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Article abstract

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# Okavango Oasis, Kalahari Desert: A Contemporary Analogue for the Late Cretaceous Vertebrate Habitat of the Gobi Basin, Mongolia

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## SUMMARY

There are conspicuous similarities between the late Cretaceous Gobi and the present-day Okavango vertebrate habitats. Both habitats combine conditions of a life-supporting haven with a life-threatening desert. Both the Gobi and the Okavango environments developed in continental, extensional settings (tectonic grabens), and both accommodate eolian and fluvio-lacustrine facies. There are also striking sedimentological similarities between the Upper Cretaceous Gobi succession of Mongolia and the modern Okavango Delta of Botswana. The most important of these similarities is an alternation of wind-blown dunes and water-laid lacustrine and fluvial deposits. Changes from arid conditions (wind-blown sand and dust) to sub-humid conditions (water-laid mud or sheet-flood sandstone) may have been gradual or instantaneous. It is inferred that tectonically induced climatic changes of various magnitudes and recurrence intervals governed the dinosaur-supporting or dinosaur-threatening habitats of the Gobi Basin in Late Cretaceous time. Recurrent conditions of extreme aridity contributed to the extermination of many late Cretaceous dinosaurs (*e.g.*, *Protoceratops*) in much the same way that antelopes and other animals are being killed by cataclysmic droughts in the Okavango oasis at the present time.

## RÉSUMÉ

Il existe des ressemblances frappantes entre l'habitat des vertébrés actuels de l'Okavango et celui du bassin de Gobi à la fin du Crétacé. Ces deux habitats présentent à la fois des caractéristiques d'un milieu accueillant et des caractéristiques d'un milieu désertique hostile. Ces deux milieux se sont développés dans un cadre tectonique continental d'extension (tectonique de fossé d'effondrement), et tous deux montrent des faciès éoliens et fluvio-lacustres. Il existe également des ressemblances frappantes entre l'empilement sédimentaire du Crétacé supérieur de Gobi et celui que l'on peut observer dans l'actuel delta de l'Okavango au Botswana. La ressemblance la plus importante est l'alternance de dépôts éoliens de dunes, de dépôts lacustres et de dépôts fluviatiles. Les changements entre les conditions de milieu aride (sables et poussières éoliens) et celles d'un milieu sub-humide (couches de boues et nappes sableuses de crue) ont pu se mettre en place graduellement ou brusquement. Nous en concluons que des changements climatiques d'ampleurs variés et à intervalles récurrents, d'origine tectonique, ont déterminé les conditions de vies des habitats des dinosaures du Bassin de Gobi de la fin du Crétacé. Ces conditions récurrentes d'extrêmes aridités qui ont contribué à l'extermination de nombreux dinosaures (par ex., Proceratops) sont très semblables aux sécheresses cataclysmiques qui sévissent actuellement dans l'oasis de Okavango et qui entraînent la mort d'antilopes et d'autres bêtes.

## INTRODUCTION

Cretaceous continental strata of central Asia continue to attract the attention of geoscientists mainly because of the presence of prolific, scientifically significant and exceptionally well-preserved vertebrate fossils, largely dinosaurs and mammals (Perle *et al.*, 1993; Novacek *et al.*, 1994; Norell *et al.*, 1994; Dashzeveg *et al.*, 1995; Novacek, 1996; Fastovsky, *et al.*, 1997; Loope *et al.*, 1998). An extraordinary collection from the Gobi Desert of Mongolia, one which is growing as new expeditions explore this area (Novacek, 1996), contains, among others, dinosaurs found in mass graves in various growth stages, including groups of babies, embryonic skeletons and nests of unhatched eggs. Canadian paleontologists and sedimentologists have shared in the international effort to investigate the central Asian dinosaur-bearing "Eldorado" (*e.g.*, Jerzykiewicz, 1989; Grady, 1992). According to Phillip Currie, head of dinosaur research at the Royal Tyrrell Museum of Palaeontology in Alberta, the Canada-China Dinosaur Project has unearthed an impressive number of dinosaurs, mammals, lizards and turtles in Inner Mongolia. This material will continue to be the basis for further co-operative studies by Canadian paleontologists and their Chinese and Mongolian partners.

What is so significant about the fossil vertebrates from the Gobi Desert? Why has this remote area been visited time and again since the 1920s by paleontologists from many countries, notably the United States, Russia, China, Poland, Sweden and Japan? And why should Canadian geoscientists, who have their own very rich dinosaur-bearing sites in western Canada, also be interested in prospecting the remote Gobi Desert?

The fascination with central Asia began near the beginning of this century when paleontologists H.F. Osborn and W.D. Matthew, from the American Museum of Natural History, suggested that most of today's land-living animal groups had predecessors in central Asia. According to this idea, elaborated by Matthew in his classic work *Climate and Evolution* (1915), all paths of vertebrate migration commenced in central Asia. Hence, in order to understand the beginning of our modern animal world we should look toward central Asia. Expeditions from the American Museum of Natural History and subsequent expeditions from many countries seem to confirm that suggestion. It appears that most families of Cretaceous dinosaurs and mammals originated in central Asia. Russell (1993) has pointed out that no Cretaceous dinosaurs are known to have origi-

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nated in North America. Among others, the North American representatives of Tyrannosauridea, Avimimidae, Hadrosauridae and Ceratopsidae had their ancestors in central Asia.

One of important aspects of the dinosaur studies is an attempt to reconstruct their natural environment. Physical and chemical properties of the dinosaur-bearing sediments in the Gobi Basin clearly indicate that some of the skeletons were buried by wind-blown sand and others were entombed in water-laid sediments (Jerzykiewicz *et al.*, 1993; Eberth, 1993; Fastovsky *et al.*, 1997; Loope *et al.*, 1998). Although it seems apparent that both subaerial/eolian and subaqueous/fluviolacustrine processes shaped the dinosaur habitat, it is still not clear which of these processes predominated over a given area of deposition at any given time of the Cretaceous period. This statement is particularly true with reference to the Djadokhta Formation, which has yielded rich and exceptionally well-preserved vertebrate faunas.

The spectrum of paleoenvironments invoked to explain the stratigraphic records of specific dinosaur-bearing sites of central Asia includes a lake (Kalugina, 1980; Verzilin, 1982; Shuvalov, 1982), a lakeshore (Lefeld, 1971), a lacustrine delta (Jerzykiewicz, 1995), a meandering-channel/flood plain (Gradzinski, 1970), an eolian/alluvial plain with ephemeral lakes (Gradzinski and Jerzykiewicz, 1974b; Jerzykiewicz *et al.*, 1993), a transitional alluvial fan-desert (Eberth, 1993; Fastovsky *et al.*, 1997), and, most recently, a dune-sand-source-alluvial fan (Loope *et al.*, 1998).

There is no question that all of the above-mentioned settings may account for specific parts of the Cretaceous stratigraphic record of central Asia. None of these settings, however, fully explains the ecological diversity, faunistic abundance and alternations of sedimentary facies representing the dinosaur-supporting environments of central Asia. This is particularly true in relation to the Late Cretaceous environments, which were characterized

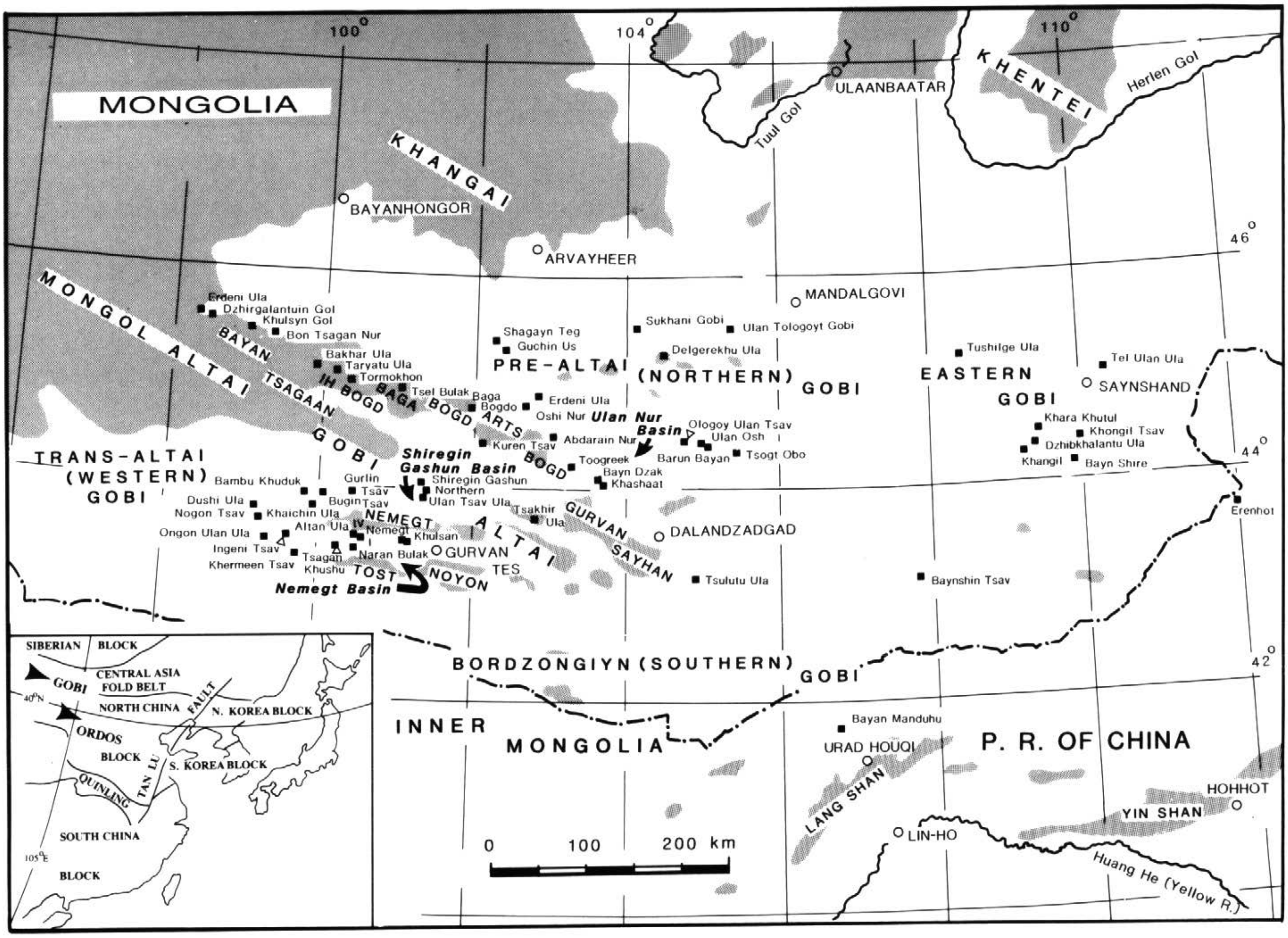

**Figure 1** Location of the Cretaceous dinosaur-bearing sites in the Gobi Basin of Mongolia. The major sites of excavations by paleontological expeditions are marked by small black cubes. For example, locality Toogreek occurs in the middle of the map in the Ulan Nur Basin (skeletons of "standing" Protoceratops and "Fighting dinosaurs" illustrated in Figs. 6 and 7 were found there), sites Altan Ula and Khulsan (see Figs. 4 and 5) are located in the southwestern corner of the map in the Nemegt Basin, and locality Bayan Mandahu (see Figs. 4D and 8), which was the main target of the Sino-Canadian Expedition in1988, is seen in the southeastern part of the map in Inner Mongolia of China. Locality Ukhaa Tolgod, recently very successfully excavated by Mongolian and American paleontologists (Dashzeveg, *et al.*, 1995; Novacek, 1996; Loope *et al.*, 1998), occurs in the Nemegt Basin, northeast of Gurvan Tes settlement. Settlements, sparse in number, are shown by open circles with names in capital letters. The figure is modified from Jerzykiewicz and Russell (1991). [Published versions of spelling of some locality names may vary because the transliteration from Mongolian, Chinese and Russian sources is often not exactly the same (for example, Bayan Manduhu is currently spelled Bayan Mandahu, and Toogreek is now being described as Tugrikin-Shireh)].

by rapid lateral and vertical facies-changes and by the occurrence of both terrestrial and aquatic fauna (*e.g.*, Kielan-Jaworowska, 1970, 1974, 1981; Osmolska and Roniewicz, 1970; Barsbold, 1972, 1983; Maryanska and Osmolska, 1975; Maryanska, 1977; Rozhdestvensky, 1977; Elzanowski, 1977; Gradzinski *et al.*, 1977; Osmolska, 1980, 1982, 1987; Ponomarenko and Kalugina, 1980; Martinson, 1982; Jerzykiewicz *et al.*, 1993; Currie and Eberth, 1993; Novacek *et al.*, 1994; Norell *et al.*, 1994; Dashzeveg *et al.*, 1995).

The purpose of this paper is to show that the present-day Okavango oasis in Botswana, Africa, best accounts for the range and complexity of the late Cretaceous vertebrate habitats of the Gobi Basin (Jerzykiewicz, 1996b; in press). It will be shown that the Okavango oasis model explains the coexistence of "sub-humid" and "arid" environmental conditions, and alternations of aquatic and terrestrial faunas, better than any of above-mentioned paleoenvironments. Rapid and dramatic environmental changes that take place in the Okavango oasis today should help us to better understand the paleoecology of the Late Cretaceous dinosaur-supporting habitats of the Gobi Basin.

The Okavango oasis, which is surrounded by sand dunes of the Kalahari Desert, is inhabited by a very rich fauna of herbivorous and predaceous vertebrates, including antelopes, zebras, buffaloes, hippopotami, elephants, giraffes, springboks, ostriches, crocodiles, hyenas, leopards and lions. The oasis has developed in geological and climatic conditions analogous to those which had developed in central Asia by the end of the Cretaceous Era. Sedimentary facies of the dinosaur-bearing Cretaceous formations of the Gobi Basin show a very close correspondence to those described from the Okavango Delta by Thomas and Shaw (1991) and McCarthy and Ellery (1995). Okavango-like oases, developing within internally drained tectonic grabens, were probably the last refuges of dinosaurs on the Asian continent before their extinction at the end of the Cretaceous. The Okavango oasis today is a refuge for a very rich and diversified biota which depends for its very existence upon a crucial, but inconsistent supply of water, which in turn depends on an annual flood event and episodic precipitation. Droughts of cataclysmic proportions for the wildlife occur in that area every few tens of years but the Okavango wildlife still survives (Lee, 1990). The length of time that this dynamic ecological system will last will be determined mainly by ongoing, careful environmental management. The environmental balance is so very delicate that it can be destroyed very easily. Certainly, no extraterrestrial cause would be needed to erase the modern Okavango oasis and similar environments from the surface of our planet.

## GEOLOGICAL AND PALEOGEOGRAPHICAL SETTING, GOBI BASIN

Cretaceous vertebrate-bearing strata infill the Gobi Basin, which extends from the Khangai and Mongol Altai mountains in the northwest to the Yellow River valley in the southeast (Fig. 1). Most of this area lies within the boundaries of Outer Mongolia, except for the southeastern periphery, which belongs to the Inner Mongolian province of China (Fig. 1).

Paleogeographically, the vertebrate-supporting environments of the Gobi Basin developed many hundreds of kilometres away from any marine coastline, in the middle of the Asiatic mainland (Fig. 2). They represent typical inland basins (Sun *et al.*, 1989).

The Gobi Basin came into existence only in the Jurassic, long after the Permian collision of Siberia and north China. The basin was created by regional extension behind an active plate-margin, where the Pacific sea floor was subducted under the Asian continent (Hsu, 1989). In the Gobi Basin, Jurassic volcanics and intrusives were accompanied by coarse clastics and were followed, after development of a regional unconformity (Morris, 1936), by a succession of predominantly fine-grained lacustrine, fluvio-lacustrine, alluvial plain and eolian sediments of Cretaceous age. These vertebrate-bearing strata were deposited largely during the last stage of

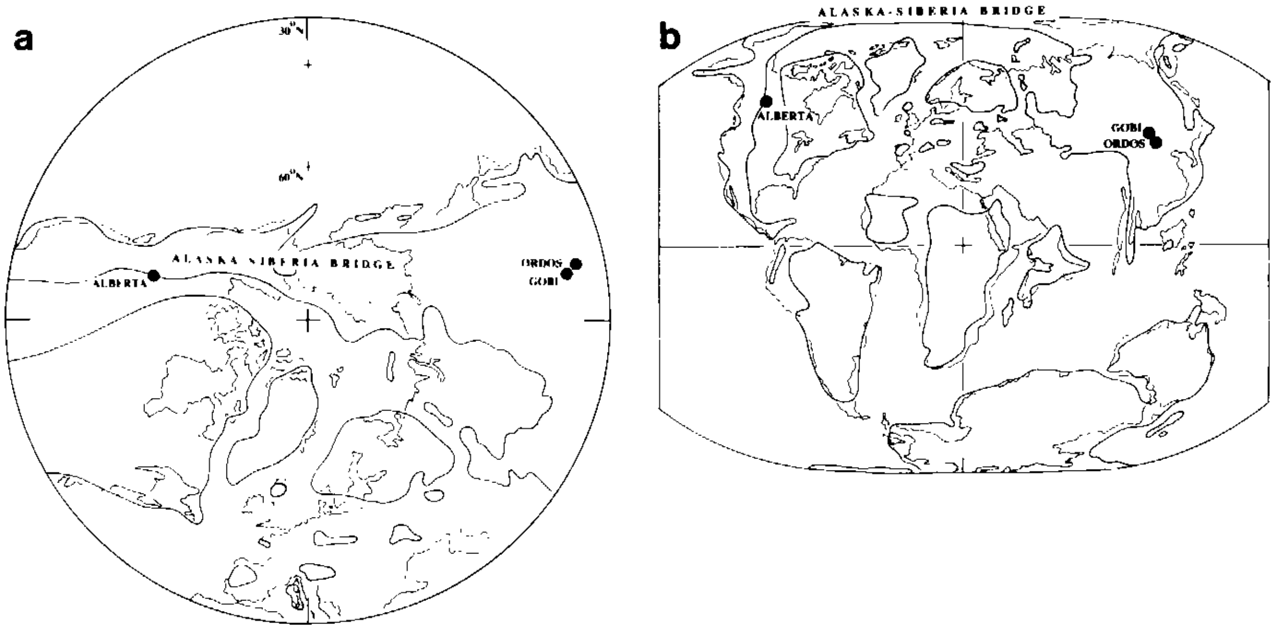

**Figure 2** Paleogeographical setting of the Gobi Basin during the Late Cretaceous (Senonian Stage, 90-80 m.y.). (**a**) Polar view. (**b**) Equatorial view. Outline of the Cretaceous continental areas (dotted) superimposed on the present outline of continents is simplified after H.G. Owen from Howarth (1981). Note the difference between the position of the Gobi and Ordos basins located far away from the seashore and the position of the Alberta Basin, located in a coastal area (modified from Jerzykiewicz, 1996a).

tectonic evolution of the Gobi Basin and the adjacent Ordos Basin farther to the south (Jerzykiewicz, 1995; Fig. 1, inset). At that stage the Gobi and Ordos basins were separated by the Lang Shan massif and partitioned into component half-grabens. The Gobi Basin has since disintegrated into the Ulan Nuur, Shiregin Gashun, Nemegt and Bayan Manduhu basins (Fig. 1).

## GOBI BASIN STRATIGRAPHY

Cretaceous strata of the Gobi Basin are represented by an unconformity-bounded succession of exclusively continental clastic deposits and rare volcanic rocks (Morris, 1936; Sochava, 1975; Gradzinski *et al.*, 1977; Martinson, 1982; Samoilov, *et al.*, 1988; Jerzykiewicz and Russell, 1991). A composite stratigraphic column of the Cretaceous formations of the Gobi Basin is shown in Figure 3. The Lower Cretaceous is represented largely by lacustrine sediments, and the Upper Cretaceous consists mainly of alluvial plain and eolian red beds.

The Upper Cretaceous Bayn Shire, Djadokhta, Barun Goyot and Nemegt formations (Fig. 3) have yielded most of the vertebrate fossils. The Djadokhta Formation is famous for yielding the first known dinosaurian hatchlings (of *Protoceratops andrewsi*), first known dinosaurian eggs, dinosaur embryos and babies, and the oldest (then) placental mammals. Numerous well-preserved skeletons of adult dinosaurs include *Protoceratops*, *Pinacosaurus, Velociraptor, Oviraptor and Saurornithoides* (Granger and Gregory, 1923; Berkey and Morris, 1927; Lefeld, 1971; Gradzinski *et al.*, 1977).

The overlying Nemegt Formation (Fig. 3) has yielded a large proportion of gigantic dinosaur skeletons (see *e.g.*, Fig. 4; Gradzinski, 1970; Barsbold, 1972; Gradzinski and Jerzykiewicz, 1974a; Gradzinski *et al.*, 1977; Verzilin, 1978; Osmolska, 1980; Jerzykiewicz and Russell, 1991).

Lack of marine fossils in the central Asian Cretaceous precludes the possibility of a direct biostratigraphic correlation with the international marine stages of the Cretaceous Period. The international correlations are also severely hampered by the largely endemic nature of central Asian Cretaceous vertebrate assemblages (Jerzykiewicz and Russell, 1991). A large number of nonmarine fossils has been utilized to approximate the temporal position of the major lithostratigraphic units of the Gobi Basin in the international standard scale for the Cretaceous (*e.g.*, Martinson, 1971, 1982; Barsbold, 1972; Kalugina, 1980; Krassilov, 1980, 1982; Ponomarenko and Kalugina, 1980; Makulbekov and Kurzanov, 1986). All of these papers, in a more or less direct manner, refer to sections outside of the Gobi Basin (either in Asia or North America), which contain interdigitations of strata with terrestrial and marine fossils.

Ages of the Lower Cretaceous formations in central Asia — Valanginian, Hauterivian, Barremian, Aptian and Albian — were estimated largely on the basis of invertebrate or plant fossils (Vasiliev *et al.*, 1959; Shuvalov, 1975; Krassilov, 1982; and Martinson, 1982). Ages of the Upper Cretaceous formations of the Gobi Basin, inferred from the evolutionary changes of the vertebrates in relation to the North American nonmarine stages (which are constrained by an ammonite zonation and palynology, and are calibrated by chronostratigraphic methods), are as follows: Bayn Shire Formation (late Cenomanian-Coniacian to ?early Santonian), Djadokhta Formation (mid-Campanian), Barun Goyot Formation (mid-late Campanian), and Nemegt Formation (late Campanian-early Maastrichtian), (Gradzinski *et al.*, 1977; Fox, 1978; Lillegraven and McKenna, 1986; Jerzykiewicz and Russell, 1991). It should be stressed, however, that age estimations of Cretaceous formations of the Gobi and their time correlations are still very uncertain.

No strata of late Maastrichtian age have been documented in the Gobi Basin and the Cretaceous-Tertiary boundary is placed at an erosional unconformity (*cf.* Jerzykiewicz, 1995). Paleontological evidence

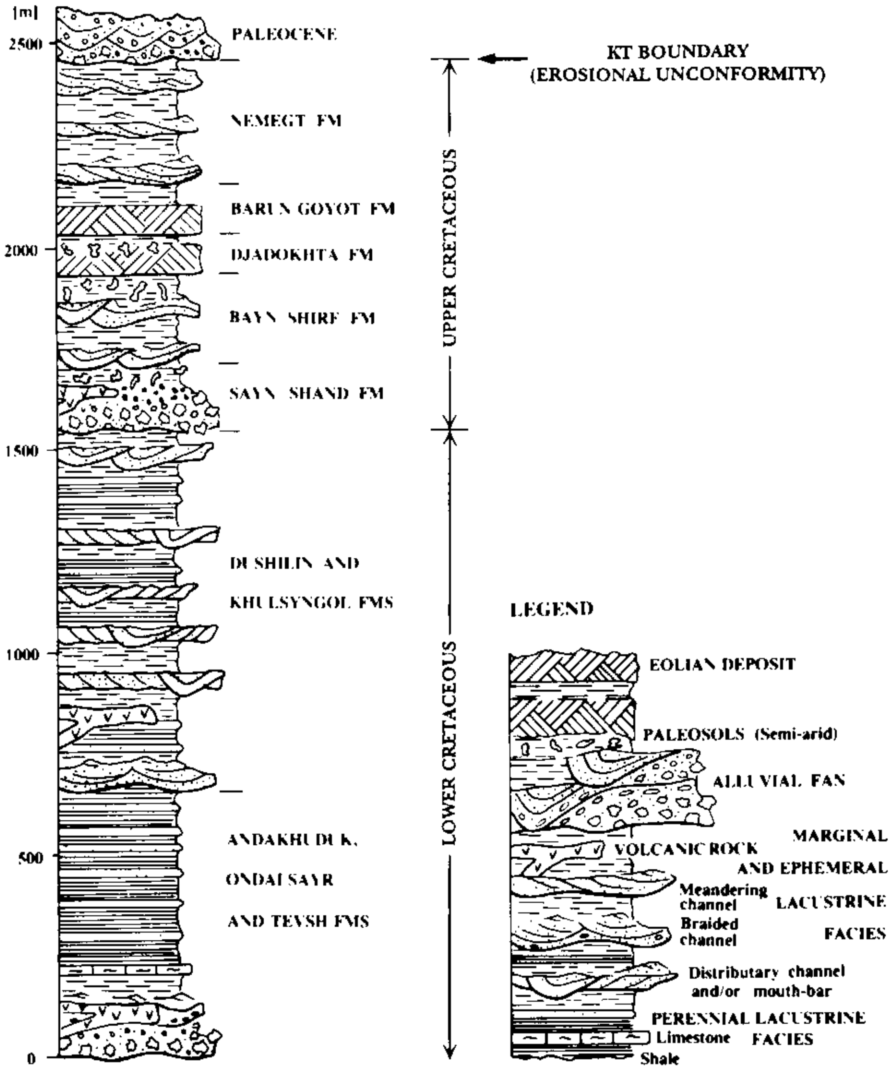

**Figure 3** Composite stratigraphic column of the Cretaceous in the Gobi Basin. Superposition relations of the formations, and facies are inferred from Gradzinski (1970); Gradzinski and Jerzykiewicz (1974a,b); Shuvalov (1975); Sochava (1975); Gradzinski *et al.*, (1977); Jerzykiewicz and Russell (1991) and Jerzykiewicz (1995).

is not sufficient to assess the magnitude of the hiatus between the Upper Cretaceous and Paleocene in the Gobi Desert (Fig. 3).

## GOBI BASIN SEDIMENTOLOGY

The Cretaceous strata of central Asia consist of continental red beds. Two facies associations are distinguished: 1) lacustrine and associated facies of subaqueous origin, mainly fluvial, and 2) eolian and associated interdune facies. The former facies association predominates in the Lower Cretaceous (Kalugina, 1980; Jerzykiewicz, 1995), and the latter facies in the Upper Cretaceous.

Windblown and associated facies of subaerial deposition, interfingering with water-laid interdune/ephemeral facies, have been documented from the Upper Cretaceous Djadokhta and Barun Goyot formations (Berkey and Morris, 1927; Lefeld, 1971; Gradzinski and Jerzykiewicz, 1974b; Fastovsky *et al.*, 1997) and also from correlative strata in Bayan Mandahu of Inner Mongolia (Jerzykiewicz *et al.*, 1989, 1993; Eberth, 1993). The most conspicuous wind-formed feature is large scale tabular- or wedge-planar cross-stratification, which is diagnostic for accumulation on slopes of eolian dunes (Fig. 5). Detailed sedimentological studies suggest the presence of various types of eolian dunes, including linear, transverse, parabolic and barchan forms (Gradzinski and Jerzykiewicz, 1974b; Jerzykiewicz, *et al.*, 1993; Eberth, 1993; Fastovsky, *et al.*, 1997). Some of these eolian forms at Toogreek (Fig. 1) have been previously interpreted as a "dry delta" in a "shallow-water, wave dominated environment" by Tvardokhlebov and Tsybin (1974).

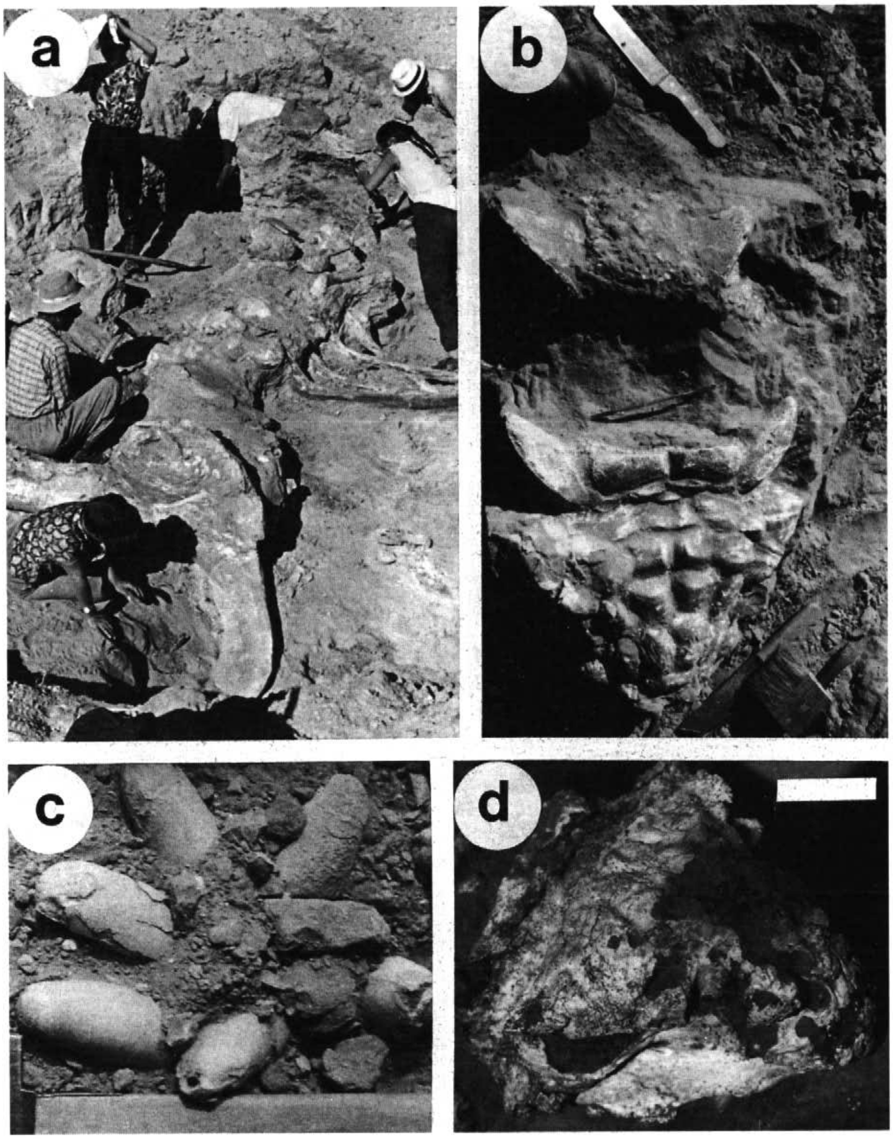

**Figure 4** Dinosaur remains in the Upper Cretaceous of the Gobi Basin. (**a**) Partly unearthed skeleton of a large sauropod in fluvial sandstone of the Nemegt Formation at the Altan Ula locality. Polish-Mongolian Expedition, 1965 (photo courtesy of R. Gradzinski). (**b**) The skull and partial skeleton of *Saichania* in eolian sandstones of the Barun Goyot Formation at Khulsan. Polish-Mongolian Expedition, 1971. (**c**) A cluster of dinosaur eggs in eolian sandstones of the Barun Goyot Formation at Khulsan. Polish-Mongolian Expedition, 1971 (photo courtesy of W. Skarzynski). (**d**) Skull of a *Pinacosaurus* juvenile recovered from eolian sandstone of the Djadokhta Formation at Bayan Mandahu, Inner Mongolia. Sino-Canadian Expedition, 1988.

Associated with the large-scale cross-stratified sandstone of eolian deposition are structureless sandstones which form the bulk of the Djadokhta and Barun Goyot formations (Fig. 3). Structureless sandstone primarily has been interpreted as vertically aggraded windblown sand, trapped by growing plants and thus similar in origin to loess (Berkey and Morris, 1927). However, the Cretaceous structureless sandstone is coarser than loess; it consists of no more than 25 % dust fraction (diameter less than 1/16 mm), and contains randomly distributed granules and pebbles, some of which have frosted and pitted surfaces of eolian origin. Occasionally, these sandstones show traces of internal stratification, which can be inferred from the orientation of large clasts of redeposited calcretes, or the debris of vertebrate bones. The polymodal grain-size distribution, disrupted traces of stratification, and the association of the structureless sandstone with eolian dunes and calcrete horizons suggest a complex origin. These deposits have been interpreted as having originated from slumping of the slipfaces of eolian dunes and/or infilling of interdune areas by high energy sand/dust storms (Jerzykiewicz *et al.*, 1989; 1993). This interpretation is consistent with the fact that many dinosaur skeletons were found in the structureless sandstone, some of them in poses suggesting that the animals were encased within the sediment at the time of their death (Figs. 6, 7). It is inferred that some of these animals were trapped and died while attempting to free themselves from a sandstorm deposit during or shortly after the storm event (Jerzykiewicz *et al.*, 1989, 1993; Fastovsky *et al.*, 1997).

Most recently, Loope *et al.* (1998) have published new results of sedimentological observations on the Djadokhta Formation in Ukhaa Tolgod of the Nemegt Basin (Fig. 1). Previous descriptions and interpretations of the major dinosaur-bearing "structural" sandstone were thus modified. Two facies within the "structureless" sandstone have been distinguished by Loope *et al.*, (*op.cit.*): 1) Vaguely bedded sandstone with oriented concretionary sheets (facies E-2), and 2) Structureless sandstones lacking oriented concretions (facies F). The E-2 facies (which corresponds closely to eolian facies Dfb on Fig. 8 as described by Jerzykiewicz *et al.*, 1993), has been interpreted as eolian dune deposits. The F facies (which corresponds to the Iss facies of Jerzykiewicz *et al.* 1993), has been interpreted in terms of a "dune-sourced alluvial fan" (Loope *et al.*, 1998).

Interdune facies consist of channelized sandstone and conglomerate, sheet flood sandstone of fluvial/alluvial fan origin, and interstratified sandstones and mudstones of ephemeral lacustrine origin (Gradzinski and Jerzykiewicz, 1974b; Jerzykiewicz *et al.*, 1993; Eberth, 1993). Fluvial deposits forming fining-upward cycles interpreted in terms of point bars of meandering chan-

**Figure 5** Large-scale cross-stratified layer of sandstone interpreted as the slipface of a transverse eolian dune. Barun Goyot Formation at Khulsan, Nemegt Basin (for location see Fig. 1).

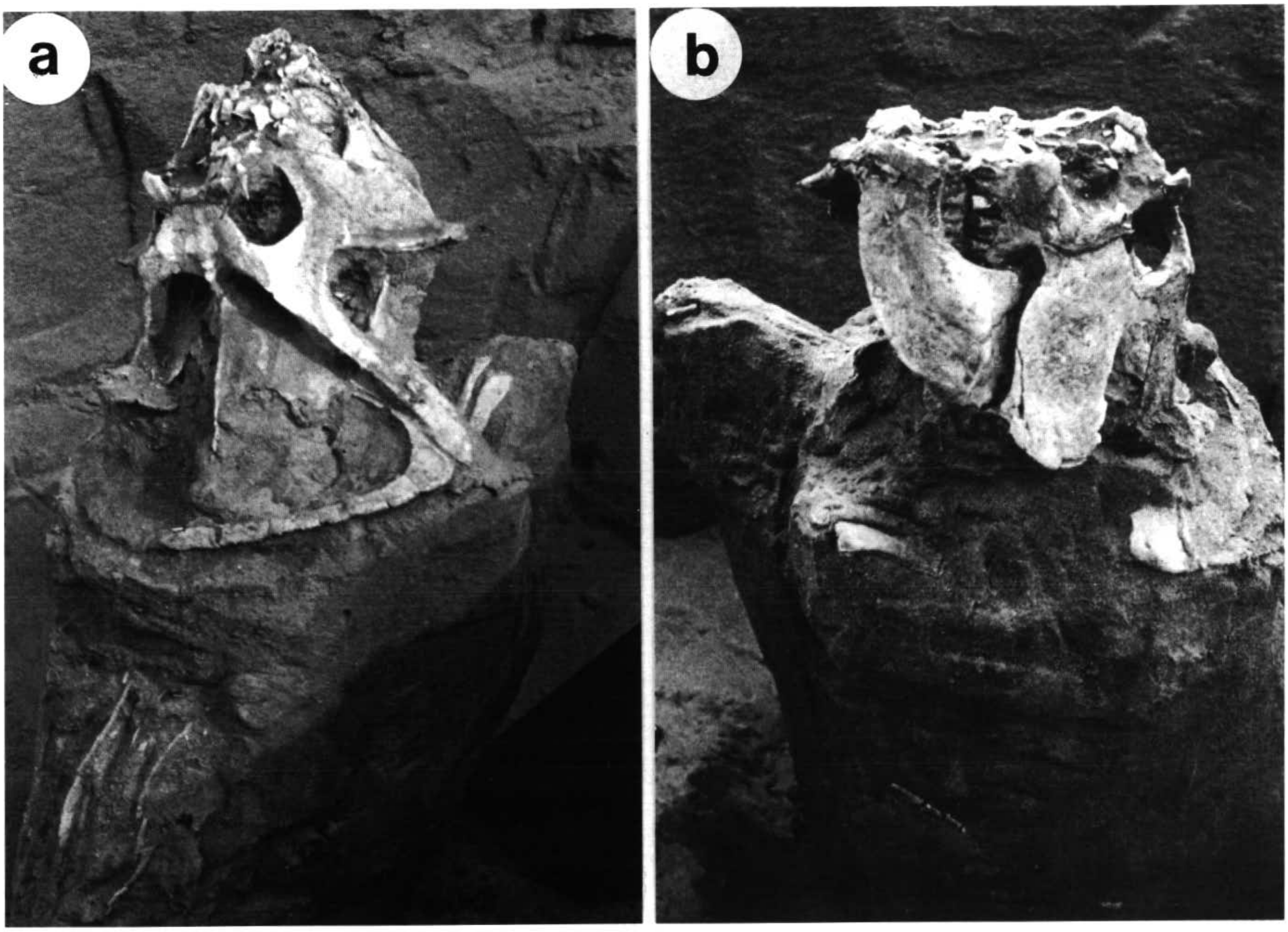

**Figure 6** Partly unearthed skeleton of "standing" *Protoceratops* discovered by the Polish-Mongolian Expedition of 1971 in the Djadokhta Formation at Toogreek (for location see Fig. 1). (**a**) Oblique view. (**b**) Side view. The standing position suggests that the animal was trapped and died while attempting to free itself from a sandstorm.

nels (Gradzinski, 1970), and fluvio-lacustrine facies (Verzilin, 1978) have been described from the Nemegt Formation (Fig. 3).

Both dune and interdune sediments contain calcrete horizons, some of which were traced laterally a distance of several hundred metres, indicating a distinct hilly topography (Eberth, 1993). An abundance of rhizoliths — *i.e.*, structures resulting in the preservation of plant roots and endogenic invertebrate traces — in some layers underlying the calcretes suggests that they represent organic-rich, vegetated and moist subenvironments (Jerzykiewicz *et al.*, 1993). The sedimentological characteristics of these facies, especially the grain size, the paleosols and related topography, as well as the color, indicate a close similarity to the Kalahari beds of the Okavango area as described in the literature (*e.g.*, Thomas and Shaw, 1991, McCarthy and Ellery, 1995).

An example of vertical and lateral distribution of the Upper Cretaceous facies in the Gobi Basin is shown in Figure 8. The wind-formed, large-scale, cross-bedded and structureless sandstones (Dxb, Dfb) are dominant volumetrically and strongly persistent laterally. They are interbedded with water-lain interdune deposits and calcrete horizons (Ims, P). Accumulations of calcretes (P) occur either in the form of nodules and hardpans developed *in situ*, or as redeposited debris in the interdune channels, which suggest that a significant proportion of the calcrete crusts was destroyed by penecontemporaneous erosion.

The calcrete horizons in the Gobi are analogous to those described by Blumel (1982) and Summerfield (1982) from the Kalahari beds of Namibia and Botswana, which form the bedrock of the modern Okavango Delta. In that area the calcretes are being formed in a multistage process involving alternation of climatic conditions. Settling of calcic dust into the host sediment occurs during a subterraneous stage in semiarid to subhumid conditions. Diagenesis, which is often followed by exhumation, weathering and redeposition, takes place during a subaerial stage in semiarid to arid conditions (Fig. 1, *in* Blumel, *op. cit.*).

The Cretaceous stratigraphic record in the Gobi Basin contains two different types of sediments: 1) "gradual-cyclic" and 2) "instantaneous-episodic." The "gradual" sediments are represented by regularly stratified eolian paleodunes (facies Dxb in Fig. 8) and by repetitions of the fining-upward successions of meandering-fluvial origin (Gradzinski, 1970). The "instantaneous" sediments are represented by conglomerate of flash-flood origin dumped on paleosol horizons (*e.g.*, facies Icg in the North Canyon column of Fig. 8), or by sheet-flood sandstones laid down directly on eolian dunes (*e.g.*, fig. 10 in Gradzinski and Jerzykiewicz, 1974b). Such abrupt changes in the pattern of sedimentation, suggesting a sudden inundation of the dune field by a flood event, are known from many localities of the Upper Cretaceous of the Gobi Basin. Another example of an instantaneous deposit, at least in part, is the structureless sandstone (facies Iss in Fig. 8). This deposit is interpreted in terms of a) slumping of the slipfaces of eolian dunes, or b) primary deposition of massive (unsorted) sediments in adjacent interdune areas (*cf.* Jerzykiewicz *et al.*, 1993; Eberth, 1993). It has been assumed that episodic dust storms contributed to the deposition of the Iss facies and the death of *Protoceratops* and other dinosaurs trapped in structureless sandstone (Figs. 6A,B, 7; and figs. 9, 11 in Jerzykiewicz *et al.*, 1993).

Loope *et al.* (1998) have recently presented a different interpretation of similar examples of buried dinosaurs from Ukhaa Tolgod locality in the Nemegt Basin: "...rapid vertical accretion of structureless sand (facies F) and accompanied in situ burial of large animals is much more likely to occur on sand fans during rain storms within a stabilized dune field than during wind storms in an active dune field." (Loope *et al.*, *ibid.*, p.29)

The cyclic and episodic sediments differ not only in mode of deposition but also in the volume and rate of accumulation, frequency of occurrence, predictibility and preservation potential (*cf.* Dott, 1983; Seilacher, 1991). In the Upper Cretaceous of the Gobi Basin, the bulk of the stratigraphic record is formed by cyclic sediments of eolian (*e.g.*, facies Dxb in Fig. 8), fluvial or lacustrine origin (*e.g.*, facies Im&s in Fig. 8). These sediments, which have a relatively low rate of accumulation and a relatively high preservation potential, form a background for the episodic sediments of disastrous floods and dust storm events. Such relatively rare and probably sudden events punctuated the continuous-gradual accumulation within the dune fields and interdune channels, ponds and lakes. Events of such large magnitude could destroy vegetation covers and paleosol crusts, causing geomorphic changes of cataclysmic proportions for the wildlife. Plant-eaters like *Protoceratops* and *Ankylosaurus*, which fed close to the ground, must have been most vulnerable.

Sudden inundations of the interdune

**Figure 7** Partly unearthed skeletons of *Protoceratops* and *Velociraptor* locked in mortal combat (the "fighting dinosaurs"), discovered by the Polish-Mongolian Expedition of 1971 in the Djadokhta Formation at Toogreek northeast of Bayn Dzak (for location see Fig. 1). Note the claw (arrow 1) of the hand clasping the top of the skull of the presumed prey, and the claws (arrow 2) of the left hind foot of the *Velociraptor* imbedded within the thorax of the *Protoceratops* (paint brush gives scale).

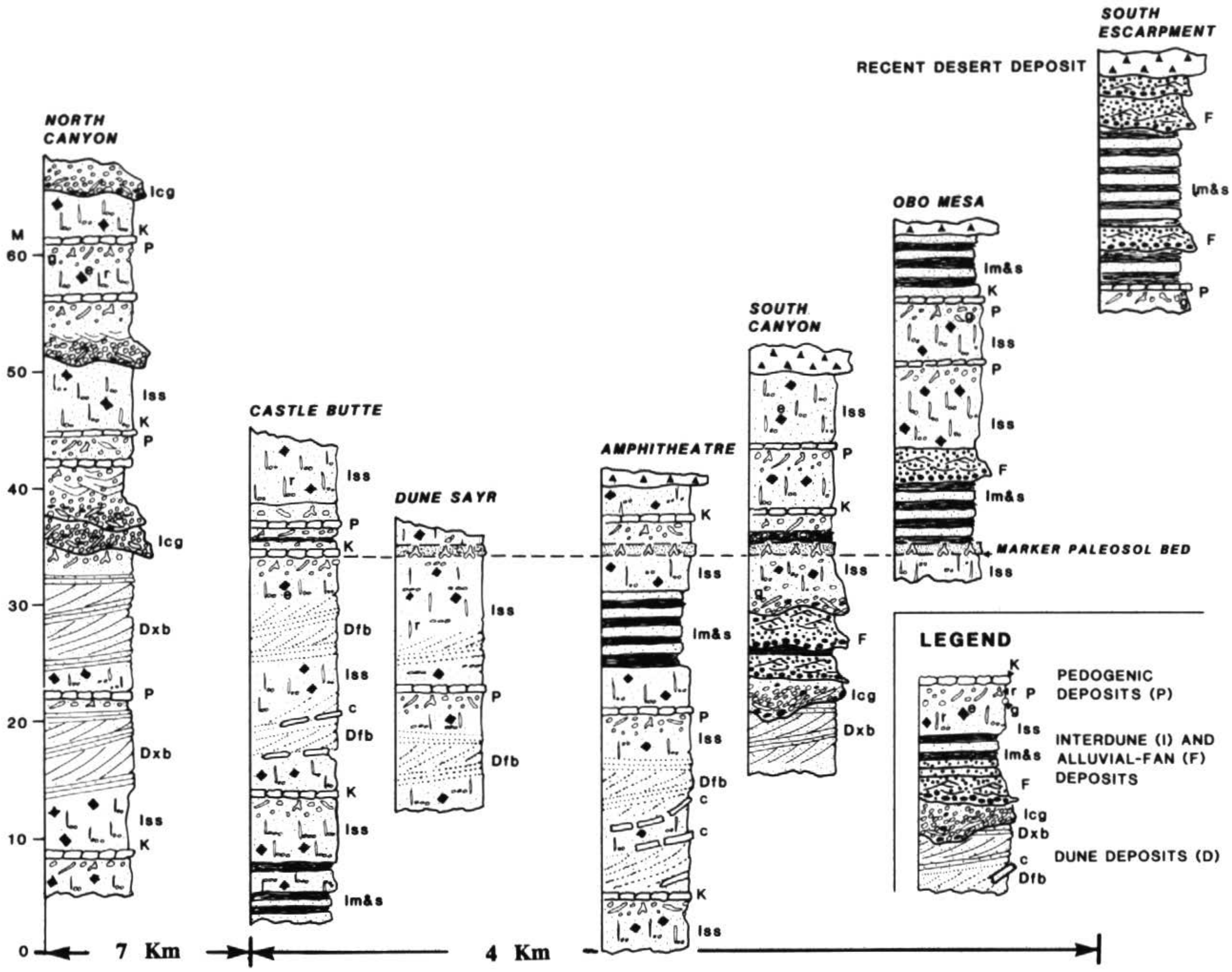

**Figure 8** Sedimentary facies in the Djadokhta Fm correlative strata in Bayan Mandahu of Inner Mongolia (from Jerzykiewicz *et al.*, 1993, for location see Fig. 1). Symbols: **Dxb**, large-scale, tabular and/or wedge planar sets of cross-stratified sandstone of eolian origin; **Dfb**, structureless and/or faintly bedded sandstone, containing inclined layers of indurated, cemented sandstone (**c**); **Im&s**, alternating sandstone and mudstone of lacustrine origin; **Iss**, structureless sandstone; **P**, calcrete deposits (**g**, concretions, **r**, rhizocretion, **K**, hardpan); **Icg**, intraformational conglomerate consisting of redeposited calcrete debris. **F**, extraformational conglomerate of alluvial fan origin.

areas by flood events and episodic droughts accompanied by sand/dust storms, which are inferred to have caused the extermination of many Cretaceous dinosaurs of the Gobi, are known to take place in the Okavango oasis of the Kalahari Desert today (Lee, 1990; Thomas and Shaw, 1991).

## THE OKAVANGO MODEL

The Okavango Delta or low sinuosity/meandering fluvial fan ("Okavango Oasis", Figs. 9, 10) and related ephemeral rivers, lakes/pans and swamps of the Kalahari Desert (Hutchins *et al.*, 1976; Thomas and Shaw, 1991; Stanistreet and McCarthy, 1993; McCarthy and Ellery, 1995) are probably the closest contemporary analogues of the Late Cretaceous vertebrate-supporting environment of central Asia (Jerzykiewicz, 1996b; in press). Upper Cretaceous dinosaur-bearing red beds of the Gobi Basin show a striking resemblance to the Kalahari Beds (Wright, 1978; McCarthy and Ellery, *op. cit*) in terms of sedimentary facies, and in other aspects of the depositional environment.

The sedimentary facies which have been recognized in the Upper Cretaceous stratigraphic record of the Gobi Desert have their modern counterparts not only within the Kalahari but also in other deserts. For example, modern analogues to the Upper Cretaceous sediments are being accumulated in the alluvial fan-desert transitional environments of the Taklimakan Desert of China (Eberth, 1993), and within the Gobi Desert itself (Fig. 11). However, the analogy between the Late Cretaceous Gobi Desert and the modern Okavango Oasis of the Kalahari desert is much more complete because it explains not only the facies pattern but also other geological and biological aspects of the dinosaur habitat.

In contrast to the modern sedimentary basins within the Taklimakan Desert (the Junggar and the Tarim basins), which are located in compressional or transpressional tectonic domains (Hsu, 1989; Hendrix *et al.*, 1992), the Gobi and the Kalahari deserts are located in extensional tectonic domains. The Okavango tectonic graben has developed within the African intercratonic basin (Thomas and Shaw, 1991) in a similar manner to the Ulan Nur and Nemegt grabens within the Gobi basin. Sedimentation in the tectonic grabens of the Kalahari and Gobi basins has been governed by tectonics and related climatic changes.

Some of the large tectonic grabens (rifts) in Africa contain large lakes in their axial parts (*e.g.*, Lake Tanganyika), whereas others, exemplified by the Okavango graben, have no large reservoirs of water and are drained by distributaries into subterranean seepage along the major faults (Fig. 9). The timing and magnitude of tectonic events exert an overriding geological control upon the drainage systems of the African rifts (Frostic and Reid, 1987). Tectonically induced changes in climate cause great changes in the area and volume of the lakes, some being temporarily reduced to swamps or even obliterated. The climatic changes vary in frequency from long-term (millions of years) to short-term changes (thousands of years). The chronology of climatic fluctuations in the Okavango-Makgadikgadi area since 50,000 years BP includes at least four phases of relative humidity, and intervening phases of relative aridity. The former were expressed by high levels of the water tables and development of lakes, and the latter by an increasing intensity of eolian processes (Thomas and Shaw, 1991).

The Okavango setting is capable of accommodating eolian-dominated, fluvial-dominated and intermediate depositional settings/facies within one environment. Both the gradual-cyclic and the instantaneous-episodic modes of accumulation of wind-blown and water-laid sediments, as postulated for the Gobi Basin (see above), are consistent with the Okavango model. This composite model consists of two contrasting depositional settings or metastable states: 1) subaerial/eolian, and 2) subaqueous/fluvio-lacustrine. Changes from one to the other, in space and time, may have been gradual or instantaneous in a geological sense in the Okavango setting. The "switching mechanisms" varied from allogenic-extrabasinal to autogenic-intrabasinal. The former was predominantly tectonic, and the latter may have been caused by a combination of tectonic and climatic factors with respect to the Gobi Basin. The dominance of one of these controls in specific areas at a given time in the Cretaceous is inferential rather than observational for most of the dinosaur-bearing sites of the Gobi Basin.

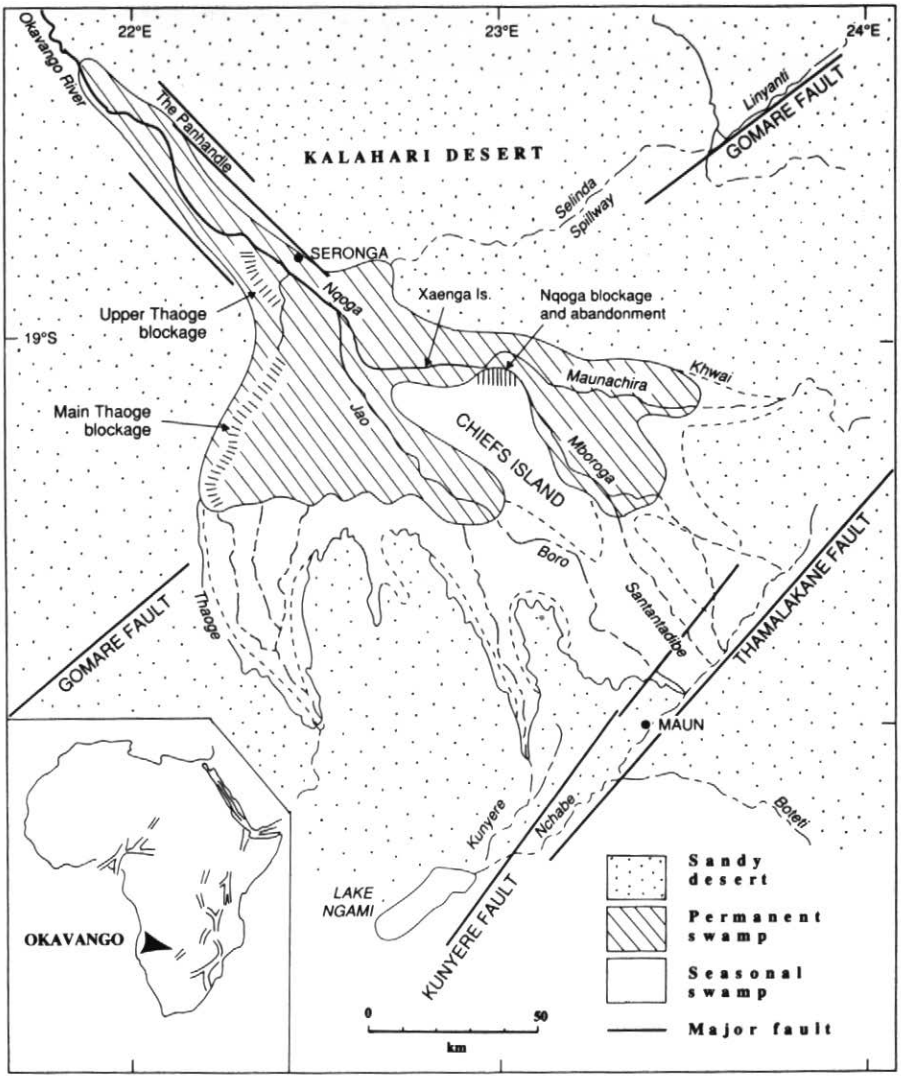

**Figure 9** Map of the Okavango Oasis/Delta in the Kalahari Desert, a contemporary analogue of the Cretaceous vertebrate-supporting environment of central Asia. The inset shows the location of the Okavango oasis in relation to other African rifts. The main features of the Okavango Delta are modified after Hutchins *et al.*, 1976; and McCarthy *et al.*, 1988 (in Thomas and Shaw, 1991). See Figure 10 for satellite view of this area.

The Okavango setting combines aspects of a life-supporting oasis for much of the time, with those of a life-threatening desert during episodic droughts and sand/dust storms. This area, which is comparable in size to the Late Cretaceous habitat of the Gobi Basin (*cf.* Figs. 1, 9), supports a large number of animals, both herbivorous grazing mammals and predators such as crocodiles and other reptiles (Thomas and Shaw, *op. cit.*). The Okavango is located within the African rift system in a semiarid climate in which evapotranspiration exceeds rainfall. This area is subject to seasonal flooding from subtropical Angola to the northwest. Water is distributed by meandering and anastomosing channels through permanent and seasonal swamps and disappears on a system of faults which abruptly terminates the delta. However, during seasonal flood events, water from the Okavango River may reach farther southeast into the distal areas of the ephemeral drainage which contains lakes, pans and playas (*e.g.*, Lake Ngami; see Figs. 9, 10), the Etosha, and the Makgadikgadi (Thomas and Shaw, *op. cit.*). The Okavango is surrounded by eolian-dune topography (Fig. 10), which is stabilized by vegetation and duricrust. However, during prolonged droughts the area is subject to dust- and sand-storms.

The most recent drought which spanned 7 years and culminated in 1987, killed hundreds of thousands of animals. The following description of the Okavango during that cataclysmic drought, published by Lee (1990, p. 43), well expresses the agony of the habitat: "Whole square kilometres looked as if a nuclear bomb had hit. Impalas had spontaneous abortions. Tsessebes were keeling over in the heat of the day. And the dust! Out of it would come tsessebes on spindly legs, like cardboard cutouts. Lions and vultures had a field day... The Savute River ran dry... Crocs and hippos crowded into pools that became mud. Elephants would pick their way among them to drink. Catfish were boiling in this black water, while hyenas fished between hippos. Eventually the elephants headed north on ancient trails towards the ever-flowing Chobe-Linyanti river system on the border. Many hippos and crocodiles followed. Some reached their goal. All that stayed died."

At present the Okavango is in a period of a relative aridity, and is subject to seasonal droughts. The environmental balance of the oasis is presently perhaps more delicate than in the past, and can be destroyed very easily. It is up to the people whether this refuge of the large African vertebrate fauna will last or will vanish like the dinosaurs from the Gobi Desert.

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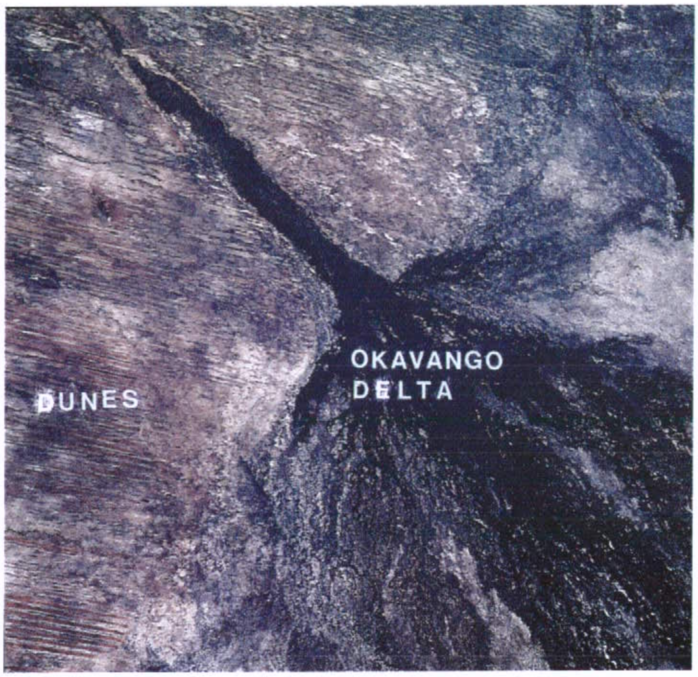

**Figure 10** Space Shuttle photograph of the Okavango Oasis/Delta taken in early November 1985 about two months after the arrival of the annual flood. Dark patches are the Okavango River and its tributaries and swamps of the delta plain. The lighter parallel lines in the northwestern part of the photographs are sand dunes stabilized by vegetation (from Strain and Engle, 1996). Published with permission.

**Figure 11** Interdune braided stream in southernmost Gobi Desert in the Yellow River Valley of Inner Mongolia in northern China. A coincidence of wind-blown and water-laid sandy deposits make this setting rather similar to the dinosaur-supporting environment of the late Cretaceous of the same area. **Inset**: Excavating a skeleton of an armoured dinosaur *Saichania* that died probably in a situation similar to one showed above. The dinosaur was buried by eolian dune sand in close proximity to an ephemeral stream or pond. Khulsan locality in the Nemegt Basin (Fig. 1). Photo taken during the Polish-Mongolian Paleontological Expedition in 1971.

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