

# Stratigraphy, sedimentology and palaeoecology of the dinosaur-bearing Kundur section (Zeya-Bureya Basin, Amur Region, Far Eastern Russia)

J. VAN ITTERBEECK\*, Y. BOLOTSKY†, P. BULTYNCK\*‡ & P. GODEFROIT‡§

\*Afdeling Historische Geologie, Katholieke Universiteit Leuven, Redingenstraat 16, B-3000 Leuven, Belgium

†Amur Natural History Museum, Amur KNII FEB RAS, per. Relochny 1, 675 000 Blagoveschensk, Russia

‡Department of Palaeontology, Institut royal des Sciences naturelles de Belgique, rue Vautier 29, B-1000 Brussels, Belgium

(Received 1 July 2004; accepted 20 June 2005)

**Abstract** – Since 1990, the Kundur locality (Amur Region, Far Eastern Russia) has yielded a rich dinosaur fauna. The main fossil site occurs along a road section with a nearly continuous exposure of continental sediments of the Kundur Formation and the Tzagayan Group (Udurchukan and Bureya formations). The sedimentary environment of the Kundur Formation evolves from lacustrine to wetland settings. The succession of megafloras discovered in this formation confirms the sedimentological data. The Tzagayan Group beds were deposited in an alluvial environment of the ‘gravel-meandering’ type. The dinosaur fossils are restricted to the Udurchukan Formation. Scarce and eroded bones can be found within channel deposits, whereas abundant and well-preserved specimens, including sub-complete skeletons, have been discovered in diamicts. These massive, unsorted strata represent the deposits of ancient sediment gravity flows that originated from the uplifted areas at the borders of the Zeya-Bureya Basin. These gravity flows assured the concentration of dinosaur bones and carcasses as well as their quick burial. Such taphonomic conditions allowed the preservation of sub-complete hadrosaurid skeletons unearthed at the Kundur site. Palaeobotanical data indicate a subtropical climate during the deposition of the Kundur and Udurchukan formations. Several elements in the composition of the Kundur vertebrate fauna suggest a strong influence of the North American late Cretaceous vertebrate communities: the abundance of corythosaur-like lambeosaurines, the probable presence of a nodosaurid dinosaur and of a eucosmodontid or microcosmodontid multituberculate. A late Maastrichtian age is tentatively proposed for the dinosaur-bearing sediments in Amur Region, by comparison with the information collected in the Western Interior Basin of North America. As it is also observed in the latter area, important floristic changes (diminution of angiosperm pollens and predominance of modern families) and the disappearance of dinosaurs mark the end of the Maastrichtian age in the Amur Region. Late Maastrichtian dinosaur localities from Amur Region are dominated by lambeosaurines, whereas these dinosaurs apparently disappeared from western North America long before the iridium horizon that defines the K/P boundary. This local disappearance is therefore probably due to ecological factors rather than indicating a gradual extinction of the dinosaurs long before the K/P boundary.

Keywords: Far Eastern Russia, Maastrichtian, vertebrate fossils, palaeoenvironment, biostratigraphy.

## 1. Introduction

Since the beginning of the twentieth century, dinosaur remains have been discovered along both the Chinese and Russian banks of Amur River (named Heilongjiang, Black Dragon River, in China). During the summers of 1916 and 1917, the Russian Geological Committee undertook two excavation campaigns at the present-day Chinese Jiayin locality (Fig. 1), leading to the description of two hadrosaurid dinosaurs by Riabinin (1925, 1930*a,b*). Since 1975, several Chinese institutions have undertaken new excavations near Jiayin. From the material collected during these excavations, Godefroit, Zan & Jin (2000, 2001) subsequently de-

scribed the lambeosaurine *Charonosaurus jiayinensis*. Rozhdestvensky (1957) was the first to mention the presence of dinosaur fossils in the Russian part of Amur Region at Blagoveschensk (Fig. 1), and along the banks of Bureya River. In 1984, the Amur Complex Integrated Research Institute (Amur KNII) of the Far Eastern Branch of the Russian Academy of Sciences discovered a very large dinosaur bonebed in the Tzagayan Group at Blagoveschensk. From this site, Bolotsky & Kurzanov (1991) described the lambeosaurine *Amurosaurus riabinini*. In 1990, the same team discovered another dinosaur site in the Tzagayan Group near the village of Kundur (Fig. 1). These dinosaur-bearing sediments have yielded the nearly complete skeleton of a lambeosaurine dinosaur, *Olorotitan arharensis* Godefroit, Bolotsky & Alifanov, 2003. The Kundur

§ Author for correspondence: pascal.godefroit@naturalscience.be

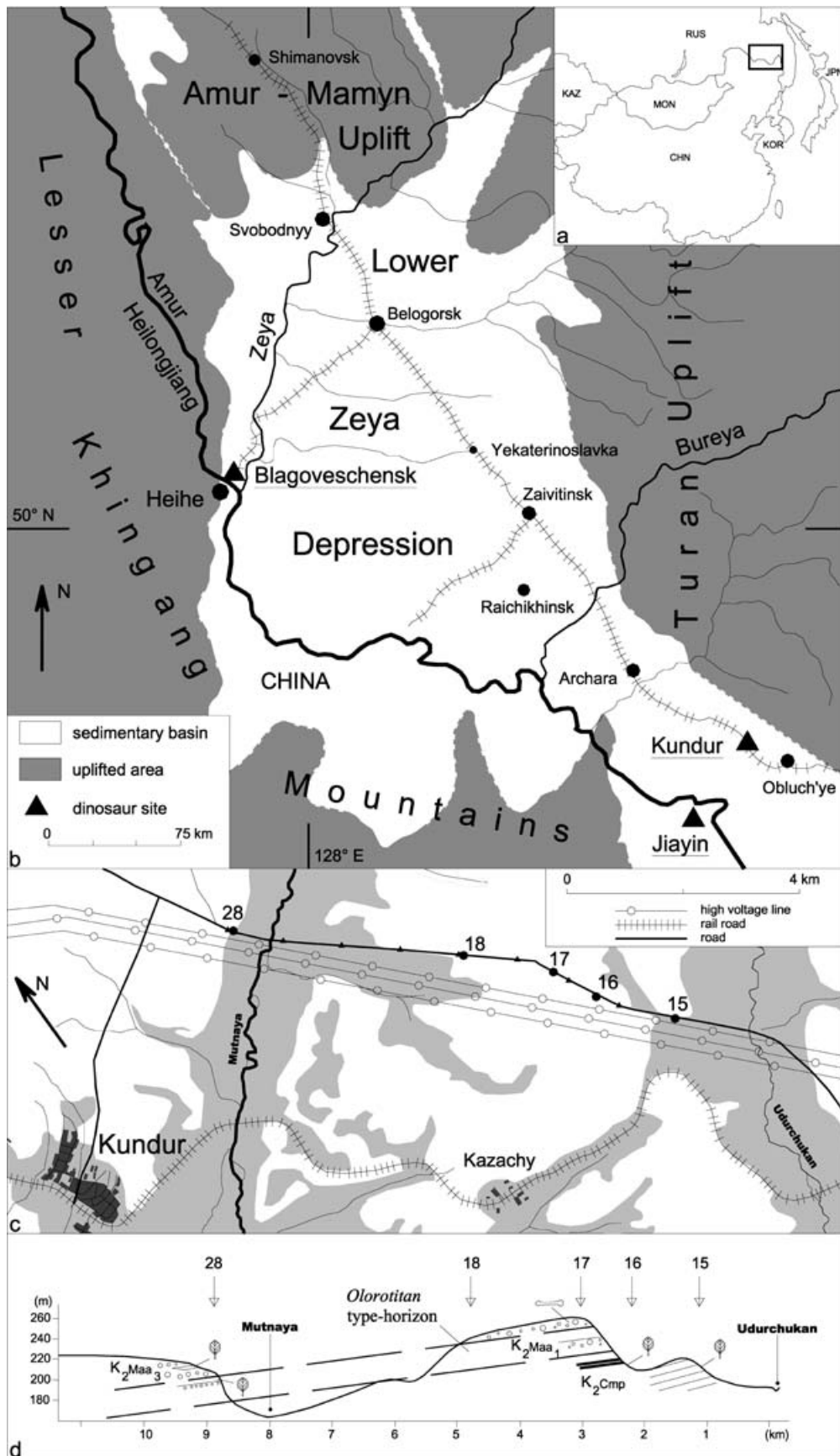


Figure 1. (a) Localization of the study area on the Asian continent. (b) Map of the Lower Zeya Depression (in white) and surrounding mountains (in grey) with the main dinosaur sites (solid triangles). (c) Detailed map of the Kundur area with the localization of the different exposures (numbers adopted from Bugdaeva, 2001), grey hatching indicates quaternary alluvial deposits, white areas indicate outcrop area of pre-quaternary rocks. (d) Simplified profile of the road section at Kundur (for legend, see Fig. 2).

site is especially interesting, because it has yielded the best-preserved dinosaur skeleton from Russia. In addition, this site is situated in a continuous series of exposures of Campanian to Maastrichtian sediments along the Chita–Khabarovsk highway. These exposures allow the study of the contemporary environment of the dinosaurs. The present paper gives an overview of the current state of knowledge with special attention to the sedimentological interpretation of the road sections in the vicinity of the Kundur dinosaur site in order to explain the well-preserved condition of the dinosaur fossils.

## 2. Geological setting

The Zeya-Bureya Basin is located in the southern and southeastern part of the Amur Province of Far Eastern Russia. The basin formed during late Jurassic time as a series of NS-trending graben (Kirillova, Markevich & Bugdaeva, 1997). The rift infill is composed of upper Jurassic and lower Cretaceous volcano-sedimentary deposits, the plate infill is composed of upper Cretaceous and Cenozoic sediments (for an overview, see Crosdale *et al.* 2002, fig. 2), including the Tsagayan Group. The Amur-Mamyn uplift divides the Zeya-Bureya Basin in two parts, the northwestern Amur-Zeya Depression and the southeastern Lower Zeya Depression (Akhmetiev *et al.* 2003, p. 12). However, some authors use the name Amur-Zeya Basin as a synonym for the Zeya-Bureya Basin (Kirillova, 2003; Kirillova, Markevich & Bugdaeva, 1997). Both the Blagoveschensk and Kundur sites are situated in the Lower Zeya Depression near its borders with the adjacent uplifted areas: the Lesser Khingang mountains and the Turan uplift (Moiseenko, Sorokin & Bolotsky, 1997). The name Lesser (or little) Khingang is used indiscriminately for two different mountain ranges: the first forms the western and southern border of the Lower Zeya Depression while the other is NS-trending and comprises the Turpan and Bureya mountains. In the present work, the Lesser Khingang mountains indicate the western and southern border of the Lower Zeya Depression (Fig. 1b).

Different exposures of Campanian to Maastrichtian continental sediments can be found in the vicinity of Kundur village (Fig. 1c, d). The Campanian sediments (exposures 15, 16) belong to the Kundur Formation, which is an equivalent of the upper part of the Zavitaya Formation (Markevich & Bugdaeva, 2001a, p. 80); the Maastrichtian sediments (exposures 17, 18, 28) are attributed to the Udurchukan and Bureya formations, respectively, the lower and middle part of the Tsagayan Group. The age interpretations are based on the micro- and macrofloral content of these exposures, described by Bugdaeva & Markevich (*in* Bugdaeva, 2001). With the enlargement of the Chita–Khabarovsk highway during the summer of 2002, several of the exposures were enlarged. Based on palynological data from a new

sampling (Markevich & Bugdaeva, pers. comm.), the age of exposure 16 has been revised from Maastrichtian to Campanian. In the present paper, the sedimentology, the palaeontology and the age of the sediments in the Kundur section will be discussed.

## 3. Sedimentology of the Kundur site

The exposures of the Kundur section (Fig. 2) discussed in this paragraph are numbered as in Bugdaeva (2001, pp. 29–36), where a short lithological description of the exposures is given. The data presented here were independently gathered during fieldwork, before and after the road works during the summer of 2002. All the palynological and palaeobotanical data cited in the present work have been taken from Bugdaeva (2001).

### 3.a. Exposure 15 (Kundur Formation)

Finely laminated clays, silts and fine sands (Fig. 3b) dominate the oldest sediments in the Kundur section. The sandy laminae, ranging from a few millimetres to 2 cm, are rich in organic detritus at their base. Near the lowest part of the exposure, homogeneous clays and silts are exposed. Channel-form medium-grained sand bodies with an erosive base interrupt the fine-grained sediments. These sands have a maximum thickness of 1 m and wedge out laterally over a distance of 25 m. They stick out in exposure as they are often cemented with calcite (Fig. 3a). The channel-form outline and the flute-marks at the base indicate a W-trending palaeocurrent. A few iron concretions and nodules have been recognized within the finely laminated strata, always 1.2 m below the base of sandy deposit.

The finely laminated sediments were most likely deposited in a lacustrine environment. Conchostracans and ostracods, reported from these strata (Markevich & Bugdaeva, 2001b), corroborate this hypothesis. The sandy channels are indicative of a fluvial influence; the association with redox features like iron nodules and concretions attest to periodical subaerial exposure.

In exposure 15, the best-preserved plant remains (see Table 1) have been mostly found within the sandy channel deposits and not within the finely laminated lacustrine sediments, so the plants within these channels probably represent the riparian flora. The absence of charophytes within the lacustrine strata has an ecological significance. Charophytes thrive in standing waters with low nutrient contents (Bornette & Arens, 2002) and occupy niches unsuited for higher aquatic plants (Coops, 2002). The abundant organic matter and the occurrence of aquatic plants like *Quereuxia* make the environment at Kundur unsuited for charophytes.

### 3.b. Exposure 16 (Kundur Formation)

Prior to the road works, exposure 16 was rather small and densely vegetated. During the summer of

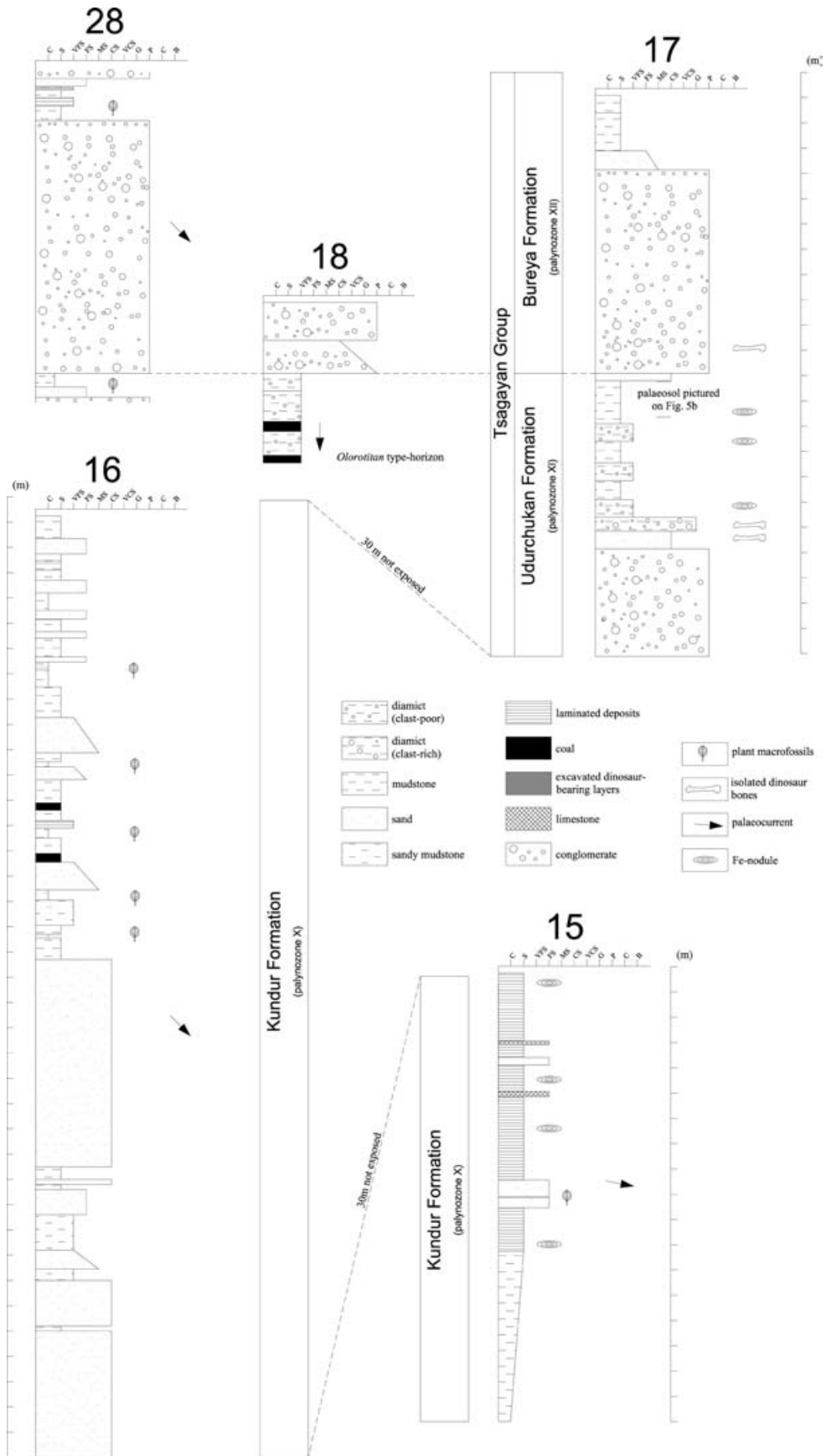


Figure 2. Lithostratigraphical column of the road section at Kundur; width indicates the granulometry, biostratigraphy of the sections based on Akhmetiev *et al.* (2003). For exact location of the exposures (numbered in bold), see Figure 1.



Figure 3. Exposure 15: (a) general view with cemented sand beds sticking out (height of the exposure = 4 m); (b) detail of the laminated clays (width of handle = 3.5 cm).

2002, the exposure was stripped of its vegetation and considerably enlarged. Thick cross-bedded sandy deposits dominate the lower half of this exposure.

Table 1. Plant macrofossils found in the Kundur section (based on Bugdaeva, 2001)

Outcrop	Plant macrofossils	Type
KUN 28 (upper)	<i>'Cephalotaxopsis'</i> sp.	3
	<i>Czekanowskia</i> sp. nov.	3
	<i>Diplophyllum amurense</i>	1
	<i>Elatocladus talensis</i>	3d
	<i>Equisetum</i> cf. <i>arctum</i>	2
	<i>'Platanus'</i> <i>raynoldsii</i>	4
	<i>Nyssa</i> cf. <i>bureica</i>	4
	<i>Taxodium</i> sp.	3d
	<i>Trochodendroides</i> ex gr. <i>artica</i>	4
KUN 28 (lower)	<i>Celastrinites</i> sp.	4d
	<i>Limnobiophyllum scutatum</i>	4a
	<i>Porosia verrucosa</i>	4a
	Taxodiaceae	3d
KUN 16	<i>Celastrinites</i> sp.	4
	<i>'Pistia'</i> <i>corrugata</i>	4a
	<i>Cupressinocladus cretaceus</i>	3
	<i>Limnobiophyllum scutatum</i>	4a
	<i>Liriophyllum</i> sp.	4
	<i>Macclintokia</i> sp. 1	4
	<i>Porosia verrucosa</i>	4a
	<i>Quereuxia angulata</i>	4ad
	<i>Taxodium olrikii</i>	3d
<i>Trochodendroides</i> sp. 1	4d	
<i>Trochodendroides</i> sp. 2	4	
KUN 15	<i>Asplenium</i> sp.	2
	<i>Cephalotaxopsis</i> aff. <i>minima</i>	3
	<i>Dicotylophyllum</i> sp.	4
	<i>Ginkgoites</i> sp.	3
	<i>Pityostrobus</i> sp.	3
	<i>'Platanus'</i> <i>raynoldsii</i>	4
	<i>Sequoia</i> sp.	3
<i>Trochodendroides arctica</i>	4	

1 – Bryophyta; 2 – Pteridophyta; 3 – Gymnospermae; 4 – Angiospermae; a – aquatic; d – dominant in assemblage.

Measurements of these cross-beds indicate a SE-trending palaeocurrent (Fig. 4a). The upper half is more heterogeneous and consists of an irregular alternation of clays, silts and finer sands. Finely laminated fine-grained sediments, the dominant facies of exposure 15, are uncommon. The most striking feature of this exposure is the frequent occurrence of organic-rich layers, including two coal layers. Five of them proved to be rich in plant macrofossils (Fig. 4b). The fossil plant assemblage is dominated by *Trochodendroides* sp. 1, *Taxodium olrikii* and *Quereuxia angulata* (see Table 1). The latter is a typical aquatic plant (Stockey & Rothwell, 1997) and *Taxodium* is typical of wetland habitats (Frederiksen, 1985). The dominance of these plants is therefore indicative of a wetland environment.

All plant-bearing layers have also yielded small amounts of fossil amber. Representatives of Taxodiaceae and Hamamelidaceae, known to generate fossil amber (Martinez-Declos, Briggs & Penalver, 2004), have been found in every layer. The exact nature of the amber at the Kundur locality has not yet been established.

The sediments of exposure 16 were deposited in a fluvial environment. The coarse- to medium-grained sandy deposits represent channel facies; the clays, silts and fine sands represent a wide variety of floodplain sediments. The finely laminated sediments represent standing water bodies (ponds, small lakes) on the floodplain. The organic-rich layers and especially the coal layers represent ancient histosols (Mack, James & Monger, 1993). These organic soils occur nowadays in almost every climatic setting but are indicative of a wetland environment with a high water table (Driessen *et al.* 2001), corroborating the palaeobotanical data.

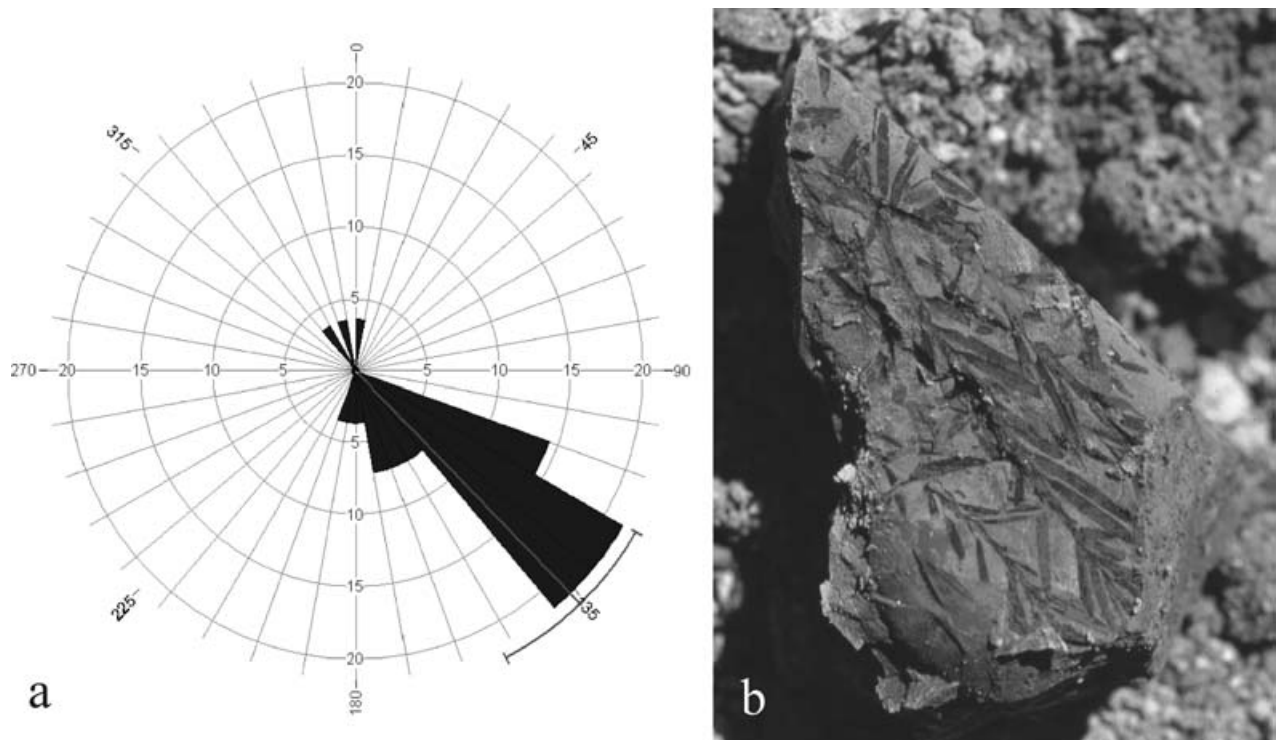


Figure 4. Exposure 16: (a) palaeocurrent direction in the lower sandy part of the exposure; (b) *Taxodium olrikii* (length of specimen = 10 cm).

### 3.c. Exposure 17 (Udurchukan and Bureya formations)

Yellow gravels form more than half of the exposure (Fig. 5a). They consist of rounded metamorphic and felsic magmatic pebbles and cobbles. The non-gravelly strata are dominated by unsorted siliciclastic sediments with coarse particles dispersed in a muddy matrix, so-called diamicts. Based on the clast size and quantity, clast-poor (<20% clasts, clasts <2 cm) and clast-rich varieties have been recognized. The remainder of the exposures are composed of coarse yellow sands, grey silts and clays. Eroded dinosaur bones and bone fragments are frequently found within the gravels and sands, whereas one well-preserved bone was found within a clast-rich diamict (Fig. 5e).

Palynomorph data (Markevich & Bugdaeva, 2001a) indicate that the basal contact of the upper gravel corresponds with the beginning of the Bureya Formation, whereas the lower part of the exposure belongs to the Udurchukan Formation. Just below this contact, a palaeosol has been recognized (Fig. 5b). The good horizonation, the absence of coal and soluble mineral accumulation, the poor *in situ* mineral alteration, the illuviation of clay and the fluctuating redox conditions attribute this palaeosol to the argillisol soil order (Mack, James & Monger, 1993), the equivalent of present-day *ulti-* and *alfisols*. These recent soil orders can only be distinguished on the basis of their base saturation. In fossil soils, this is impossible to measure and therefore Mack, James & Monger (1993) regrouped these

soil orders under the term *argillisols*. According to Retallack (1988), the absence or presence of chemically unstable minerals, such as feldspars, can be used as a proxy for base saturation. XRD-analysis of the soil horizons demonstrated the absence of feldspar in the clay fraction, indicative of a low base status, whereas feldspar and quartz form the principal non-clay minerals in the clay fraction in all the other samples from the Kundur section. Thus the palaeosol can be classified as a *dystric argillisol* (Mack, James & Monger, 1993), which is the fossil equivalent of the recent *ultisols*. Like these present-day soils, the studied palaeosol displays reddish colours resulting from the presence of iron oxides. Although *ultisols* can occur in any soil moisture and temperature regime except aridic, they are best developed under warm and humid climates with a seasonal deficit of precipitation (Soil Survey Staff, 1999). According to Mack & James (1994), *argillisols* occur within the wet equatorial and the moist mid-latitude climatic belt. At Kundur, palynological data also indicate a subtropical climate (Markevich & Bugdaeva, 2001b) during the deposition of the Udurchukan Formation. The absence of vertic features in the smectite-rich palaeosol suggests generally humid conditions. The presence of redoximorphic features like iron nodules (Fig. 5d) corroborates this hypothesis. In a small road cut, not separately numbered and located between exposure 17 and 18, an organic-rich layer underlain by an albic horizon with root traces has been

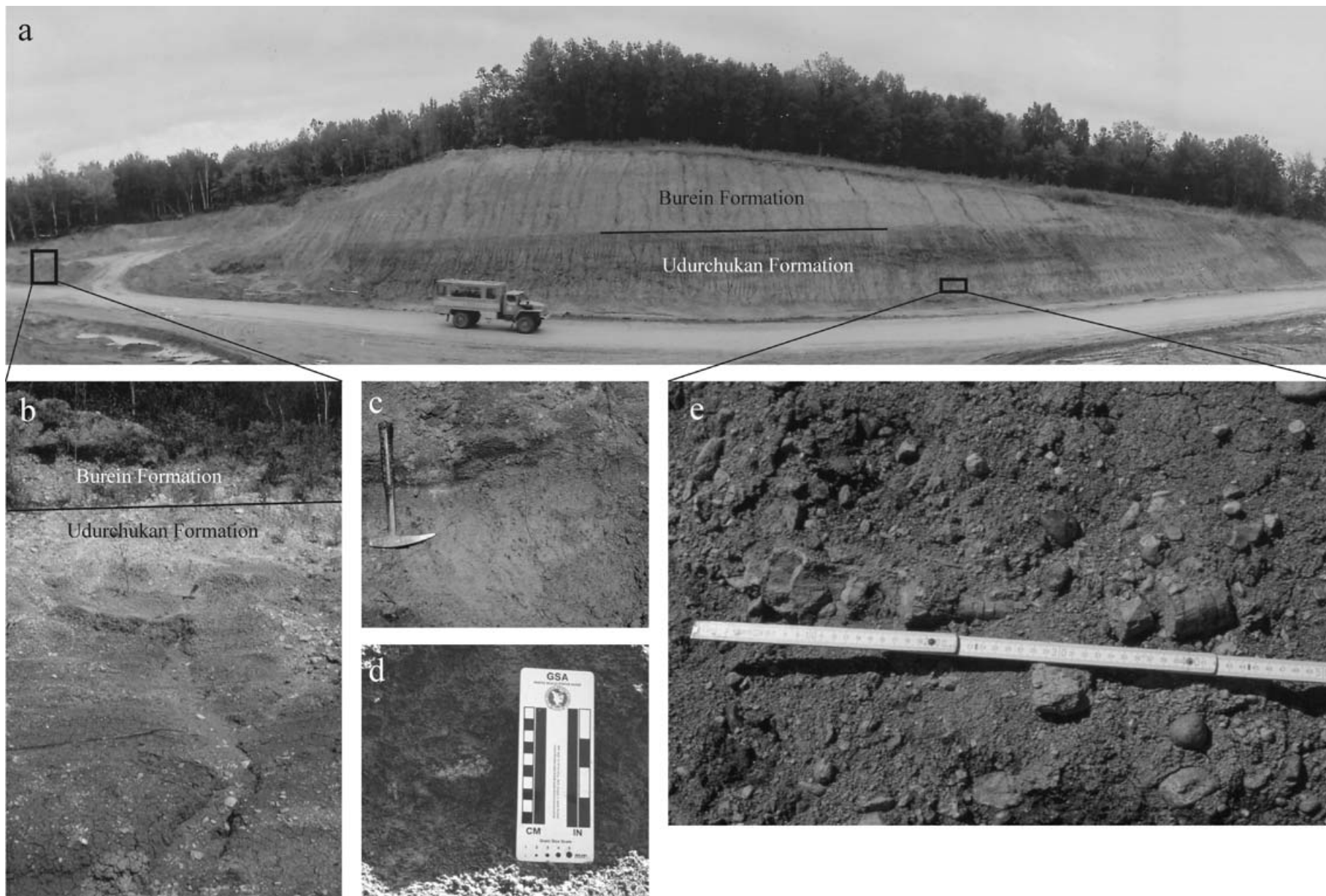


Figure 5. Exposure 17: (a) general overview with yellow gravels and grey fine-grained sediments; (b) dystric argillisol at the top of the Udurchukan Formation (depth of the soil profile = 2 m, see Fig. 2); (c) histol comprising an organic-rich layer underlain by an albic horizon with root traces (length of hammer = 35 cm); (d) iron nodule in clast-poor diamict; (e) dinosaur bone in clast-rich diamict.

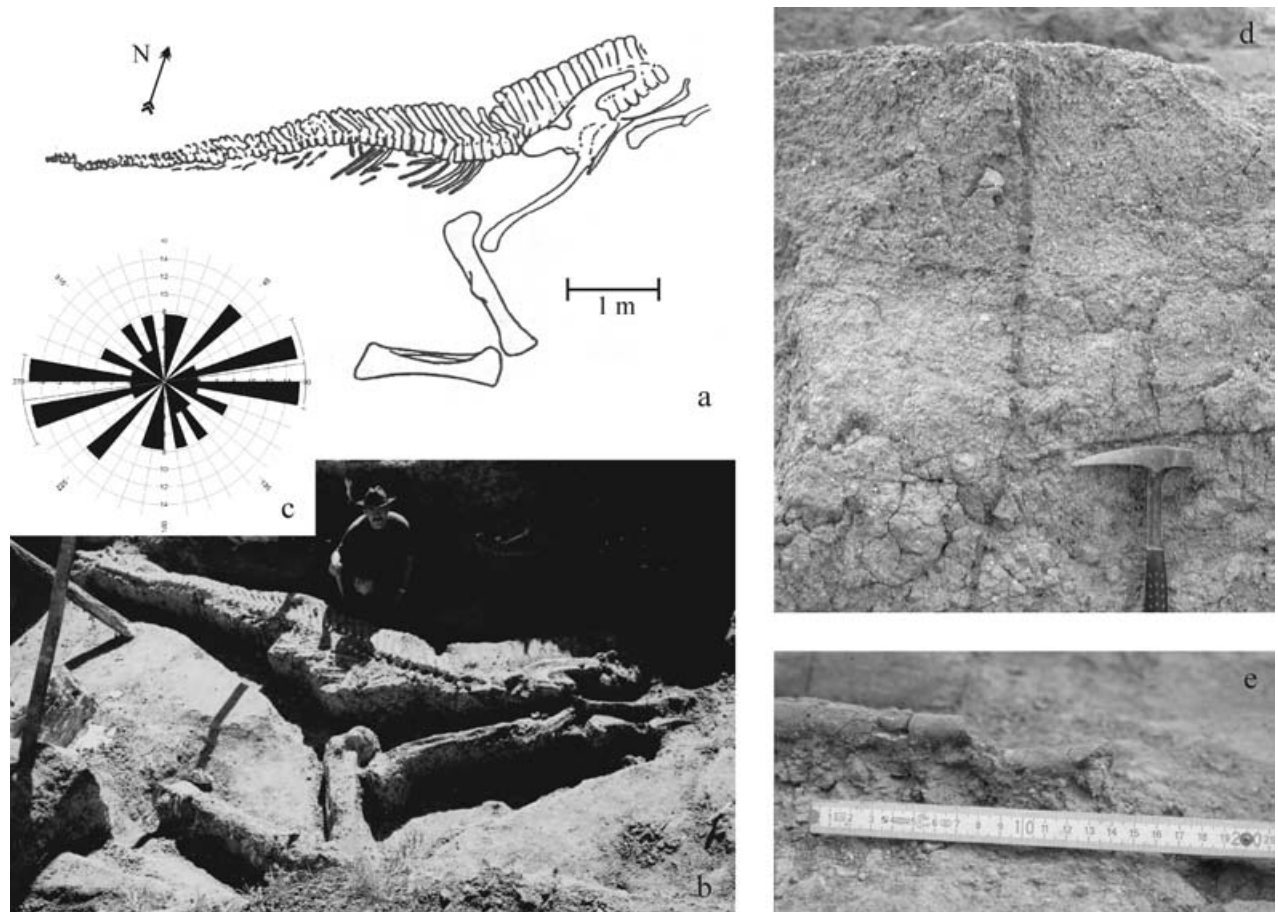


Figure 6. Exposure 18: (a) sketch of part of the *Olorotitan* skeleton excavated during summer of 2000; (b) picture of skeleton sketched in (a); (c) orientation of dispersed bones; (d) detail of dinosaur-bearing clast-poor diamict with rusty-coloured joints; (e) minor fault along a joint displacing part of a dinosaur rib.

observed (Fig. 5c). This histol attests to at least local humid conditions. Unlike in exposure 16, histosols are no longer the dominant feature in exposure 17. Thus the sedimentary environment of the exposure cannot be interpreted as a fluvial wetland but as a more dry alluvial plain of a major river responsible for the gravel deposits. Based on the general facies assemblage, this river can be tentatively classified as a 'gravel-meandering river' (Miall, 1985, 1996, fig. 8.8E). Although the sediments indicate a drier (more drained) environment for the Udurchukan than for the Kundur Formation, the occurrence of *Taxodium* and aquatic plants does indicate generally humid conditions.

### 3.d. Exposure 18 (Udurchukan Formation)

The main fossil site occurs 3.25 m below the contact with the Bureya Formation and has yielded sub-complete dinosaur skeletons together with a mixture of isolated bones. Both have an EW-orientation (Fig. 6a–c) indicating a NS-palaeocurrent. Most of the bones lie in horizontal position but a vertically orientated dentary and rib have been observed. The fossil-bearing sediments consist of an olive-grey muddy matrix,

with scattered very coarse sand particles and pebbles < 2 cm, and can be described as a clast-poor diamict (Fig. 6d). The clays are dominantly smectite with some illite and kaolinite. These strata have a pattern of brown-coloured joints, some of which have evolved to minor faults (Fig. 6e).

The observed mixture of both fine and coarse material is typical for sediment gravity flow deposits. The smectite-rich nature of the mud matrix is very favourable for mass flow deposits (Svendsen *et al.* 2003). The articulated nature of the unearthed *Olorotitan arharensis* skeleton indicates a rapid and *in situ* burial before decomposition of the soft parts, within a few days after death (Koster, 1987). The horizontal orientation of the skeleton and its uniform preservation indicates that it was buried by one event. A sediment gravity flow can account for the rapid burial of such a large animal and even for its death (Loope *et al.* 1998; Loope, Mason & Dingus, 1999). However, the sub-complete nature of the skeleton (the left hindlimb, the right foot, the distal part of the forelimbs, and some dorsal vertebrae and ribs are missing) suggests scavenging prior to burial, implying that the sediment gravity flow was not the cause of death.



The observed sediment gravity flow deposits have the characteristics of both debris flows and hyperconcentrated flows (Dasgupta, 2003). Only areas with a distinct relief can generate debris flows. Recent debris flows show a correlation between the amplitude of the flow and the recurrence interval (Vallance, Cunico & Schilling, 2003): the largest debris flows (with a travel distance of several tens of kilometres) have the largest recurrence interval (in the order of one or two centuries). Their travel distance (5–25 km) is strongly controlled by local topography; debris flows of a given volume will have a larger travel distance in confined steep drainages than in broad drainages with gentle gradients. The height of the region of origin also determines the travel distance of the flow (Iverson, 1997). Uplifted areas, located at a distance of a few tens of kilometres from the Kundur site, are known along the borders of the Lower Zeya Depression. Both the Turpan uplift and the Lesser Khingang mountains are possible source regions for such debris flows. Markevich & Bugdaeva (2001b) consider the palaeo-Khingang mountains (*sensu* Turpan Uplift: Markevich & Bugdaeva, pers. comm.) as the source region of these ancient flows, and this hypothesis is confirmed by the flow data and the position of the Kundur site within the basin. The large distance between the source region and the Kundur site makes the recorded sediment gravity flow deposits exceptional phenomena, if they are indeed debris flows. However, the dominance of diamicts within the lower part of the Tsagayan Group indicates that these sediment gravity flows occurred frequently. One could argue that an event with a recurrence interval of a century or more could be classified as frequent in the geological time scale. However, a more nearby source region for these debris flows cannot be excluded. More detailed palaeogeographical studies need to be conducted to determine the true source region of these sediment gravity flows. Such studies will be severely hampered by the lack of exposures in the present-day landscape.

Zaleha & Wiesemann (2005) have described such deposits from the dinosaur-bearing Cloverly Formation, a low-relief alluvial plain sedimentary environment at a large distance from the mountain front. With the current state of knowledge, the characterization of the sediment gravity flow deposits as hyperconcentrated flows seems more likely, considering their frequent occurrence and the distance to the mountain front.

### 3.e. Exposure 28 (Udurchukan and Bureya formations)

This exposure is the only place in the Kundur section where the internal structure of the gravel (Fig. 7a–c) can be studied, although the quality of this nearly vertical exposure is rapidly declining. The gravels (Fig. 7f) are dominated by lateral accretion surfaces (Fig. 7c) and channel infills (Fig. 7a). The palaeocurrent measurements indicate a SE-trending flow. The dominance of

lateral accretion structures observed within the gravels confirms the classification of the ancient channel as a gravel-meandering type of river. The ancient river shows the same orientation and flow direction as the present-day Amur River.

In the upper gravel bed, a lens of fine-grained material (Fig. 7d) rich in plant macrofossils, with a maximum thickness of 1.3 m, can be observed. These sediments are finely laminated (Fig. 7e) and clearly represent in-channel ponded water deposits after abandonment or during low water stages (which can be considered as a temporary abandonment). Fine-grained sediments, intercalated between two gravel deposits and also rich in plant macrofossils, occur at the base of the exposure. Because of lack of exposures, it is unclear whether the lower fine-grained deposits also have a lenticular outline. However, the more massive nature of the sediments suggests another origin and they are interpreted as floodplain sediments.

### 4. Vertebrate faunal diversity and palaeogeographical implications

The first fossil bones were discovered in 1990, but systematic excavations of this vertebrate locality have been undertaken from 1999 by the palaeontological team of the AmurKNII FEB RAS, in cooperation with the Royal Belgian Institute of Natural Sciences, the Paleontological Institute RAS (Moscow), the Institute of Biology and Pedology FEB RAS (Vladivostok), and the Zoological Institute RAS (St Petersburg).

Lambeosaurine dinosaurs are the dominant vertebrates in this locality. The most spectacular find is the sub-complete skeleton of *Olorotitan arharensis* Godefroit, Bolotsky & Alifanov, 2003 that was unearthed during the 2000 and 2001 field campaigns. *Olorotitan* is the sister-taxon of *Corythosaurus* and *Hypacrosaurus*, from the late Campanian of western North America (Godefroit, Bolotsky & Alifanov, 2003). A second sub-complete skeleton, belonging to a smaller, thus probably younger, lambeosaurine specimen, was unearthed at exposure 18 in 2003. Disarticulated lambeosaurine bones are dispersed around the sub-complete specimens. The holotype of *Olorotitan arharensis* was a relatively old adult when it died: the scapulae and coracoids are completely fused together and, with a calculated length of 8 m and a height at the hip of 3.5 m, it was a rather large animal. Besides this specimen, the Kundur locality has yielded lambeosaurine bones belonging to different age classes. In the Blagoveschensk locality, on the other hand, the lambeosaurine assemblage is apparently characterized by an over-representation of juveniles, whereas fossils belonging to large adult specimens are rare. The size–frequency distribution of lambeosaurine bones from both Kundur and Blagoveschensk localities is currently under study by Lauters *et al.* In dinosaurs, size–frequency distributions are used as approximations for

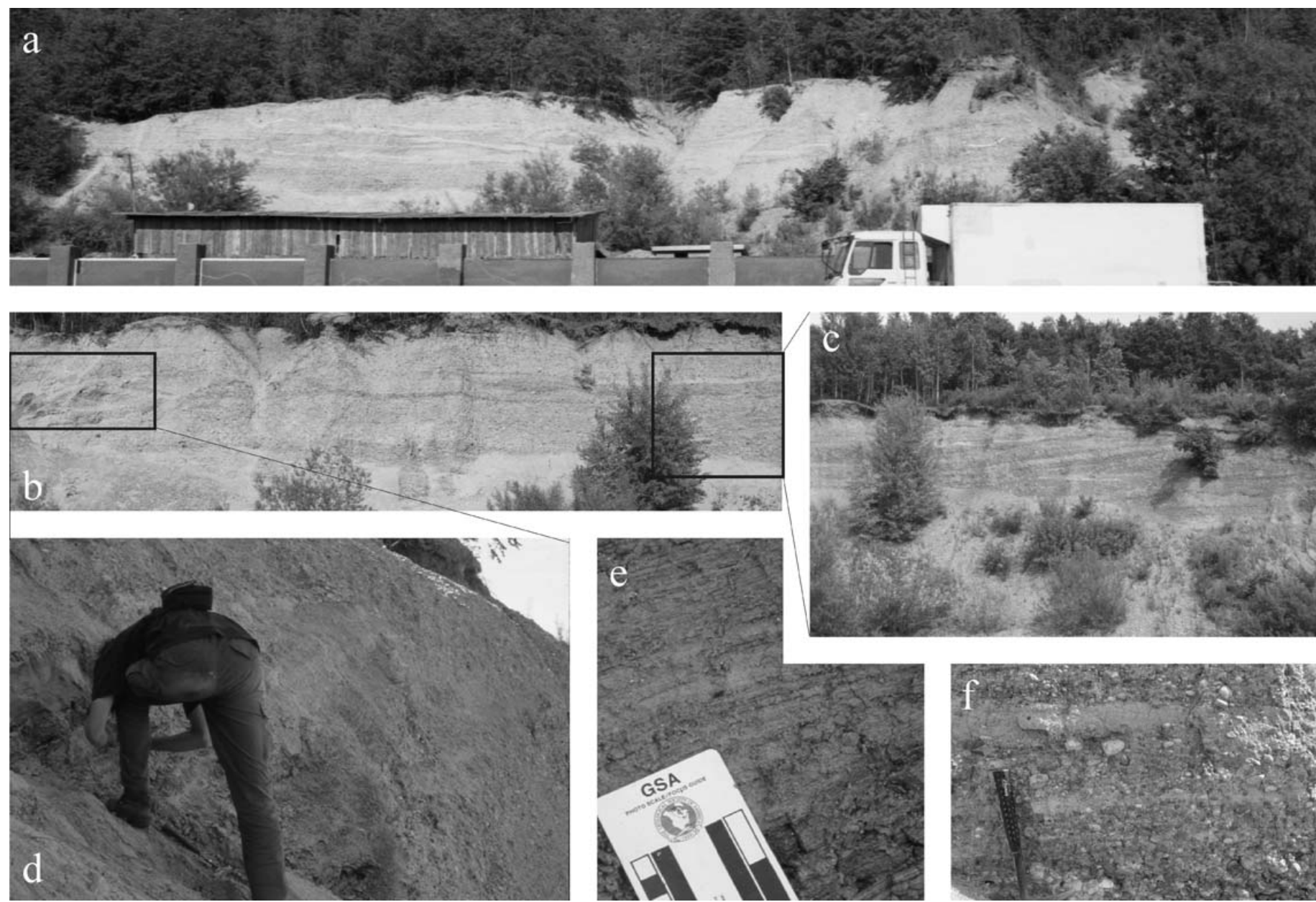


Figure 7. Exposure 28: (a) view of northern part with lateral accretion surfaces and channel infills; (b) view of southern part (height of the vertical cliff = 10 m); (c) detailed view of lateral accretion surfaces (height of the vertical cliff = 10 m); (d) detailed view of lens with plant macrofossils; (e) detail of finely laminated sediments within the lens; (f) detail of the gravel.

age profiles and have proved useful in the interpretation of the taphonomy of bonebeds (Rogers, 1990; Varricchio & Horner, 1993). Flat-headed hadrosaurine dinosaurs are also represented at Kundur by one partial skull, one complete pelvic girdle and many disarticulated elements. These fossils are currently under study. They do not belong to *Kerberosaurus manakini* Bolotsky & Godefroit, 2004, originally described from the Blagoveschensk locality. Carrano, Janis & Sepkoski (1999) suggest that lambeosaurines and hadrosaurines lived in different habitats. By comparison with present-day ungulates, they consider the monomorphic hadrosaurines as open-habitat gregarious animals, whereas dimorphic lambeosaurines are seen as more solitary animals preferring a more closed habitat with possible male territoriality. The co-occurrence of sub-complete skeletons belonging to both lambeosaurines and hadrosaurines in the same layers of exposure 18 at Kundur is in contradiction with this theory, rather indicating that these animals could be sympatric, frequenting the same kinds of habitats.

Ankylosaurian dinosaurs are represented by a single osteodermal scute and two isolated teeth. This material was tentatively assigned to the Nodosauridae family (Tumanova, Bolotsky & Alifanov, 2004). If this identification is correct, it would be the first nodosaurid specimen ever discovered in Asia.

Theropod dinosaurs are represented at Kundur by isolated teeth and one single fourth cervical vertebra. According to Alifanov & Bolotsky (2002) and to Akhmetiev *et al.* (2003), the following taxa are represented at Kundur: Dromaeosauridae (cf. *Saurornitholestes* sp. and cf. *Dromaeosaurus* sp.), Tyrannosauridae (cf. *Tarbosaurus* sp., '*Albertosaurus*' *periculosus*, *Aublysodon* sp. 1 and 2), Troodontidae (*Troodon* sp.) and *Richardoestesia* sp. 1 and 2 (Theropoda fam. indet.). By comparison with the theropod assemblage from the Nemegt Formation in Mongolia, Alifanov & Bolotsky (2002) suggest a pre-Maastrichtian age for the dinosaur-bearing sediments in Amur Region. However, we believe that these results must be cautiously considered, because identification of isolated theropod teeth is always hazardous and because theropod tooth morphotypes are known to have a wide stratigraphic range (Codrea *et al.* 2002).

The lindholmemydid turtle *Amuremys planicostata* (Riabinin, 1930b) is known at Kundur from about 100 specimens, mainly fragmentary plates (Danilov *et al.* 2002). Lindholmemydids are Cretaceous to Paleocene testudinoid turtles known only in Asia. They occupy a special place among Asian turtles, because of their occurrence in mass burials during the late Cretaceous and because they apparently crossed the K/P boundary without any problem (Sukhanov, 2000). Crocodile shed teeth are also relatively abundant at Kundur. Akhmetiev *et al.* (2003) refer these teeth to the Paralligatoridae family, but this identification needs to be confirmed.

The sediments surrounding the dinosaur bones at Kundur were carefully screen-washed, leading to the discovery of the first mammal fossil from the late Cretaceous of Russia. Averianov, Bolotsky & Godefroit (2002) identified this tooth fragment as the posterior part of right p4 of a Cimolodonta multituberculate. This specimen is most similar to *Stygimys*, a Paleocene Eucosmodontidae from North America, and to Microcosmodontidae, from the late Cretaceous–Paleocene of North America.

Several elements in the composition of the Kundur vertebrate fauna therefore suggest a strong influence of the North American late Cretaceous vertebrate communities: the abundance of corythosaur-like lambeosaurines, the probable presence of a nodosaurid dinosaur and of a eucosmodontid or microcosmodontid multituberculate. A land route between eastern Asia and western North America across the Beringian isthmus probably opened during the Aptian–Albian and persisted during most of late Cretaceous time (Jerzykiewicz & Russell, 1991; Russell, 1993), allowing faunal exchanges both from west to east and from east to west (Bolotsky & Godefroit, 2004).

##### 5. Age of the dinosaur-bearing sediments

The dinosaur-bearing sediments from the Udurchukan Formation in Amur Region belong to the *Wodehouseia spinata*–*Aquilapollenites subtilis* palynozone, as defined by Markevich (1994, 1995). Markevich & Bugdaeva (1997, 2001b) date this palynozone as middle Maastrichtian. The dinosaur-bearing Juliangze Formation exposed at Jiayin on the Chinese side of the Amur River belongs to the same palynozone (Godefroit, Zan & Jin, 2000, 2001; Markevich & Bugdaeva, 2001a, p. 80). Recently, the ages of the different sites have been revised: although the three sites belong to the same *Wodehouseia spinata*–*Aquilapollenites subtilis* palynozone, Kundur and Jiayin are dated as early Maastrichtian, whereas Blagoveschensk is dated as middle Maastrichtian (Akhmetiev *et al.* 2003, p. 18; Bugdaeva, 2001). The proposed ages are based on comparisons with other palynological assemblages in neighbouring basins (Markevich, 1994). To date, none of these age estimations of the palynozones in Far Eastern Russia has been calibrated by radiometric dating or palaeomagnetostigraphy.

The end of the *W. spinata*–*A. subtilis* palynozone is marked, in Amur Region, by the disappearance of dinosaur fossils (Bugdaeva *et al.* 2000) and by important floristic changes, including a sharp reduction in 'unica' and 'oculata' pollens (for terminology, see Hengreen & Chlonova, 1981 and Hengreen *et al.* 1996), a reduction in angiosperm pollen and the dominance of modern families like Ulmaceae, Platanaceae, Betulaceae, Juglandaceae and Fagaceae (Markevich & Bugdaeva, 2001b). In North America, the same floristic changes as those observed at the

end of the Asian *W. spinata*–*A. subtilis* palynozone coincide with the K/P boundary (Braman & Sweet, 1999; Nichols, 1990; Nichols, 2002; Nichols & Sweet, 1993; Sweet, Braman & Lerbekmo, 1999; Tschudy & Tschudy, 1986), which is now firmly established by the Iridium-spike and associated features (Bohor *et al.* 1984, 1987; Gilmore *et al.* 1984; Jerzykiewicz & Sweet, 1986; Lerbekmo, 1999; Lerbekmo, Evans & Baadsgaard, 1979a; Lerbekmo, Sweet & Louis, 1987; Lerbekmo, Sweet & Davidson, 1999; Nichols & Fleming, 1990; Nichols *et al.* 1986; Orth *et al.* 1981; Pillmore *et al.* 1984; Sweet, Braman & Lerbekmo, 1999). The floristic changes related to the K/P boundary can be recognized in different climatic settings and at different latitudes within the Western Interior Basin (Sweet, Braman & Lerbekmo, 1990). During Late Cretaceous time, Far Eastern Russia and the Western Interior Basin of North America were part of the same palaeofloristic province, the *Aquilapollenites* province (Herngreen & Chlonova, 1981; Herngreen *et al.* 1996). Therefore, similar palynological changes are expected at the K/P boundary everywhere in this palaeofloristic province. Indeed, Saito, Yamanoi & Kaiho (1986) observed similar palynological changes in a marine K/P boundary section, calibrated on foraminiferal evidence, in eastern Hokkaido, Japan.

The problem of the coincidence of the extinction of non-avian dinosaurs with the K/P boundary in North America is still intensively debated, although a multitude of papers have already been written about this subject. As far as we know, dinosaur extinctions were a worldwide phenomenon, but direct evidence for this event comes principally from the Hell Creek Formation, in two counties in Montana (Dodson & Tatarinov, 1990). Therefore, what we currently know about the tempo of dinosaur extinction is based on data principally collected in a very limited area. According to Clemens & Archibald (1980), dinosaurs disappeared from the Western Interior Basin before the K/P boundary, on the basis of the so-called ‘3 m gap’ at the top of the Hell Creek Formation. However, their arguments were subsequently refuted: Sheehan *et al.* (2000) report the discovery of several dinosaur bones within this interval. In any case, whether or not the last dinosaur trace discovered in the Hell Creek Formation strictly coincides with the K/P boundary, dinosaurs were still abundant and diversified during the latest Maastrichtian in Montana (see Russell & Manabe, 2002). On the other hand, several authors (e.g. Rigby *et al.* 1987; Russell & Singh, 1978; Sloan *et al.* 1986; Van Valen, 1988) claimed to have proven the existence of dinosaurs above the K/P boundary in different places in the world. In all cases, fossils are disarticulated and very scarce, probably reworked in Palaeogene deposits (e.g. Dodson & Tatarinov, 1990; Eaton, Kirkland & Doi, 1989; Lerbekmo *et al.* 1979b). In Asia, Zhao *et al.* (2002) claimed to have found multiple Ir-anomalies and Palaeogene dinosaurs.

Buck *et al.* (2004) proved that the late Cretaceous sediments with enclosed dinosaur eggshell fossils have been reworked in the Palaeogene and so refuted the existence of Palaeogene dinosaurs in Asia. To close this discussion, Dodson & Tatarinov (1990) wisely state that ‘Whether or not any individuals straggled across the K/T boundary, there seems no doubt that in an ecological sense, the dinosaur chronofauna terminated at the end of the Cretaceous’.

Therefore, both the floristic changes and the disappearance of dinosaur fossils occurring at the end of the Asian *W. spinata*–*A. subtilis* palynozone suggest a late Maastrichtian age for the dinosaur-bearing sediments in Amur Region, as already proposed by Godefroit, Jan & Zin (2000, 2001), Godefroit, Bolotsky & Alifanov (2003) and Godefroit, Bolotsky & Van Itterbeeck (2004). These authors observed that, among the angiosperm palynomorphs listed at Kundur (Markevich & Bugdaeva, 2001a), eight are characteristic for the *Wodehouseia spinata* assemblage zone in the United States (Nichols, 2002; Nichols & Sweet, 1993): *Aquilapollenites reticulatus*, *A. quadrilobus*, *A. conatus*, *Orbiculapollis lucidus*, *Ulmipollenites krempii*, *Wodehouseia spinata*, *Proteacidites thalmanii* and *Erdtmanipollis albertensis*. The *Wodehouseia spinata* assemblage zone (Nichols, 2002 and references therein) is the palynostratigraphic zone that represents late Maastrichtian time in continental rocks in western North America, including the Hell Creek Formation. It is recognized across western North America from New Mexico to the Yukon and Northwest Territories (Nichols & Sweet, 1993). It was demonstrated that the Ir-anomaly at the K/P boundary also falls within the *Wodehouseia spinata* assemblage zone in the Western Interior Basin (Lerbekmo, Sweet & Louis, 1987; Nichols *et al.* 1986). *Aquilapollenites conatus*, recorded both at Blagoveschensk and Kundur, is also interesting from a biostratigraphic point of view and speaks for a late Maastrichtian age for this dinosaur locality. Indeed, this species is restricted to the upper half of the *Wodehouseia spinata* assemblage zone in North Dakota (subzones C to E: Nichols, 2002) and in Alberta (subzone VIIIa: Srivastava, 1970). In Manitoba, it appears in the upper part of the *Porosipollis porosus*–*Aquilapollenites notabile* Subzone of the *Wodehouseia spinata* range zone (Braman & Sweet, 1999).

A late Maastrichtian age for the Udurchukan Formation, as postulated in the present study, implies a younger (possibly Danian) age for the Bureya Formation, a possibility already discussed by Vakhrameev (1991, p. 192).

The top of the *Wodehouseia spinata*–*Aquilapollenites subtilis* palynozone is characterized by a hiatus at Kundur. Therefore, more complete sections should be investigated in Amur Region for independent calibration points (Ir-spike, shocked quartz, radiometric datings, magnetostratigraphy) to solve this problem. These calibrations have to prove the diachroneity

between Asian and North American palynozones in order to confirm the early–middle Maastrichtian age, as proposed by Markevich (1994). Recent investigations in the Amur Region have led to the selection of potential K/P boundary sections, including the Baishantou section (Sun *et al.* 2002). Absolute age estimates based on fission tracks (Suzuki, 2004) and radiometric dating (Li *et al.* 2004) in these selected K/P boundary sections indicate that at least part of the Bureya Formation and equivalent strata in China (middle Tsagayan) are Danian in age, indicating that the K/P boundary is situated lower than previously thought (Sun *et al.* 2004).

## 6. Conclusions

During the deposition of the sediments in the Kundur section, the climate showed a distinct cooling and evolved from humid subtropical to humid temperate conditions (Markevich & Bugdaeva, 2001*b*). The sedimentary environment shows a distinct drying trend and evolves from lacustrine over wetland to well-drained alluvial settings. These alluvial deposits can be classified as a ‘gravel-meandering’ river (*sensu* Miall, 1996). Sediment gravity flows regularly occurred in the uplifted areas bordering the sedimentary basin. The largest of these flows arrived onto the floodplain and were responsible for the concentration, burial and preservation of the dinosaur remains. Both dispersed and anatomically connected elements have been found within these sediment gravity flow deposits. Although channel deposits often form productive horizons for vertebrate fossils (Behrensmeyer, 1982), they have only yielded eroded and reworked dinosaur bones in the Kundur section.

The abundance of corythosaur-like lambeosaurines at Kundur and the probable presence of a nodosaurid dinosaur and of a eucosmodontid or microcosmodontid multituberculate indicate faunal exchanges with North American late Cretaceous vertebrate communities. Based on the new hadrosaurine material of the Blagoveschensk locality, migrations of several hadrosaurid lineages from western North America to Asia were proposed by Bolotsky & Godefroit (2004). The vertebrate fauna at Kundur confirms these migration ways. However, if a late Maastrichtian age can be accepted for the Kundur dinosaur assemblage, as suggested in the present paper, important differences can be observed with potential synchronous dinosaur faunas from western North America. In Kundur and in other localities from Amur Region, lambeosaurine dinosaurs dominate the vertebrate fauna. Surprisingly, there is no indication of the presence of ceratopsian or titanosaurid dinosaurs in the thousands of dinosaur bones collected in the different latest Cretaceous localities of the Amur Region. In any case, even if these groups are represented in Amur Region, they form only a minor part of the latest Cretaceous dinosaur fauna in

this area. On the other hand, ceratopsian dinosaurs, including *Triceratops*, *Torosaurus* and *Leptoceratops* (Lehman, 1987; Russell & Manabe, 2002) usually dominate the late Maastrichtian dinosaur faunas in western North America. Hadrosauridae are usually also well represented by members of the edmontosaur clade (*Edmontosaurus* and *Anatotitan*). The ‘titanosaurid’ sauropod *Alamosaurus* also characterizes late Maastrichtian dinosaur assemblages in Utah, New Mexico, Colorado and Texas. Lambeosaurinae apparently disappeared from western North America by late Maastrichtian time, or are represented only by scarce and doubtful material (Boyd & Ott, 2002; Russell & Manabe, 2002). It may therefore be concluded that the absence of lambeosaurine dinosaurs in late Maastrichtian deposits from North America is probably due to ecological factors rather than indicating a gradual extinction of the dinosaurs beginning long before the K/P boundary.

**Acknowledgements.** This study was realized through the execution of S&T bilateral cooperation agreements on behalf of the Belgian State, Federal Scientific Policy. The excavations at the Kundur locality were also supported by a grant from the National Geographic Society. The authors thank all the participants in the field campaigns at Kundur, and particularly Valentina Markevich and Evgenia Bugdaeva for their support and fruitful discussions. Dale A. Russell reviewed the manuscript and his comments significantly improved the paper.

## References

- AKHMETIEV, M. A. (ed.), BOLOTSKY, Y. L., BUGDAEVA, E. V., GOLOZOUBOV, V. V., KEZINA, T. V., KODRUL, T. M., MARKEVICH, V. S. & SOROKIN, A. P. 2003. *The 2nd International Symposium on Cretaceous biota and K/T-boundary in Amur (Heilongjiang) River area*. Blagoveschensk: Geos, 36 pp.
- ALIFANOV, V. R. & BOLOTSKY, Y. L. 2002. New data about the assemblages of the Upper Cretaceous carnivorous dinosaurs (Theropoda) from the Amur Region. In *Cretaceous continental margin of East Asia: stratigraphy, sedimentation, and tectonics* (ed. G. L. Kirillova), pp. 25–6. Khabarovsk: Unesco-IUGS-IGCP.
- AVERIANOV, A. O., BOLOTSKY, Y. L. & GODEFROIT, P. 2002. First multituberculate mammal from Russia. In *Cretaceous continental margin of East Asia: stratigraphy, sedimentation, and tectonics* (ed. G. L. Kirillova), pp. 27–8. Khabarovsk: Unesco-IUGS-IGCP.
- BEHRENSMEYER, A. K. 1982. Time resolution in fluvial vertebrate assemblages. *Paleobiologie* **8**(3), 211–27.
- BOHOR, B. F., FOORD, E. E., MODRESKI, P. J. & TRIPLEHORN, D. M. 1984. Mineralogic evidence for an impact event at the Cretaceous–Tertiary boundary. *Science* **224**, 867–9.
- BOHOR, B. F., TRIPLEHORN, D. M., NICHOLS, D. J. & MILLARD, H. T. J. 1987. Dinosaurs, spherules, and the ‘magic’ layer: a new K–T boundary clay site in Wyoming. *Geology* **15**, 896–9.
- BOLOTSKY, Y. L. & GODEFROIT, P. 2004. A new hadrosaurine dinosaur from the Late Cretaceous of Far Eastern

- Russia. *Journal of Vertebrate Paleontology* **24**(2), 354–68.
- BOLOTSKY, Y. L. & KURZANOV, S. K. 1991. The hadrosaurs of the Amur Region. In *Geology of the Pacific Ocean Border* (eds V. G. Moiseenko and I. A. Zagruzina), pp. 94–103. Blagoveschensk: AmurKNII, FEBRAS.
- BORNETTE, G. & ARENS, M.-F. 2002. Charophyte communities in cut-off river channels: the role of connectivity. *Aquatic Botany* **73**, 149–62.
- BOYD, C. & OTT, C. J. 2002. Probable lambeosaurine (Ornithischia, Hadrosauridae) specimen from the Late Cretaceous Hell Creek Formation of Montana. *Journal of Vertebrate Paleontology* **22** (suppl. to 3), 38A.
- BRAMAN, D. R. & SWEET, A. R. 1999. Terrestrial palynomorph biostratigraphy of the Cypress Hills, Wood Formation, and Turtle Mountain areas (Upper Cretaceous–Paleocene) of western Canada. *Canadian Journal of Earth Sciences* **36**, 725–41.
- BUCK, B. J., HANSON, A. D., HENGST, R. A. & HU, S. 2004. “Tertiary dinosaurs” in the Nanxiong Basin, Southern China, are reworked from the Cretaceous. *Journal of Geology* **112**, 111–18.
- BUGDAEVA, E. V. 2001. *Flora and dinosaurs at the Cretaceous–Paleogene boundary of the Zeya-Bureya Basin (IGCP project 434)*. Vladivostok: Dalnauka, 162 pp.
- BUGDAEVA, E. V., MARKEVICH, V. S., BOLOTSKII, Y. L. & SOROKIN, A. P. 2000. Extinction of dinosaurs in Cretaceous period: paleobotanists’ view. *Bulletin of the Far Eastern Branch, Russian Academy of Sciences* **1**, 80–8.
- CARRANO, M. T., JANIS, C. M. & SEPKOSKI, J. J. 1999. Hadrosaurs as ungulate parallels: lost lifestyles and deficient data. *Acta Palaeontologica Polonica* **44**, 237–61.
- CLEMENS, W. A. & ARCHIBALD, J. D. 1980. Evolution of terrestrial faunas during the Cretaceous–Tertiary transition. *Mémoires de la Société géologique de France* **139** (new series), 67–74.
- CODREA, V., SMITH, T., FOLIE, A., GARCIA, G., GODEFROIT, P. & VAN ITTERBEECK, J. 2002. Dinosaur egg nests, diapsids and mammals in a new Maastrichtian site of the Hateg Basin (Romania). *Comptes Rendus Palevol* **1**(3), 173–80.
- COOPS, H. 2002. Ecology of charophytes: an introduction. *Aquatic Botany* **72**, 205–8.
- CROSDALE, P. J., SOROKIN, A. P., WOOLFE, K. J. & MACDONALD, D. I. M. 2002. Inertinite-rich Tertiary coals from the Zeya-Bureya Basin, Far Eastern Russia. *International Journal of Coal Geology* **51**, 215–35.
- DANILOV, I. G., BOLOTSKY, Y. L., AVERIANOV, A. O. & DONCHENKO, I. V. 2002. A new genus of lindholmemydid turtle (Testudines, Testudinoidea) from the Late Cretaceous of the Amur River Region, Russia. *Russian Journal of Herpetology* **9**, 155–68.
- DASGUPTA, P. 2003. Sediment gravity flow – the conceptual problems. *Earth-Science Reviews* **62**, 265–81.
- DODSON, P. & TATARINOV, L. P. 1990. Dinosaur extinction. In *The Dinosauria* (eds D. B. Weishampel, P. Dodson and H. Osmolska), pp. 55–62. Los Angeles: University of California Press.
- DRIESSEN, P., DECKERS, J., SPAARGAREN, O. & NACHTERGAELE, F. 2001. *Lecture notes on the major soils of the world*. World Soil Resources Report, 94. Food and Agricultural Organization of the United Nations, Rome, 307 pp.
- EATON, J. G., KIRKLAND, J. E. & DOI, K. 1989. Evidence of reworked Cretaceous fossils and their bearing on the existence of Tertiary dinosaurs. *Palaios* **4**, 281–6.
- FREDERIKSEN, N. O. 1985. Review of early tertiary spore-morph paleoecology. *AASP Contribution Series* **15**, 1–92.
- GILMORE, J. S., KNIGHT, J. D., ORTH, C. J., PILLMORE, C. L. & TSCHUDY, R. H. 1984. Trace element patterns at a non-marine Cretaceous–Tertiary boundary. *Nature* **307**, 224–8.
- GODEFROIT, P., BOLOTSKY, Y. L. & ALIFANOV, V. 2003. A remarkable hollow-crested hadrosaur from Russia: an Asian origin for lambeosaurines. *Comptes Rendus Palevol* **2**, 143–51.
- GODEFROIT, P., BOLOTSKY, Y. L. & VAN ITTERBEECK, J. 2004. The lambeosaurine dinosaur *Amurosaurus riabinini*, from the Maastrichtian (Late Cretaceous) of Far Eastern Russia. *Acta Palaeontologica Polonica* **49**, 585–618.
- GODEFROIT, P., ZAN, S. & JIN, L. 2000. *Charonosaurus jiyinensis* n.g., n.sp., a lambeosaurine dinosaur from the Late Maastrichtian of northeastern China. *Comptes Rendus de l’Académie des Sciences de Paris, Sciences de la Terre et des planètes* **330**, 875–82.
- GODEFROIT, P., ZAN, S. & JIN, L. 2001. The Maastrichtian (Late Cretaceous) lambeosaurine dinosaur *Charonosaurus jiyinensis* from north-eastern China. *Bulletin de l’Institut Royal des Sciences Naturelles de Belgique* **71**, 119–68.
- HERNGREEN, G. F. W. & CHLONOVA, A. F. 1981. Cretaceous microfloral provinces. *Pollen et Spores* **23**(3–4), 441–555.
- HERNGREEN, G. F. W., KEDVES, M., ROVNINA, L. V. & SMIRNOVA, S. B. 1996. Cretaceous palynofloral provinces: a review. In *Palynology: principles and applications* (eds J. Jansonius and D. C. McGregor), pp. 1157–88. American Association of Stratigraphic Palynologists Foundation.
- IVERSON, R. M. 1997. The physics of debris flows. *Review of Geophysics* **35**, 245–96.
- JERZYKIEWICZ, T. & RUSSELL, D. A. 1991. Late Mesozoic stratigraphy and vertebrates of the Gobi basin. *Cretaceous Research* **12**, 345–77.
- JERZYKIEWICZ, T. & SWEET, A. R. 1986. The Cretaceous–Tertiary boundary in the central Alberta Foothills. I: Stratigraphy. *Canadian Journal of Earth Sciences* **23**, 1356–74.
- KIRILLOVA, G. L. 2003. Cretaceous tectonics and geological environments in East Russia. *Journal of Asian Earth Sciences* **21**, 967–77.
- KIRILLOVA, G. L., MARKEVICH, V. S. & BUGDAEVA, E. V. 1997. Correlation of geologic and biologic events in the Cretaceous Basins of Southeast Russia. *Geology of the Pacific Ocean* **13**, 507–26.
- KOSTER, E. H. 1987. Vertebrate taphonomy applied to the analysis of ancient fluvial systems. In *Recent developments in fluvial sedimentology (Contributions from the Third International Fluvial Sedimentology Conference)* (eds F. G. Ethridge, R. M. Flores and M. D. Harvey), pp. 159–68. SEPM Special Publication no. 39.
- LEHMAN, T. M. 1987. Late Maastrichtian paleoenvironments and dinosaur biogeography in the western interior of North America. *Palaeogeography, Palaeoclimatology, Palaeoecology* **60**, 189–217.
- LERBEKMO, J. F. 1999. Magnetostratigraphy of the Canadian Continental Drilling Program Cretaceous–Tertiary (K–T) Boundary Project core holes, western

- Canada. *Canadian Journal of Earth Sciences* **36**, 705–15.
- LERBEKMO, J. F., EVANS, M. E. & BAADSGAARD, H. 1979a. Magnetostratigraphy, biostratigraphy and geochronology of Cretaceous–Tertiary boundary sediments, Red Deer Valley. *Nature* **279**, 26–30.
- LERBEKMO, J. F., SINGH, C., JARZEN, D. M. & RUSSELL, D. A. 1979b. The Cretaceous–Tertiary boundary in south-central Alberta: a revision based on additional dinosaurian and microfossil evidence. *Canadian Journal of Earth Sciences* **16**(9), 1866–9.
- LERBEKMO, J. F., SWEET, A. R. & DAVIDSON, R. A. 1999. Geochemistry of Cretaceous–Tertiary (K–T) boundary interval: south-central Saskatchewan and Montana. *Canadian Journal of Earth Sciences* **36**, 717–24.
- LERBEKMO, J. F., SWEET, A. R. & LOUIS, R. M. S. 1987. The relationship between the iridium anomaly and palynological floral events at three Cretaceous–Tertiary boundary localities in western Canada. *Geological Society of America Bulletin* **99**, 325–30.
- LI, X., LI, W., CHEN, P., WAN, X., LI, G., SONG, B., JIANG, J., LIU, J., YIN, D. & YAN, W. 2004. SHRIMP U–Pb zircon dating of the uppermost Cretaceous Furao Formation near the Heilong River: An age closest to the K/T boundary. *Chinese Science Bulletin* **49**, 860–2.
- LOOPE, D. B., DINGUS, L., SWISHER, C. C. I. & MINJIN, C. 1998. Life and death in a late Cretaceous dune field, Nemegt Basin, Mongolia. *Geology* **26**, 27–30.
- LOOPE, D. B., MASON, J. A. & DINGUS, L. 1999. Lethal landslides from eolian dunes. *Journal of Geology* **107**, 707–13.
- MACK, G. H. & JAMES, C. W. 1994. Paleoclimate and the global distribution of paleosols. *Journal of Geology* **102**, 360–6.
- MACK, G. H., JAMES, C. W. & MONGER, C. H. 1993. Classification of paleosols. *Geological Society of America Bulletin* **105**, 129–36.
- MARKEVICH, V. S. 1994. Palynological zonation of the continental Cretaceous and early Tertiary of eastern Russia. *Cretaceous Research* **15**, 165–77.
- MARKEVICH, V. S. 1995. *The Cretaceous palynoflora of the north of East Asia*. Vladivostok: Dalnauka, 172 pp.
- MARKEVICH, V. S. & BUGDAEVA, E. V. 1997. Flora and correlation of layers with dinosaur fossil remains in Russia's Far East. *Geology of the Pacific Ocean* **16**(6), 114–24.
- MARKEVICH, V. S. & BUGDAEVA, E. V. 2001a. Chapter 5: Correlation of the Upper Cretaceous and Palaeogene plant-bearing deposits of the Russian Far East. In *Flora and dinosaurs at the Cretaceous–Paleogene boundary of Zeya-Bureya Basin (IGCP project 434)* (ed. E. V. Bugdaeva), pp. 79–96. Vladivostok: Dalnauka.
- MARKEVICH, V. S. & BUGDAEVA, E. V. 2001b. The Maastrichtian flora and dinosaurs of the Russian Far East. In *Proceedings of the IX International Palynological Conference, Houston, Texas, USA, 1996* (eds D. K. Goodman and R. T. Clarke), pp. 139–48. AASP Foundation.
- MARTINEZ-DECLOS, X., BRIGGS, D. E. G. & PENALVER, E. 2004. Taphonomy of insects in carbonates and amber. *Palaeogeography, Palaeoclimatology, Palaeoecology* **203**, 19–64.
- MIALL, A. D. 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth Science Reviews* **22**, 261–308.
- MIALL, A. D. 1996. *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology*. New York: Springer Verlag, 582 pp.
- MOISEENKO, V. G., SOROKIN, A. P. & BOLOTSKY, Y. L. 1997. *Fossil reptiles of the Amur Region*. Khabarovsk: AmurKNII FEBRAS, 53 pp.
- NICHOLS, D. J. 1990. Geologic and biostratigraphic framework of the non-marine Cretaceous–Tertiary boundary interval in western North America. *Review of Palaeobotany and Palynology* **65**, 75–84.
- NICHOLS, D. J. 2002. Palynology and biostratigraphy of the Hell Creek Formation in North Dakota: a microfossil record of plants at the end of Cretaceous time. In *The Hell Creek Formation and the Cretaceous–Tertiary boundary in the northern Great Plains: an integrated continental record of the end of the Cretaceous* (ed. D. J. Nichols), pp. 393–456. Geological Society of America, Special Paper no. 361. Boulder, Colorado.
- NICHOLS, D. J. & FLEMING, F. R. 1990. Plant microfossil record of the terminal Cretaceous event in the western United States and Canada. In *Global catastrophes in Earth history; an interdisciplinary conference on impacts, volcanism and mass mortality* (eds V. L. Sharpton and P. D. Ward), pp. 445–55. Geological Society of America, Special Paper no. 247. Boulder, Colorado.
- NICHOLS, D. J., JARZEN, D. M., ORTH, C. J. & OLIVER, P. Q. 1986. Palynological and iridium anomalies at the Cretaceous–Tertiary boundary, South-Central Saskatchewan. *Science* **231**, 714–17.
- NICHOLS, D. J. & SWEET, A. R. 1993. Biostratigraphy of Upper Cretaceous non-marine palynofloras in a north-south transect of the Western Interior Basin. In *Evolution of the Western Interior Basin* (eds W. G. E. Caldwell and E. G. Kauffman), pp. 539–84. Geological Association of Canada, Special Paper no. 39.
- ORTH, C. J., GILMORE, J. S., KNIGHT, J. D., PILLMORE, C. L., TSCHUDY, R. H. & FASSETT, J. E. 1981. An iridium abundance anomaly at the palynological Cretaceous–Tertiary boundary in northern New Mexico. *Science* **214**, 1341–3.
- PILLMORE, C. L., TSCHUDY, R. H., ORTH, C. J., GILMORE, J. S. & KNIGHT, J. D. 1984. Geological framework of nonmarine Cretaceous–Tertiary boundary sites, Raton Basin, New Mexico and Colorado. *Science* **223**, 1180–3.
- RESTALLACK, G. J. 1988. Field recognition of paleosols. *Geological Society of America Special Paper* **216**, 1–20.
- RIABININ, A. N. 1925. A mounted skeleton of the gigantic reptile *Trachodon amurense* nov. sp. *Izvestija Geologicheskogo Komiteta* **44**, 1–12.
- RIABININ, A. N. 1930a. *Manschurosaurus amurensis* nov. gen. nov. sp., a hadrosaurian dinosaur from the Upper Cretaceous of the Amur River. *Memoirs of the Russian Palaeontological Society* **2**, 1–36.
- RIABININ, A. N. 1930b. On the age and fauna of the dinosaur beds on the Amur River. *Memoirs of the Russian Mineralogical Society* **59**(serie 2), 41–51.
- RIGBY, J. K. JR, NEWMAN, K. R., SMIT, J., VAN DER KAARS, S., SLOAN, R. E. & RIGBY, J. K. 1987. Dinosaurs from the Paleocene part of the Hell Creek Formation. *Palaios* **2**, 296–302.
- ROGERS, R. R. 1990. Taphonomy of three dinosaur bone beds in the Upper Cretaceous Two Medicine Formation of northwestern Montana: evidence for drought-related mortality. *Palaios* **5**, 394–413.

- ROZHDESTVENSKY, A. K. 1957. On the Upper Cretaceous dinosaur localities on the Amur River. *Vertebrata Palasiatica* **1**, 285–91.
- RUSSELL, D. A. 1993. The role of Central Asia in dinosaur biogeography. *Canadian Journal of Earth Sciences* **30**, 2002–12.
- RUSSELL, D. A. & MANABE, M. 2002. Synopsis of the Hell Creek (uppermost Cretaceous) dinosaur assemblage. In *The Hell Creek Formation and the Cretaceous–Tertiary boundary in the northern Great Plains: an integrated continental record of the end of the Cretaceous* (eds J. H. Hartman, K. R. Johnson and D. J. Nichols), pp. 169–76. Geological Society of America, Special Paper no. 361. Boulder, Colorado.
- RUSSELL, D. A. & SINGH, C. 1978. The Cretaceous–Tertiary boundary in south-central Alberta – a reappraisal based on dinosaurian and microfloral extinctions. *Canadian Journal of Earth Sciences* **15**, 284–92.
- SAITO, T., YAMANOI, T. & KAIHO, K. 1986. End-Cretaceous devastation of terrestrial flora in the boreal Far East. *Nature* **323**, 253–5.
- SHEEHAN, P. M., FASTOVSKY, D. E., BARRETO, C. & HOFFMANN, R. G. 2000. Dinosaur abundance was not declining in a “3m gap” at the top of the Hell Creek Formation, Montana and North Dakota. *Geology* **28**, 523–6.
- SLOAN, R. E., RIGBY, J. K. JR, VAN VALEN, L. M. & GABRIEL, D. 1986. Gradual dinosaur extinction and simultaneous ungulate radiation in the Hell Creek Formation. *Science* **232**, 629–33.
- SOIL SURVEY STAFF. 1999. *Soil Taxonomy* (2nd ed.) US Department of Agriculture Handbook, 436. Printing Office, Washington D.C., 871 pp.
- SRIVASTAVA, S. K. 1970. Pollen biostratigraphy and paleoecology of the Edmonton Formation (Maestrichtian), Alberta, Canada. *Palaeoecology, Palaoclimatology, Palaeoecology* **7**, 221–76.
- STOCKEY, R. A. & ROTHWELL, G. W. 1997. The aquatic angiosperm *Trapago angulata* from the Upper Cretaceous (Maastrichtian) St. Mary River Formation of southern Alberta. *International Journal of Plant Sciences* **158**(1), 83–94.
- SUKHANOV, V. R. 2000. Mesozoic turtles of Middle and Central Asia. In *The age of dinosaurs in Russia and Mongolia* (eds M. J. Benton, M. A. Shishkin, D. M. Unwin and E. N. Kurochkin), pp. 309–67. Cambridge: Cambridge University Press.
- SUN, G., AKHMETIEV, M. A., ASHRAF, A. R., SUN, Y. W., DONG, Z. M., BUGDAEVA, E. V., MARKEVICH, V. S., KEZINA, T. V., KODRUL, T. M., JOHNSON, K., NICHOLS, D. J., NISHIDA, H., OKADA, H., SUN, C. L., SUZUKI, S., DILCHER, D. L., LU, J. S., LUO, K. L., BOLOTSKY, Y. L., HICKS, J. F., YANG, H. X., HARDING, I. & QUAN, C. 2004. Recent advances on the research of Cretaceous–Tertiary boundary in Jiayin of Heilongjiang, China. In *Proceedings of the 3rd Symposium on Cretaceous biota and K/T boundary in Heilongjiang River Area* (eds G. Sun, Y. W. Sun, M. A. Akhmetiev and A. R. Ashraf), pp. 1–6. Changchun, China.
- SUN, G., AKHMETIEV, M. A., DONG, Z. M., ASHRAF, A. R., SUN, Y. W., BUGDAEVA, E. V., DILCHER, D. L., GOLOVNEVA, L., HARDING, I., JOHNSON, K., KEZINA, T. V., KODRUL, T. M., LU, J. S., MARKEVICH, V. S., NISHIDA, H., OKADA, H., PARK, S. O., SUN, C. L., XIONG, X. Z., XING, Y. L. & ZHOU, Z. L. 2002. In search of the Cretaceous–Tertiary boundary in the Heilongjiang River Area of China. *Journal of Geoscientific Research in Northeast Asia* **5**, 105–13.
- SUZUKI, S. 2004. Fission-track zircon age of a tuff sample from the Tsagayan Formation, the Amur River Area, the Russian Far East. In *Proceedings of the 3rd Symposium on Cretaceous biota and K/T boundary in Heilongjiang River Area* (eds G. Sun, Y. W. Sun, M. A. Akhmetiev and A. R. Ashraf), pp. 75–6. Changchun, China.
- SVENDSEN, J., STOLLHOFEN, H., CRAPF, C. B. E. & STANISTREET, I. G. 2003. Mass and hyperconcentrated flow deposits record dune damming and catastrophic breakthrough of ephemeral rivers, Skeleton Coast Erg, Namibia. *Sedimentary Geology* **160**, 7–31.
- SWEET, A. R., BRAMAN, D. R. & LERBEKMO, J. F. 1990. Palynofloral response to K/T boundary events; a transitory interruption within a dynamic system. In *Global catastrophes in Earth history; an interdisciplinary conference on impacts, volcanism and mass mortality* (eds V. L. Sharpton and P. D. Ward), pp. 457–65. Geological Society of America, Special Paper no. 247. Boulder, Colorado.
- SWEET, A. R., BRAMAN, D. R. & LERBEKMO, J. F. 1999. Sequential palynological changes across the composite Cretaceous–Tertiary boundary claystone and contiguous strata, western Canada and Montana, U. S. A. *Canadian Journal of Earth Sciences* **36**, 743–68.
- TSCHUDY, R. H. & TSCHUDY, B. D. 1986. Extinction and survival of plant life following the Cretaceous/Tertiary boundary event, Western Interior, North America. *Geology* **14**, 667–70.
- TUMANOVA, T. A., BOLOTSKY, Y. L. & ALIFANOV, V. R. 2004. The first finds of armored dinosaurs in the Upper Cretaceous of Russia (Amur Region). *Paleontologicheskii Zhurnal* **38**, 73–7.
- VAKHRAMEEV, V. A. 1991. *Jurassic and Cretaceous floras and climates of the Earth*. Cambridge: Cambridge University Press, 318 pp.
- VALLANCE, J. W., CUNICO, M. L. & SCHILLING, S. P. 2003. Debris-flow hazards caused by hydrologic events at Mount Rainier, Washington. *U. S. Geological Survey Open-file Report* 03–368, 1–4.
- VAN VALEN, L. M. 1988. Paleocene dinosaurs or Cretaceous ungulates in South America. *Evolutionary Monographs* **10**, 1–79.
- VARRICCHIO, D. J. & HORNER, J. R. 1993. Hadrosaurid and lambeosaurid bone beds from the Upper Cretaceous Two Medicine Formation of Montana: taphonomic and biologic implications. *Canadian Journal of Earth Sciences* **30**, 997–1006.
- ZALEHA, M. J. & WIESEMANN, S. A. 2005. Hyperconcentrated flows and gastroliths: sedimentology of diamictites and wackes of the upper Cloverly Formation, Lower Cretaceous, Wyoming, U. S. A. *Journal of Sedimentary Research* **75**, 43–54.
- ZHAO, Z., MAO, X.-Y., CHAI, Z.-F., YANG, G.-C., KONG, P., EBIHARA, M. & ZHAO, Z.-H. 2002. A possible causal relationship between extinction of dinosaurs and K/T iridium enrichment in the Nanxiong Basin, South China: evidence from dinosaur eggshells. *Palaeoecology, Palaoclimatology, Palaeoecology* **178**, 1–17.