxonomy that can be applied on regional to global scales. The evolution and extinction of taxa, dispersal events and varying influences of local environmental factors as well as regional to global climatic factors have all contributed to the very complex stratigraphic records of Cretaceous non-marine ostracods. One large problem is the separation of biologically-induced variation (genetic variation) and environmentally induced variation (ecophenotypy). Heading towards a global ostracod biostratigraphy, the goal of global taxonomic concepts and stability appears achievable but is not expected to be reached quickly.

On the basis of the characteristic composition of ostracods in non-marine Cretaceous strata in China, Wang et al. (2012) preliminarily reviewed and established seven ostracod assemblages: 1) ?Valanginian, and Hauterivian–Barremian, *Jingguella-Minheella-Pinnocypridea* assemblage, 2) Barremian, but probably extending downward into the Hauterivian and upward into the Aptian, *Cypridea-Latonia-Darwinula* assemblage, 3) Aptian–Albian, *Cypridea (Morinina)-Bisulcocypridea-Mongolocypis* assemblage, 4) Early Valanginian–Barremian, but mainly Hauterivian–Barremian, *Cypridea-Mongolianella-Darwinula* assemblage, 5) Barremian–Aptian, but probably extending downward into Hauterivian, *Cypridea (Cypridea)-Cypridea (Uwellia)-Limnocypridea* assemblage, 6) Cenomanian–Santonian, *Cypridea-Triangulicypris-Sunliavia-Lycocypris* assemblage, and 7) Campanian–Maastichtian, but mainly Maastichtian, *Talicypridea-Cyp-*

*ridea-Quadracypris-Candona* assemblage. Seventy-one ostracod-bearing formations/groups distributed in 25 areas of China were correlated by Wang and co-authors. This synthesis, though, is avowedly preliminary, pending more detailed studies of Cretaceous ostracod taxonomy.

#### 4.4 Conchostracans

Nine conchostracan faunas are known from the Cretaceous rocks in China. Here, Chen (2012) reviews the biostratigraphical subdivision and correlation of these conchostracan-bearing strata and illustrates their biogeography. The Early Cretaceous *Ortheastheria* and Late Cretaceous *Aglestheria* faunas are from the SW Lake group biogeographic province; the Early Cretaceous *Eosestheria* and *Yanjiestheria* faunas are from the North and Southeast China province; the Late Cretaceous *Linhaiella* and *Tenuestheria* faunas are from the Yunmeng Lake drainage system and the *Euestherites* and *Daxingestheria* faunas from the paleo-Songhua Lake province of NE China. The *Nemestheria* fauna is widely distributed in Cenomanian strata in most regions of China.

#### 4.5 Non-marine molluscs

Freshwater clams and gastropods are an important component of many Cretaceous non-marine fossil assemblages. They are particularly abundant and well studied in Asia and Europe, as seen by the papers involving non-marine molluscan stratigraphy that were contributed to this volume.

Munt et al. (2012) review the diverse record (59 taxa from 16 stratigraphic levels) of European (mostly from England, France and Spain) non-marine molluscs. These are mostly unionid bivalves and viviparid gastropods, but pulmonate gastropods are also present. During the Hauterivian and Barremian, the mollusc assemblages undergo major changes in both freshwater and marginal marine settings, and by the Barremian a European freshwater mollusc community had developed. The Early Cretaceous Wealden Group of southern England is the most continuous non-marine Cretaceous sequence in Europe, and its upper part was connected to strata deposited at Las Hoyas (Spain) and Wassy (France). Together with the Jurassic-Cretaceous transitional Purbeck faunas, these three localities are the key to understanding the European Cretaceous

freshwater fauna.

The extensive Early Cretaceous non-marine mollusc record of Japan is reviewed by Kozai et al. (2012). Four faunal associations of brackish and freshwater molluscs characterize the Early Cretaceous in Japan: 1~2) Hauterivian–Early Barremian Tatsukawa and Shobu faunal associations, 3) Late Barremian Sebayashi faunal association and 4) Early Aptian Hibihara faunal association. Several marine intertongues provide accurate age constraints for the well-studied non-marine faunas. Differences between assemblages, at the specific level, can be attributed to paleoenvironmental factors.

Pan (2012) recognizes four gastropod assemblages from the non-marine Cretaceous of China: Valanginian–Barremian *Probaicalia vitimensis-Ptychostylus-Reesidella robusta* (opercula fossil) assemblage; Aptian–Albian *Bellamyia clavilithiformis-Mesocoshliopa cretacea-Zptychius costatus-Brotiopsis* assemblage, which is separated into two groups by biogeography; Coniacian–middle-late Maastrichtian *Mesolanistes nanxiongensis* assemblage, which also include two groups (*Mesolanistes ziziformis* group maybe from the Coniacian, and *Mesolanistes nanxiongensis* group from middle-late Maastrichtian); and the *Palaeoancylus nanxiongensis* assemblage from the latest Maastrichtian.

By means of the non-marine and marine correlation, particularly the common marine and non-marine molluscan fossils' linking, together with the radiometric dating, Sha et al. (2012b) studied the correlation of the Early Cretaceous strata of eastern Heilongjiang and western Liaoning in NE China, the Gyeongsang Basin of SE Korea and the Makito/Shokawa area of northern Gifu in the Inner Zone, and the Tokushima and Monobe areas of Shikoku in the Outer Zone of SW Japan. They reached the following conclusions: The well-known coal-bearing Longzhaogou and Jixi groups and the Jehol Biota/Fauna-bearing Jehol Group of NE China are all Hauterivian/Barremian–Aptian in age, and the overlying Huashan Group and Suinjiawan Formation are Albian. The Sindong Group and the Hayang Group, with the exception of the Jindong Formation, in SE Korea is Aptian–Albian, and the Myogog Formation unconformably underlying the

Sindong Group is mainly Hauterivian. The Tetori Group in the Makito/Shokawa area and the Monobegawa Group in the Tokushima and Monobe areas of SW Japan are both Hauterivian–Albian. *Cuniopsis kihongi*, *Nakamuranaia leei*, *Koreanaia cheongi* and *Trigonioides (Wakinoa) tetoriensis* are Hauterivian-early Barremian in age. *Viviparus onogoensis*, *Unio ogamigoensis*, *Myrene (Mesocorbicular) tetoriensis* and *Tetoria (Tetoria) yokoyami* range from Hauterivian to Aptian. *Arguniella* cf. *quadrata*, *A.* cf. *ventricosa*, *Sphaerium (Sphaerium) anderssoni*, *Probaicalia vitimensis* and *Pr. gerassimovi* range from Hauterivian/Barremian to Aptian. *Nakamuranaia qingshanensis*, *Plicatounio (Plicatounio) multiplicatus*, *Sphaerium (Sphaerium) coreanicum* and *Micromelania? katoensis* are Aptian–Albian. *Nippononaia sinensis*, *Nip. tetoriensis*, *Nip. ryosekiana* and *Trigonioides (Wakinoa) wakinoensis* are good indicators of the Aptian. *Trigonioides (Trigonioides) quadratus*, *T. (T.) heilongjiangensis*, *Plicatounio (Plicatounio) naktongensis*, *Unio longus* and *Sphaerium (Sphaerium) chintaoense* are good indicators of late Aptian–Albian or Albian. The three areas—NE China, SE Korea and SW Japan—were connected and contained a single fluvial system during the Early Cretaceous. However, the eastern part of this landmass, the Outer Zone of SW Japan facing the Paleo-Pacific, was low topographically and mainly occupied by the sea in Hauterivian–Albian time, and there were some shallow and narrow embayment(s) that were subjected to marine transgressions in the Makito/Shokawa area and eastern Heilongjiang. Before the Valanginian, and particularly before the Hauterivian/Barremian, the NE China-SE Korea-SW Japan landmass was a plateau that was affected by uplift and subsidence associated with orogeny, which led to widespread and long-lasting erosion. The non-marine Cretaceous basins, containing volcanic rocks including lavas and tuffs, oriented subparallel to NE- to NNE-trending fault zones, mostly did not develop until the Hauterivian/Barremian, although possibly a little earlier (Valanginian) in some areas (134–126 Ma), within the peak time (130–120 Ma) of destruction of the North China Craton, indicating that they were controlled by faulting associated with tectonic movements and violent volcanic eruptions and local transgressions along the

northwestern margin of the Paleo-Pacific and the Tan–Lu fault system.

Cretaceous sedimentary rocks are widespread in Thailand, Lao PDR and Vietnam, and are composed of non-marine facies. Previously, however, the biostratigraphy of these rocks was not studied in detail. On the basis of the stratigraphic sequences and fossil correlation, Sha et al. (2012a) recognized two assemblages of trigonioidid bivalves, the indicators of the non-marine Cretaceous, from the Khorat Plateau of the northeastern and the Peninsular Region of southern Thailand, and the Savannakhet (Donghen) Basin of southern Lao PDR: Aptian (but could extend up into Albian) *Trigonioides (Trigonioides) kobayashi-Plicatounio (Guanxiconcha) suzukii* assemblage, and Aptian–Albian (but mainly Albian) *Trigonioides (Diversitrigonioides) diversicostatus-Pseudohyria subovalis* assemblage. According to the published information central Vietnam probably yields the Early Cretaceous (Aptian–Albian) trigonioidid bivalve *Plicatounio* sp.-*Trigonioides* sp. Assemblage. By means of the correlation of the bivalve assemblages, together with the other fossils, including palynomorphs and dinosaurs, the non-marine Cretaceous strata were dated and correlated from Berriasian–Barremian to Late Cretaceous in northern and southern Thailand, southern Lao PDR and central Vietnam by the three authors, making a major step towards a Cretaceous chronology of non-marine events in SE Asia.

#### 4.6 Vertebrate fossils

Cretaceous vertebrate fossils are known from all the world's continents, and biostratigraphy based on them encompasses both body fossils (bones and teeth) and footprints. In China, numerous articles and monographs on vertebrate fossils involving biostratigraphy have been published (e.g., Young, 1958; Dong, 1992; Chang et al., 2001, 2003; Ji et al., 2004; Li et al., 2008 (2<sup>nd</sup> edition); Wang, Feng et al., 2008). For instance, the strata of Early Cretaceous Jehol Biota including various vertebrates were summarized in the famous monograph on the "Jehol Biota" edited by Chang et al. (2001, 2003) and described in the monograph "Mesozoic Jehol Biota of western Liaoning, China" written by Ji et al. (2004). The Cretaceous reptile-bearing strata of China were summarized in the monograph "The Chinese fossil reptiles and their kin" edited by Li

et al. (2008, 2<sup>nd</sup> edition). Wang, Feng et al. (2008) summarized the division and correlation of dinosaur egg-bearing strata of the Late Cretaceous in China. Provincial biochronologies based on vertebrate body fossils have been proposed for western North America (e.g., Russell, 1964, 1975; Lucas, 1993; Kirkland et al., 1998; Sullivan & Lucas, 2006); the Cretaceous of eastern Asia (Mongolia and China: e.g., Jerzykiewicz & Russell, 1991; Lucas & Estep, 1998; Lucas, 2001, 2006) and the Cretaceous of Argentina (Bonaparte, 1986; Leanza et al., 2004). Lucas (2007) reviewed the global Cretaceous footprint record and recognized two global biochrons. Elsewhere knowledge and stratigraphic organization of the vertebrate record is still in its early phases.

In this volume, Le Loueff et al. (2012) review the Early Cretaceous dinosaur-dominated faunas of Africa to identify four temporally-successive assemblages: 1) Late Jurassic (Kimmeridgian–Tithonian) to earliest Cretaceous (Valanginian) assemblage with stegosaurids, brachiosaurids and diplodocids; 2) Hauterivian–Barremian? assemblage with baryonychine spinosaurids, the pholidosaurid crocodile *Sarcosuchus*, large iguanodontids and the shark *Priohybodus arambourgi*; 3) Aptian? to early Albian assemblage that still includes iguanodontids but in which spinosaurine spinosaurids replace baryonychines; and 4) an early Cenomanian assemblage characterized by the association of dinosaurs (*Spinosaurus*, *Carcharodontosaurus*), sharks (*Onchopristsis numidus*) and crocodyles (libyosuchids, stomatosuchids). Correlations of these assemblages to the sges are in part based on marine intercalations, but the precise succession and ages of many localities remain tentative.

Dinosaur eggs are abundant and widely distributed in China. They play an important role in the division and correlation of continental strata. By studying the lithostratigraphy, chronostratigraphy and dinosaur egg biostratigraphy of the Tiantai Basin, comparison of the dinosaur egg faunas and strata of the major dinosaur eggs-bearing basins and overall stratigraphic framework of the Upper Cretaceous terrestrial red beds of China, Wang et al. (2012) find that the dinosaur egg fauna of the Tiantai Basin is the oldest (early Late Cretaceous), and is successively followed by younger faunas from the Xixia Basin (early-middle Late Cre-

taceous), Laiyang Basin (middle-late Late Cretaceous) and Nanxiong Basin (late Late Cretaceous) in age.

Averianov & Sues (2012) assess the relative stratigraphic positions and ages of the Late Cretaceous continental vertebrate assemblages from Middle and Central Asia by means of parsimony analysis of 26 proposed biostratigraphic marker taxa. Thereby, they review the compositions and successions of the vertebrate assemblages and the correlation of vertebrate fossils-bearing strata of the Late Cretaceous in Middle and Central Asia, including those in the Kyzylkum Desert of Uzbekistan, Kazakstan, Fergana depression of Kyrgyzstan, the Gobi of Mongolia and Inner Mongolia of China.

As a local example of progress in establishing non-marine Cretaceous correlations in Asia, Lucas et al. (2012a) here use a combination of vertebrate- and plant-based biostratigraphy to more precisely place the Cretaceous-Paleogene boundary in the Zaysan Basin of eastern Kazakstan. They document a stratigraphic succession of Late Cretaceous (Maastrichtian?) dinosaur eggshell overlain by late? Paleocene paleoflora capped by middle Eocene mammals. They conclude that the Cretaceous-Paleogene boundary in the Zaysan Basin is located stratigraphically very low in the sedimentary section deposited by paleo-Lake Zaysan, and it is not a complete section of the boundary, but likely one marked by one or more unconformities and/or a condensed section produced by slow sedimentation.

Lucas et al. (2012b) review and revise the vertebrate biochronology of the Cretaceous of the North American Western Interior. The development of this vertebrate biochronology began in the 1890s. More than one dozen stages, land-vertebrate "ages" or land-mammal "ages" have been proposed, though very few have been precisely defined and only a few have been widely recognized and used. They redefine/define 10 land-vertebrate "ages" to encompass all of Cretaceous time in the Western Interior (oldest to youngest) -Comobluffian (~Tithonian–Hauterivian), Buffaloga-pian (~Barremian–early Aptian), Cashenranchian (~early Aptian–late Albian), Mussentuchian (~late Albian–Cenomanian), Fencelakean (~Turonian–late Santonian), Aquilan (~late Santonian–early Campanian), Judithian (~middle Campanian), Kirtlandian

(~late Campanian), Edmontonian (~latest Campanian–early Maastrichtian) and Lancian (~late Maastrichtian). Each of these "ages" has its beginning defined by the first appearance of a dinosaur or mammal taxon, and the end of an "age" is defined by the beginning of the succeeding "age". The vertebrate biochronology thus defined represents a complete Cretaceous timescale, though some intervals (especially much of the Neocomian and parts of the "middle" Cretaceous) lack adequate terrestrial vertebrate fossil characterization. The Cretaceous land-vertebrate "ages" are a timescale with which the evolutionary history of vertebrates in the Western Interior can be organized and interpreted.

The global record of Cretaceous tetrapod footprints is reviewed by Lockley et al. (2012) in this volume. Knowledge of this record has been growing rapidly, especially in eastern Asia (China and Korea). Like Lucas (2007), they identify two global Cretaceous footprint biochrons: an Early Cretaceous biochron characterized by sauropod and ornithomimid tracks; and a Late Cretaceous biochron that has fewer sauropod tracks as well as the tracks of hadrosaurs, tyrannosaurids and ceratopsians. Furthermore, according to Lockley et al. (2012), the Cretaceous footprint record includes important biostratigraphic datum points, including the mid-Cretaceous extirpation of sauropod dinosaurs in North America and the end-Cretaceous extinction of dinosaurs. The Asian Cretaceous footprint record also may provide a more refined, provincial Cretaceous footprint biochronology, in which three or four Cretaceous footprint biochrons based on the stratigraphic distributions of endemic theropod dinosaur and bird ichnogenes can be posited. Also, the prolific and rather endemic Asian Cretaceous avian ichnofauna may indicate that a diverse avian fauna existed in eastern Asia during the Cretaceous.

## 5 Prospectus

What is the future of research on non-marine Cretaceous chronology and correlation? The non-marine strata must be integrated into a chronostratigraphic scheme by correlating non-marine with marine as the sgs is based on marine strata/fossils, even though not all the non-marine strata/fossils can be directly correlated with the marine strata. Therefore, we have to use

multidisciplinary approaches to resolve the problems of non-marine Cretaceous chronology and correlation. Here, we suggest six ways forward to the solution of this problem:

First of all, we need to identify precisely both marine and non-marine fossils in marine, alternating marine and non-marine Cretaceous strata, to determine or constrain the age of the non-marine strata/fossils, by means of the cross-correlation of alternating marine and non-marine strata/fossils, and thereby to link the non-marine and marine strata. As a result, the non-marine strata can be integrated into the Cretaceous chronostratigraphic scale (chronostratigraphy).

Second, microfossils usually have a wide distribution, particularly terrestrial spore and pollen grains, which can be recorded in both non-marine and marine deposits. Furthermore, some of the microfossil zones have shorter time ranges than do stages. The high-resolution of the microfossil assemblages/zonations is, therefore, very advantageous to precisely subdivide, correlate and date the non-marine Cretaceous strata (microbiostratigraphy).

Third, we need to precisely and successively measure radioisotopic ages of the interbedded datable volcanic and volcanoclastic rocks to constrain the age of the associated sedimentary rocks/fossils. This will refine the precision of the non-marine Cretaceous chronostratigraphic framework and further establish the Cretaceous numerical timescale (geochronology). The non-marine Cretaceous fossils, the indicators of non-marine Cretaceous biostratigraphic correlation, constrained by marine index and isotopic dating in age could be widely used in non-marine Cretaceous correlation and dating.

Fourth, the development of more magnetostratigraphy in direct relationship to non-marine biostratigraphy will lead to greater correlation by allowing the global polarity timescale to be used for precise age determination.

Fifth, the recognition of depositional systems and subsystems and the determination of their fluctuation in space and time could lead to a high-resolution sequence stratigraphic analysis and an internally consistent sequence stratigraphic scheme of marginal and continental deposits. Sedimentation in the shallow and epicontinental basins is particularly sensitive to

changes in sea level. The recognition of the coeval effects, i.e., the recognition of transgressive surfaces in marine deposits and their correlative surfaces in continental strata can provide very significant and reliable evidence for subsequent stratigraphic correlation between the fossiliferous non-marine and marine deposits and constrain the ages of non-marine strata/fossils (Sha et al., 2006b) (sequence stratigraphy). The recognition of orbitally-forced cyclic strata in non-marine strata (especially lacustrine rocks) also provides an astrochronology that, if developed sufficiently, can aid in non-marine Cretaceous chronology (cf. cyclostratigraphy).

Sixth, if the variations of the chemical elements and isotopes in sediments are synchronous, whatever the causes (Cotillon, 1988), the trace elements, particularly Sr, and Na, K, and Ca/Mg (elemental geochemistry), as well as the isotopes of oxygen (particularly  $\delta^{18}\text{O}$ ), carbon (particularly  $\delta^{13}\text{C}$ ), strontium (e.g.,  $^{87}\text{Sr}/^{86}\text{Sr}$ ), and sulphur (e.g.,  $^{34}\text{S}/^{32}\text{S}$ ) (stable isotopic geochemistry), and the organic matter, can be widely used in stratigraphic correlation (chemostratigraphy). In particular, the variations of stable isotopic  $\delta^{13}\text{C}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  can be the valuable tool in the correlation of Cretaceous non-marine deposits.

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