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SEDIMENTATION OF DINOSAUR-BEARING UPPER CRETACEOUS DEPOSITS OF THE NEMEGT BASIN, GOBI DESERT

(Plates XXXV—XLII

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Abstract. — The Upper Cretaceous (? Campanian-Maastrichtian) deposits of the Nemegt Basin are clastic, continental sediments of red-beds type. Two formations were distinguished and named the Lower and Upper Nemegt Beds. There is no break in sedimentation between the Lower and Upper Nemegt Beds; instead, a gradual passage between them may be discerned. Skeletal remains of dinosaurs are largely confined to the Upper Nemegt Beds. This formation has a vertical thickness of at least 450 m. Sedimentary features of the Upper Nemegt Beds indicate a fluviatile origin. The sediments represent fossil flood-plain deposits, with point-bar and channel-bar sediments predominating. The depositional basin was a plain, transected by numerous, laterally migrating river channels and showing a marked tendency to aggradation. There are pronounced local differences in transport direction of clastic material, but the main trend is towards WSW. Dinosaur remains of the Upper Nemegt Beds display a variable state of preservation (completness of skeletal material). Nearly whole skeletons predominate, while single bones and bone fragments are scarce. Most remains occur in the sandy and gravelly sediments. Current traction played an insignificant rôle in the distribution of bone material. Most of the dinosaur remains were buried in varying states of disarticulation, either *in situ* or close to the place of death. Point-bars or channel-bars constituted the micro-environment of burial. The Lower Nemegt Beds contain only scarce reptilian remains. This formation is exposed in the eastern part of the Nemegt Basin and has a vertical thickness of at least 150 m. The Lower Nemegt Beds may be of lacustrine origin, but the possibility of a fluvial environment cannot be excluded.

INTRODUCTION

The Upper Cretaceous sediments of the Nemegt Basin were discovered by the Mongolian Palaeontological Expedition of the USSR Academy of Sciences in 1946. Excavation work was carried out during subsequent Soviet expeditions in 1948 and 1949. Numerous specimens of various dinosaurs were collected. Thus it was shown that the Upper Cretaceous of the Nemegt Basin should be considered as one of the richest formations in dinosaur remains in the world.

During the Polish-Mongolian Palaeontological Expeditions 1963—1965 (see KIELAN-JAWOROWSKA & DOVCHIN, 1968/69) the Upper Cretaceous sediments of the Nemegt Basin were re-examined in 1964 and 1965 and yielded a further 34 dinosaur specimens. These expeditions were organized jointly by the Palaeozoological Institute of the Polish Academy of Sciences and by the Institute of Biological Sciences, Academy of Sciences of the Mongolian People's Republic. The author participated in the 1964 and 1965 expeditions as geologist, responsible for the making of plans and profiles of exposures, with localization and description of sites at which dinosaur remains were excavated (GRADZIŃSKI *et al.*, 1968/69). In addition, the author carried out geological investigations devoted mainly to sedimentological problems. The results of these investigations are described in the present paper, which is largely concerned with the reconstruction of the depositional environment of the dinosaur-bearing Upper Cretaceous sediments in the Nemegt Basin.

Because there is no detailed information relating to the geological structure of the Nemegt Basin and to the lithology of the rock sequences occurring in this area, these latter are briefly treated in the present paper.

Rock and soft-sediment samples collected by the author during the 1964 and 1965 expeditions were given successive numbers, together with the year: 1/64, 2/64..., 1/65, 2/65...; 155 samples were collected in 1964, 252 in 1965. The numbers of some samples are given in the text and tables of the present account, as well as in the papers by SZCZECHURA & BŁASZYK (1970) and KARCZEWSKA & ZIEMBIŃSKA-TWORZYDŁO (1970). This collection is housed in the Department of Geology of the Jagellonian University, Cracow, while fossils found in particular samples are housed in the Palaeozoological Institute of the Polish Academy of Sciences, Warsaw.

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GEOLOGICAL SETTING

The Nemegt Basin lies in the Gobi region of the Mongolian People's Republic and forms the western part of a larger basin extending in an East-West direction. Mountain massifs belonging to the Gobi-Altai range flank the Nemegt Basin. North of the basin occur Altan Ula, Nemegt Ula and Gilbent Ula, while in the South are Tost Ula and Noyon Ula (Text-fig. 1).

Hitherto no detailed geological investigations have been made of the Nemegt Basin and neighbouring mountain massifs. Some general data are given in papers by EFREMOV (1954*a*, 1955), NOVOZHILOV (1954*a*), VASILEV *et al.* (1959) and MARINOV (1957). The Nemegt Basin is also included on the general geological map of the Mongolian People's Republic (OBRUCHEV, 1957).

According to the papers quoted above, the Nemegt Basin is a graben bordered by horst massifs. The graben is filled with flat-lying sedimentary rocks of late Cretaceous and Paleogene ages belonging to a continental sedimentary series, deposited during late Mesozoic and Tertiary time in the present-day Gobi and in adjoining areas of Central Asia.

Upper Cretaceous sediments are exposed in the northern and central part of the Nemegt Basin, while Paleogene sediments cover the southern part of the basin. The latter were assigned to the Eocene by the Soviet authors (NOVOZHILOV, 1954*a*; EFREMOV, 1954*a*; MARINOV, 1957). Recently the lower part of the Paleogene complex was regarded by KIELAN-JAWOROWSKA & DOVCHIN (1968/69) as being of the same age as that of Khashaat (Gashato) and thus was considered to be Paleocene in age, though these authors point out (*l. c.*, p. 16) that an early Eocene age is also possible. The general lithostratigraphic division of the Upper Cretaceous and Paleogene rocks of the Nemegt Basin was presented in an earlier paper (GRADZIŃSKI *et al.*, 1968/69).

Gently sloping flat surfaces of pediments extend North and South of the axis of the basin, towards the bordering massifs. The morphology is characterized by the presence of two pediment surfaces of different ages. The younger one is related to the base of the recent drainage system.

The surfaces of the pediments are covered by a layer of gravels and silts. Exposures of older sediments are almost entirely lacking. The existing exposures of older sediments are

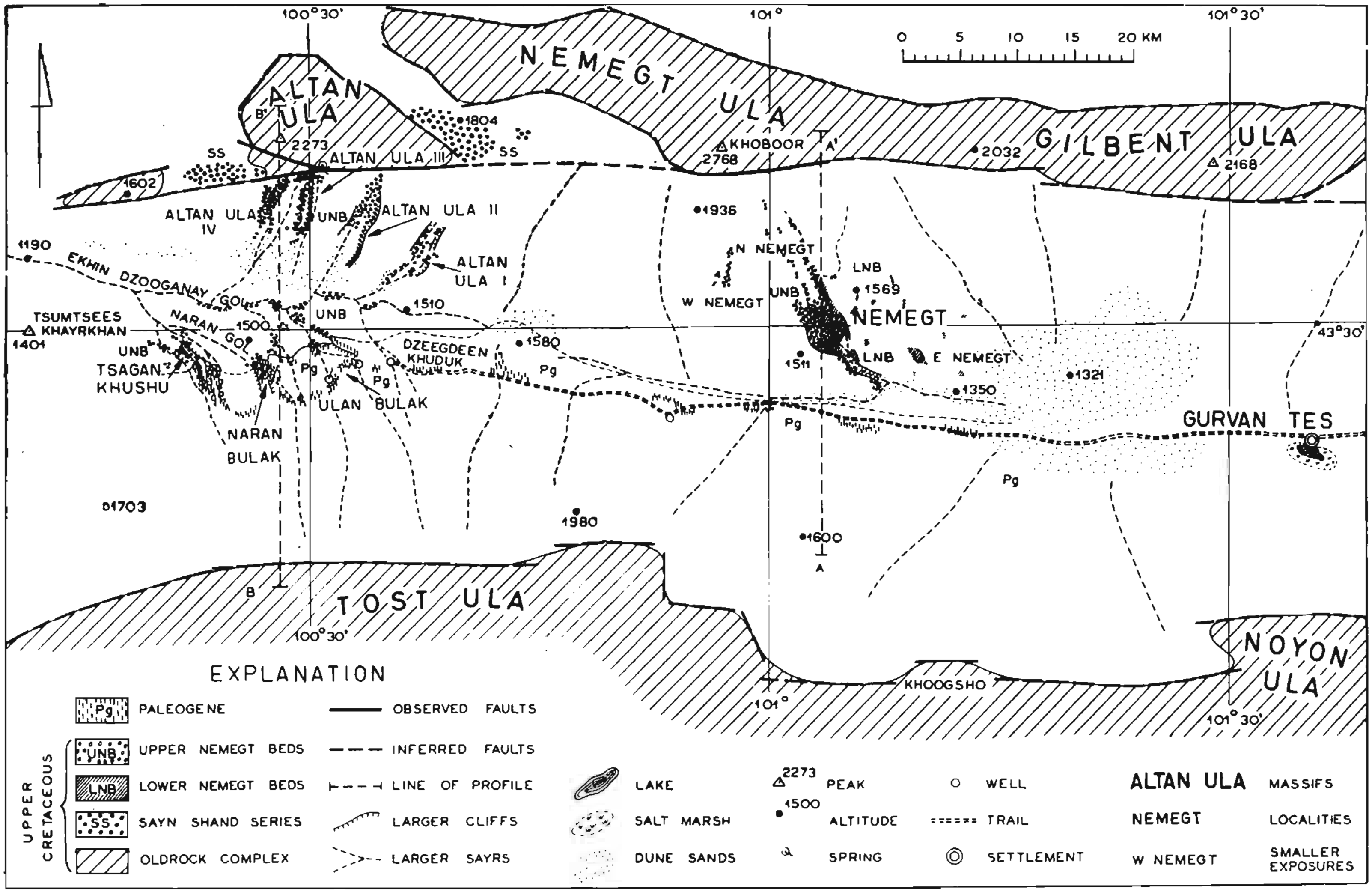

Fig. 1
Geological reconnaissance map of the Nemegt Basin. Surrounding massifs drawn schematically.

restricted to erosional scarps, cut in the older pediment surface. In areas where marked expansion of the lower pediment surface is taking place the erosional scarps are strongly dissected. Systems of deep gorges and isolated hills offer excellent exposures on their steep slopes.

Separate systems of such exposures distributed sporadically throughout the Nemegt Basin were investigated by the Soviet and Polish-Mongolian Palaeontological Expeditions. The groups of exposures are referred to as the localities (see GRADZIŃSKI *et al.*, 1968/69) Nemegt, Altan Ula I, II, III and IV, Tsagan Khushu, Naran Bulak and Ulan Bulak. It should be added that in the Altan Ula area, the Soviet expeditions explored only the locality here called Altan Ula II. Soviet authors writing in general terms about Altan Ula refer in fact, to this single locality.

Furthermore, larger exposures of Upper Cretaceous rocks occur along the main sayr of the western part of the basin, and are dispersed up to a dozen km North-East, North and South-East of the central part of the Nemegt locality.

The height of the exposures ranges usually from 10 to 30 m, reaching exceptionally 45 m at Nemegt and about 80 m at Altan Ula II.

The horst massifs flanking the Nemegt Basin are built principally of Palaeozoic rocks, as are other massifs of the Gobi Altai range (MARINOV, 1957; VASILEV *et al.*, 1959). They consist of various igneous, metamorphic and detrital sedimentary rocks, the latter being usually slightly metamorphosed. All rocks of the massifs display strong tectonic deformation of various types and presumably of various ages. The strongly deformed rocks which form the massifs, and the substratum of the late Mesozoic and Tertiary sedimentary rocks of the Gobi area are termed here "oldrock complex", following BERKEY and MORRIS (1927), who introduced this name.

Within the horst massifs forming the northern flank of the Nemegt Basin, the oldrock complex is covered in places by continental sediments, preserved in a tectonic downfaulted area. These sediments probably belong to the Cretaceous and are older than the Cretaceous sediments exposed within the graben of the Nemegt Basin (see OBRUCHEV, 1957).

The faults are certainly younger than the sediments filling the graben. This is indicated by tectonic contacts between the Upper Cretaceous sediments and the oldrock complex, visible in many places along the borders of the massifs. The writer also observed tectonic deformations of the Upper Cretaceous sediments in the immediate neighbourhood of the Altan Ula and Nemegt Ula massifs. These deformations consist of small faults and flexures, more or less parallel to the border of the massifs. The presence of a distinct tectonic step in the SE part of Altan Ula massif and the southern dip of the fault planes evidence the tensional character of the faults. Narrow zones of step-faults are present on the southern border of the Altan Ula and Nemegt Ula massifs. It seems probable that a similar situation exists on the southern border of the basin.

The geological and morphological conditions existing in the Nemegt Basin do not permit a more exact determination of the age of faulting. However, the uniform tectonic character of the entire Gobi-Altai and Mongolian Altai supports the assumption that the principal faulting occurred after the Oligocene or even after the Pliocene, as in other parts of these mountain chains, where faulting of this age has been proved (VASILEV *et al.*, 1959, NEKHOROSHEV, 1966). The concept of relatively late faulting is supported by the fact that the upper limit of the pediments of the Nemegt Basin coincides nearly everywhere with the faults bordering the graben from the North.

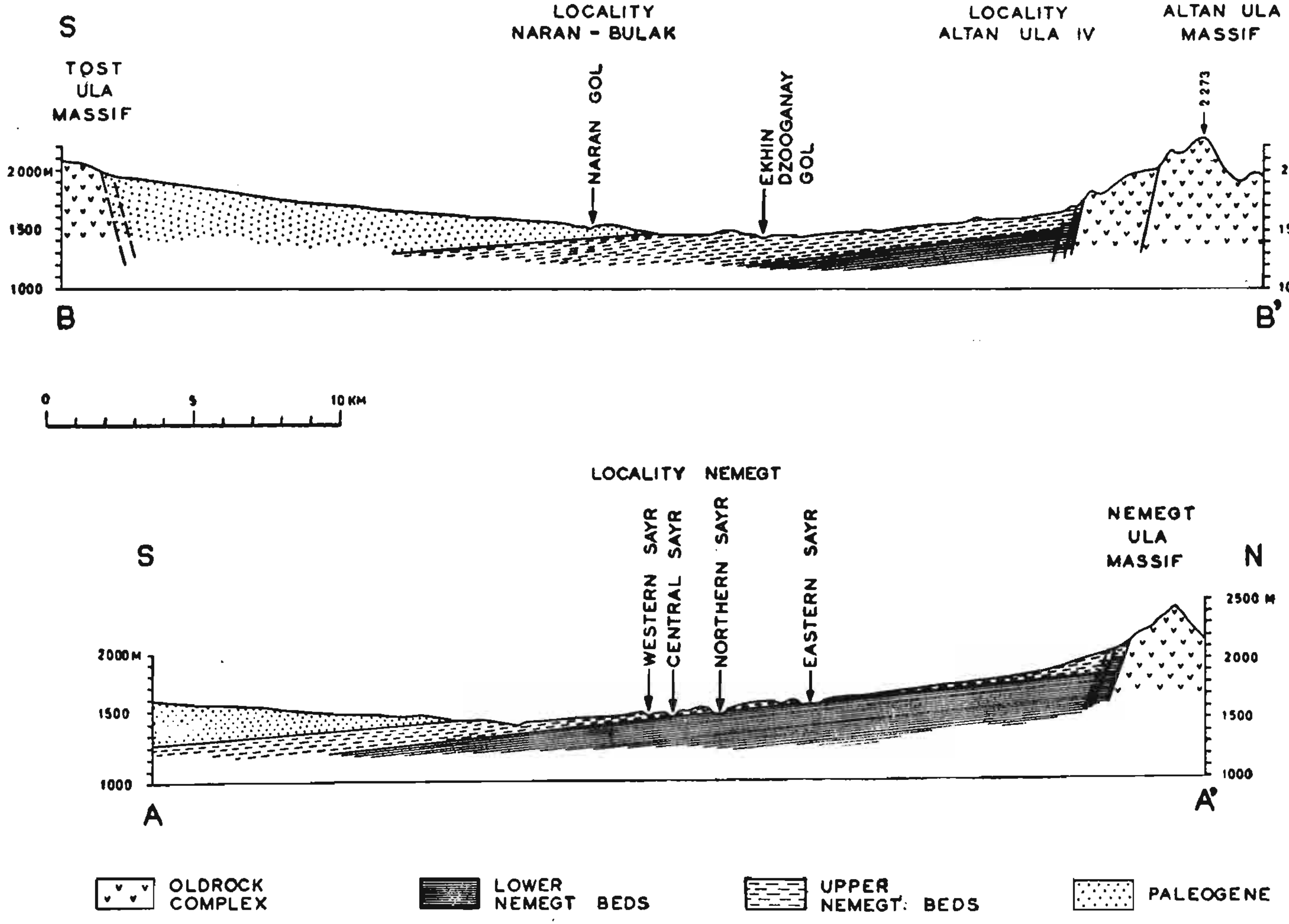

Fig. 2
Geological cross-sections of the Nemegt Basin.

STRATIGRAPHY

PREVIOUS WORK

The first information on succession, lithology and age of the Cretaceous rocks of the Nemegt Basin is given by EFREMOV (1950, 1954*a*, 1955). According to this writer, an erosional "channel" is present at the Nemegt locality. EFREMOV regarded this "channel" as cutting into older Upper Cretaceous rocks, represented by red unfossiliferous sandstones (the so-called "unfossiliferous series" — nemaya tolshcha). The "channel", about 4 km wide, is filled with sandy-clayey-gravelly sediments, usually light-coloured. Fossils, mostly dinosaur remains, occur within these "channel deposits". The relations between the two types of sediments is shown by a schematic cross-section and map of the Nemegt locality, which were twice published (EFREMOV, 1950, Figs. 16, 17; 1954*a*, Figs. 3, 4).

The discussed channel, filled with fossiliferous sediments, was considered to be a "subaqueous deltaic channel" (podwodnoe deltovoe ruslo of EFREMOV, 1954*a*, 1955). According to EFREMOV, the fossiliferous sediments at Altan Ula and Tsagan Khushu occur within other channels of similar type, which have cross-sections resembling that of Nemegt and the same or somewhat smaller width. According to EFREMOV (1955, p. 791), the channels occur within the "unfossiliferous series", which extends over tens of kilometres. In the papers by EFREMOV (*l. c.*) the thickness of the "unfossiliferous series" is described generally as "large" and the depth of the channels and the thickness of the fossiliferous series filling them as "small". On the cross--section of the Nemegt locality mentioned above, the thickness of the fossiliferous series is given as around 50 m in one instance (EFREMOV, 1950, Fig. 17), and about 80 m in the second instance (EFREMOV, 1954*a*, Fig. 4). The original thickness of the sediments of the fossiliferous series was regarded by EFREMOV (1955, p. 801) as probably not exceeding twice the thickness observed at present in the exposures.

The fossiliferous series was assigned (EFREMOV, 1954*a*) to the middle part of the Upper Cretaceous (in the Soviet literature the Cretaceous is divided into Lower and Upper Cretaceous). The "unfossiliferous series" was regarded as corresponding in age to the sediments of the lower part of the Upper Cretaceous exposed at Bayn Dzak (i.e. the Djadokhta formation established by BERKEY and MORRIS, 1927).

MALEYEV (1952, 1954) published a comparative table of Late Cretaceous formations of Mongolia and North America, based upon results of palaeontological studies. The fossiliferous series of the Nemegt Basin is regarded by this author as being coeval with the upper part of the Belly River formation (Alberta), the Judith River formation (Montana) and the lowest part of the younger Edmonton formation (Alberta).

These stratigraphic correlations were revised by ROZHDESTVENSKY (1957, 1965), who correlated the fossiliferous series of the Nemegt Basin with the Edmonton formation of America and the Maastrichtian stage in the European division of the Cretaceous.

At the beginning of the fifties, the Soviet geologists working in eastern Gobi introduced a stratigraphic division of the Cretaceous rocks into five series (sing. "svita"), out of which two, the Sayn Shand Series and the Bayn Shireh Series represent the Upper Cretaceous. This division was subsequently extended over the whole of the Mongolian People's Republic, and was utilized among others in the map edited by OBRUCHEV (1957) and in the paper by MARINOV (1957). Examination of OBRUCHEV's map shows that both fossiliferous series and the "unfossiliferous series" are included in the Bayn Shireh Series (Senonian).

The paper by MARINOV (1957) did not provide a clear picture of the succession and age of the Upper Cretaceous of the Nemegt Basin. MARINOV divided the Upper Cretaceous into two series: the Sayn Shand Series (Cenomanian) and the Bayn Shireh series (Senonian). The sediments exposed at the Nemegt, Altan Ula and Tsagan Khushu localities are regarded by MARINOV as belonging to the Sayn Shand Series. At the same time, however, this author notes, that a fauna of phyllopods of Senonian age occurs in these sediments (MARINOV, *l. c.*, p. 194). Elsewhere, MARINOV mentions the Bayn Shireh age of the fossiliferous sediments of the Nemegt Basin (*l. c.*, p. 203). According to MARINOV (1957), rocks of Bayn Shireh age also occur in the Nemegt Basin. The lithologic description is given by him according to unpublished observations of VOLKHONIN (*in* MARINOV, 1957, pp. 198, 199). Nothing is said about either the occurrence of fossils or the criteria by which these sediments were assigned to the Bayn Shireh Series. Inadequate lithological descriptions and lack of details on the location of exposures make the identification of these sediments in the field impossible.

LITHOSTRATIGRAPHIC DIVISION OF UPPER CRETACEOUS DEPOSITS, NEMEGT BASIN

The papers quoted above represent the state of knowledge of the sequence and stratigraphy of the Upper Cretaceous sediments of the Nemegt Basin at the beginning of the Polish-Mongolian Palaeontological Expeditions. The observations carried out by the present writer during these expeditions provide new data on the position and relationship of the fossiliferous sediments to the underlying "unfossiliferous series" and on their distribution in the Nemegt Basin.

In an earlier paper (GRADZIŃSKI *et al.*, 1968/69), the author divided the Upper Cretaceous sediments (? Campanian-Maastrichtian) occurring in the Nemegt Basin into two formations. The older one was termed "Lower Nemegt Beds"; the younger one, "Upper Nemegt Beds". Generally, the Lower Nemegt Beds correspond to the "unfossiliferous series" of EFREMOV (1954*a*), and the Upper Nemegt Beds correspond to the fossiliferous series of the same author.

The Upper Nemegt Beds represent a zone of *Tarbosaurus bataar* (MALEYEV), *Saurolophus angustirostris* ROZHDESTVENSKY and *Dyoplosaurus giganteus* MALEYEV, while the fauna in the Lower Nemegt Beds is very scanty, consisting of shell fragments of the shells of dinosaur eggs, rare fragments of lizard skulls and scarce remains of small dinosaur bones. As these latter remains are so far unidentified, it is impossible to define a faunal zone in the Lower Nemegt Beds.

The above division is based chiefly upon observations of exposures at the Nemegt locality, where two lithologically and palaeontologically differing complexes of beds are exposed. The lower complex, forming the Lower Nemegt Beds consists mainly of fine-grained red sandstones, alternating with thin-bedded siltstones. In the upper complex, constituting the Upper Nemegt Beds, light-coloured, unconsolidated or poorly consolidated sands and silts predominate. Claystones, sandstones, gravels and intraformational conglomerates occur in reduced amounts. The Upper Nemegt Beds contain numerous fossils, represented mainly by dinosaurs.

The combined profiles at the Nemegt locality make up a series about 85 m in thickness. Of this, the Lower Nemegt Beds comprise about 30 m, and the Upper Nemegt Beds about 55 m.

The Upper Nemegt Beds are not separated from the underlying Lower Nemegt Beds by a distinct erosive contact, as stated EFREMOV (1954*a*, 1955). Instead, a gradual passage between the two formations is observed. The boundary between them, according to the present author, is at the base of the first bed of the type characteristic for the Upper Nemegt Beds, a light-coloured sand, usually containing intraformational clasts at the base. This bed usually contains fragmented bones or skeletons of dinosaurs. Single beds of sandstones of the "Lower Nemegt Beds"-type are present up to 16—18 m above the base of the Upper Nemegt Beds. This indicates clearly a gradual passage between the two formations.

The lower part of the Upper Nemegt Beds, in which occur intercalations of sandstones similar to the Lower Nemegt Beds was termed by the author (GRADZIŃSKI *et al.*, 1968/69) "Passage Series".

In and around the exposures of the Nemegt locality, the beds dip towards SSW at a very low angle (about $1\frac{1}{2}°$) in an area of around 40 sq. km. The top of the Lower Nemegt Beds is concordant with this dip. The older pediment surface dissected by the ravines dips generally towards SSE in this area. Accordingly, the Lower Nemegt Beds are exposed in the eastern and north-eastern part of the area, while the Upper Nemegt Beds are seen exclusively in the western and south-western part. The exposed profile of the Upper Nemegt Beds is truncated by the older pediment surface in this region. The nearest exposures, situated about 6—8 km West of the central part of the Nemegt locality, consist of small erosion scarps in which the Upper Nemegt Beds are exposed. These exposures are marked as "W Nemegt" in Text-fig. 1.

The observations of the present writer indicate that view reflected both in published schematic cross-sections of this locality (EFREMOV, 1950, Fig. 17; 1954*a*, Fig. 4) and geological sketch-maps (EFREMOV, 1950, Fig. 16; 1954*a*, Fig. 3) are untenable. All facts are against the existence of a large erosive "channel" which, according to EFREMOV (1950, 1954*a*, 1955) is cut into the "unfossiliferous series" (the Lower Nemegt Beds) and was filled with the fossiliferous series (the Upper Nemegt Beds). The observations made at the Nemegt locality indicate that the two formations lie concordantly one upon another and both dip at a low angle to SSW.

Furthermore, in localities situated West of the Nemegt locality, the author found no evidence of the existence of "channels" described by EFREMOV (1950, 1954*a*, 1955). It should be added that West of the meridian of the Nemegt locality, the members of the expedition found only exposures of the Upper Nemegt Beds, or of younger sediments within the Nemegt Basin. On the other hand, East of this meridian, the Upper Cretaceous is represented entirely by the Lower Nemegt Beds. Reconnaissance trips covered the area up to 15 km east of the Nemegt locality.

The individual exposures and groups of exposures are scattered over a large area. They are separated by flat pediment surfaces practically devoid of even small exposures. Thus the establishment of a continuous profile of the Upper Cretaceous sediments is impossible in the Nemegt Basin. Large lithological variability, both vertical and horizontal (especially in the Upper Nemegt Beds) and the lack of correlation horizons renders the construction of such a profile on the basis of the scattered exposures impossible. The fauna collected at different localities does not show appreciable age differences.

In this situation, only the method of spatial extrapolation provides a mean of determination of the relations between the parts of the sequence exposed in the various outcrops and localities. This method was used with the assumptions that: 1) the direction and angle of dip are constant over the whole area, and 2) the floor of the Nemegt Basin is not traversed by major faults. These assumptions are substantiated by the following data.

The author carried out a detailed topographic survey in three separate areas (localities Nemegt, Altan Ula IV, Tsagan Khushu). On the basis of this work and clisimetric measurements of altitude in the area of squares, with sides at least 1 km long, the slope of selected beds (chiefly of red claystones) was calculated. The data thus obtained were used to compute the angle and direction of dip by the method given by NEVIN (1949, p. 340). In all cases, the bed inclination was 30 ± 2 m per 1 km, giving a dip of 1°43′. The strike of beds was about $105°\pm5°$. It should be added that within the measured areas other beds displayed slightly larger (up to 2½) or slightly smaller angles of dip, and departures from the above strike direction in the range of 100°—115°. These departures had a local character and did not influence the average value for the whole measured area.

Various other field methods giving less accurate results were used in other exposures, and the results obtained were always very near to the above values. All these data support the view that the dip and strike of the Upper Cretaceous sediments is uniform throughout the whole area of the Nemegt Basin.

Scarce steeper dips are confined to a narrow zone (up to 600 m wide) along the horst massifs (Text-fig. 2). Near the limits of these massifs, faults and flexures are observed occasionally.

No tectonic dislocations in the remainder of the Nemegt Basin were observed. A close examination of the boundary of the Lower and Upper Nemegt Beds along several kilometres at the Nemegt locality also did not reveal the presence of faults. The consistently undisturbed position of beds is indicated also by the fact that the presence of Upper Nemegt Beds was found in all exposures lying West of the Nemegt locality, while in exposures situated East of this locality only the Lower Nemegt Beds are exposed. Taking into account the small angle of dip and the small inclination of the surface in the same direction, one would expect distinct deviations from this general rule in the case of existence of vertical faults, even of small throw.

The altitudes a.m.s.l. of the individual exposures were determined from photogrammetric maps with an accuracy of a few m.

The above data were used for computing the position of the profiles of each of the exposures with relation to the boundary between the Lower and Upper Nemegt Beds. In order to reduce possible errors, the position of the profiles exposed in the western part of the Nemegt Basin was calculated in relation to a reference horizon selected in the profile of the Altan Ula IV locality, and then the position of these profiles was calculated with respect to the area of the Nemegt locality.

The results of these calculations are presented in Text-fig. 3. It follows from this figure, that the uppermost members of the Upper Nemegt Beds are exposed in the central part of the Tsagan Khushu locality, where they are overlain with slight discordance by Paleogene rocks. The lowest part of the Lower Nemegt Beds known to the author are exposed at a distance of about 15 km East of the central part of the Nemegt locality.

It should be stressed that the setting up of profiles is of a preliminary character. Future, more detailed geological investigations may change either the assumptions on which it has been based, or the numerical data used for computation.

In the present state of geological exploration of the Nemegt Basin, the thickness of the Upper Nemegt Beds is determined approximately as not less than 420 m, and the thickness of the Lower Nemegt Beds as not less than 150 m.

The thickness of the Lower Nemegt Beds is probably larger. According to ROZHDESTVENSKY (1954, and personal communication) during the Soviet expeditions rocks of type of the Lower Nemegt Beds were followed for a distance of at least 25 km East of the Nemegt locality.

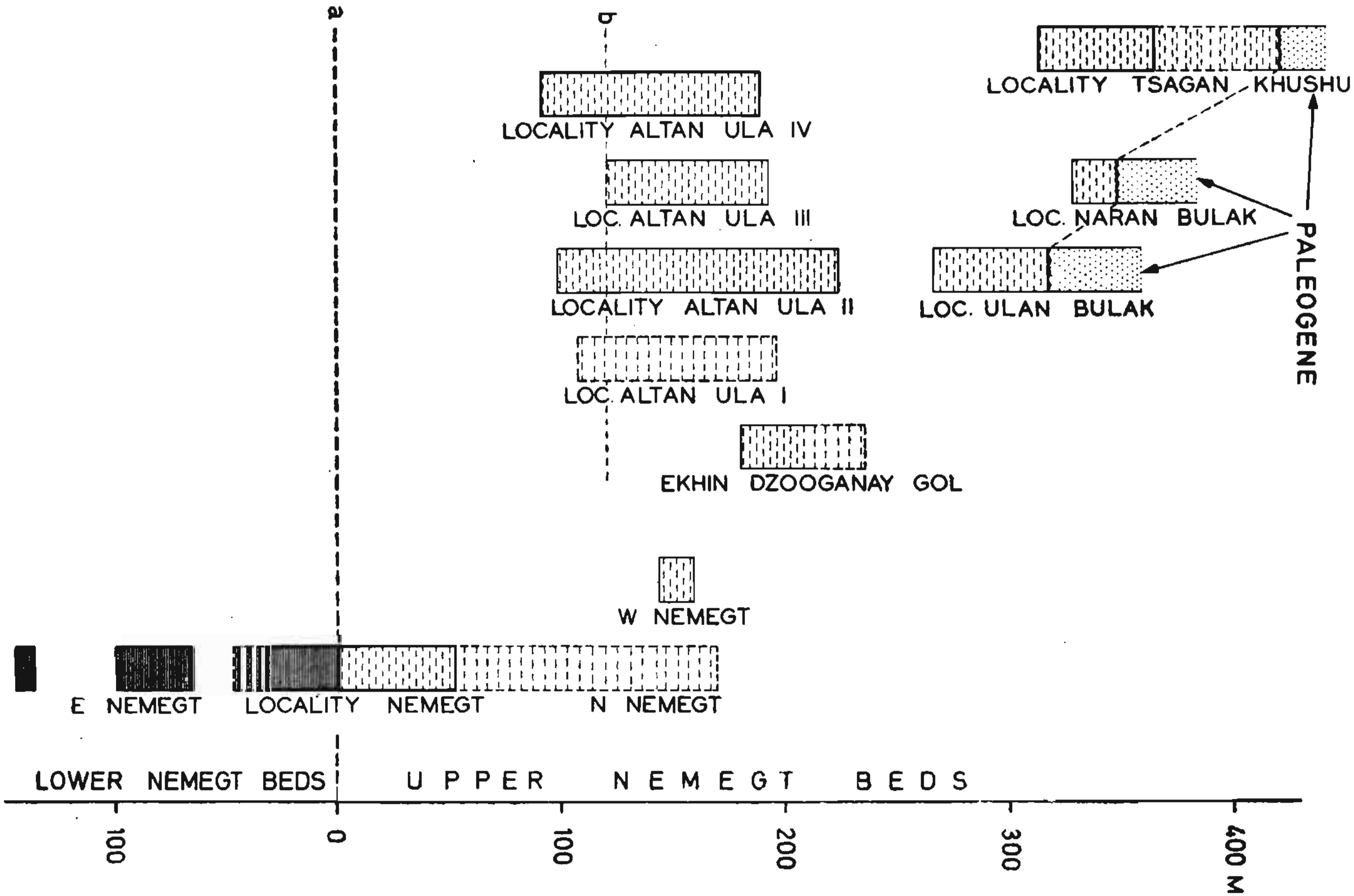

Fig. 3

Location of exposures on the basis of extrapolation with respect to the contact (line *a*) between the Lower and Upper Nemegt Beds at Nemegt locality. For the Altan Ula localities, the level of the bottom of Eagle Sayr at locality Altan Ula IV is indicated as line *b*. Solid lines indicate groups of exposures making up almost complete profiles. Groups of isolated exposures marked with a dashed line. Profiles studied in detail indicated by a thick solid line.

The base of the Lower Nemegt Beds has not been found in the Nemegt Basin. It is supposed that older rocks are represented by gravels exposed North of the basin outside the bordering fault zone. The gravels occur within the downthrown area separating the Nemegt Ula and Altan Ula massifs, and the latter and another small massif situated farther West. The gravels are poorly exposed. During three reconnaissance trips, the present author noted that the gravels are at least several tens of metres thick and lie on a flat surface of older rocks forming the neighbouring massifs. On the geological map of OBRUCHEV (1957) the gravels have been assigned to the Sayn Shand Series (Cenomanian).

LITHOLOGY

PRINCIPAL SEDIMENT-TYPES

The Lower and Upper Nemegt Beds consist entirely of clastic sediments. Sediments of sand-grade predominate, silt-grade and clay-grade rocks occur in smaller amounts, and those of gravel-grade form a minor constituent (Text-fig. 4).

The percentage of lithified and non-lithified sediments in these principal grades is shown in Text-fig. 4*A*. Even the lithified rocks are generally poorly cemented and friable.

The Lower Nemegt Beds consist almost entirely of lithified sediments. In the Upper Nemegt Beds, all clay-grade sediments, the majority of gravel-grade sediments and a part of the silt-grade sediments are consolidated, while most of sand-grade sediments are non-lithified. Therefore, for purposes of general description of rocks of various grades, the author uses the terms conglomerates, siltstones and sands, if the consolidation of sediments is not important for the discussion of a particular problem.

The Nemegt Beds are of red-beds type. In general terms, the sediments were divided into two groups on the basis of colour: red and drab. The colours of rocks were determined by visual comparison with the Rock Color Chart of GODWARD (1951). Rocks assigned to the red group have hue values 5 R, 8 R, 10 R and 5 YR, while those assigned to the drab group have hue values 10 YR, 5 Y, 10 Y and 5 GY (that is, yellow-orange, yellow and greenish). The sediments are, as a rule, light coloured, with lightness values in the range 8—6; the chroma (saturation) values lie in the range 1—6.

In the Lower Nemegt Beds, nearly all sediments belong to the red group, while in the Upper Nemegt Beds drab colours are predominating (Text-fig. 4*B*).

PETROGRAPHIC DESCRIPTION

The petrographic characteristics of the Nemegt Beds are based upon analysis of 53 thin sections of various types of rocks, 15 grain mounts of sand, 9 DTA and derivatograms of clay-grade rocks (the latter by Dr. S. CEBULAK, Upper Silesia Branch of the Geological Institute, Sosnowiec), 4 diffractograms (made in the Geological Institute, Warsaw), 12 chemical analyses (carried out by Mrs. A. PELCZAR, M. Sc., Carpathian Branch of the Geological Institute, Cracow) and 50 determinations of calcium carbonate content (made by Dr. K. PROCHAZKA, Dept. of Mineralogy and Petrography of the Jagellonian University, Cracow).

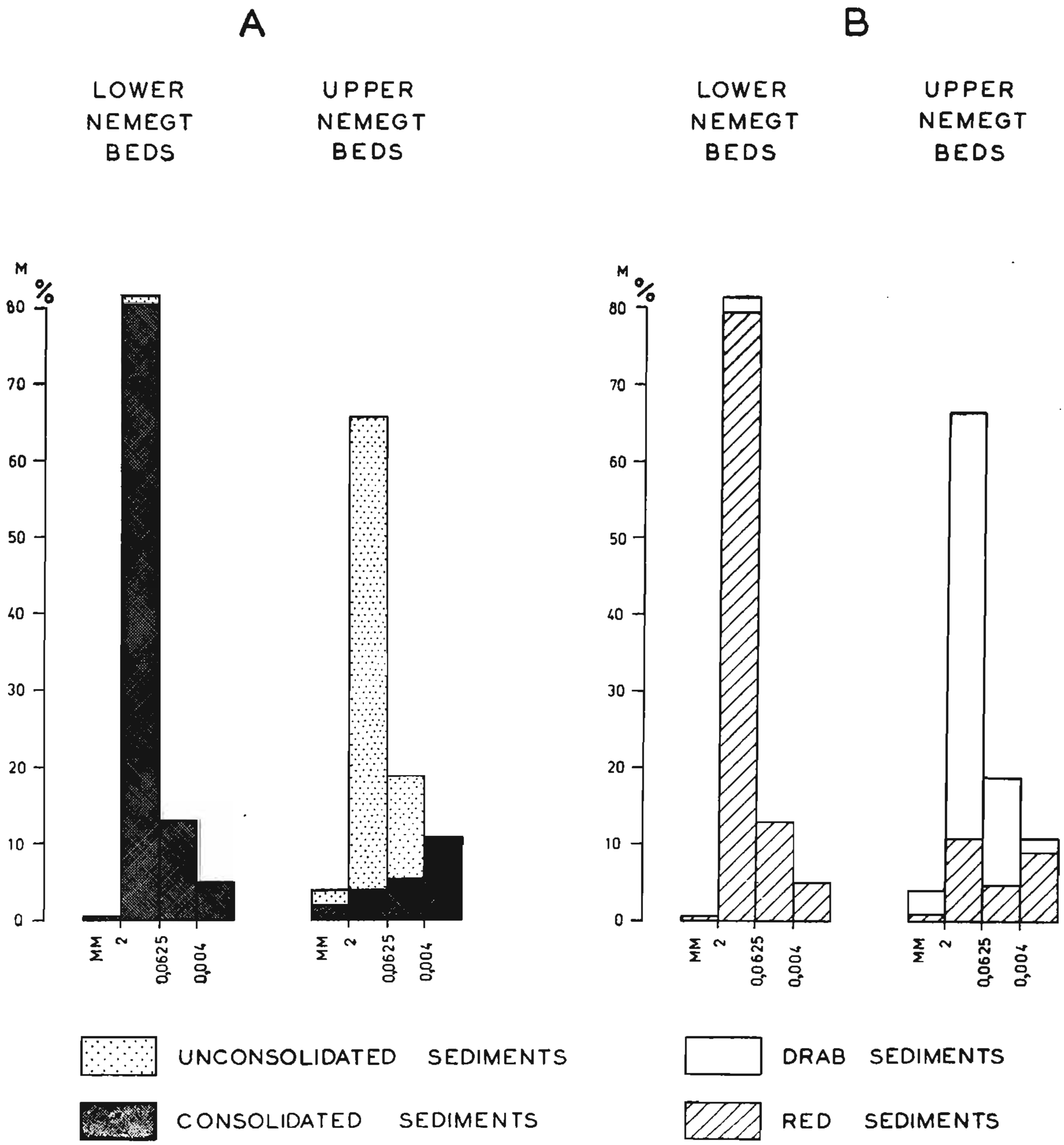

Fig. 4
Principal sediment types in the Nemegt Beds: *A*—degree of consolidation of sediments, *B*—colour of sediments. Data for Upper Nemegt Beds based upon profiles exposed at localities Nemegt, Altan Ula IV and Tsagan Khushu. Data for Lower Nemegt Beds based upon profiles exposed at locality Nemegt and exposures at E Nemegt.

MAJOR CONSTITUENTS

The main constituents of the sediments of the Nemegt Beds are: quartz, feldspars, rock fragments and clay minerals.

Monocrystalline quartz grains prevail over polycrystalline ones. Wavy extinction is uncommon. The common inclusions are trails of liquid/gas bubbles, while mineral inclusions, mostly of zircon, are rare.

Feldspars are represented mainly by microcline and orthoclase, but plagioclases (mostly albite and oligoclase) are fairly common. The feldspars are usually fresh, but grains weathered to varying degrees are also present. Both weathered and non-weathered grains occur together, and were often observed in the same thin section.

The clay minerals determined by means of diffractograms and DTA are represented by montmorillonite, illite and kaolinite.

Among the rock fragments, two groups can be distinguished: fragments of source rocks and fragments of intraformational derivation. Both groups are represented among sand-grade grains and among pebbles. The source-rock fragments are fine-grained granites, granophyres, acid volcanic rocks, silicified pyroclastic rocks and arkoses, quartzites and jaspers. Exotic pebbles of similar rocks occur in the gravels (see page 167).

Rocks of intraformational origin are represented by fragmented calcareous concretions, siltstones and claystones.

The sediments of the Nemegt Beds also contain small amounts of mica (chiefly muscovite), heavy minerals (mainly epidote, see p. 165) and variable amounts of calcite cement (see p. 166). Moreover, some samples contained chamosite, turingite, chlorite, psilomelane, barite (forming concretions), (see p. 161) and rare small crystals of gypsum. Compounds of both bivalent and trivalent iron were present in all analysed samples (see Table 1).

Table 1

Iron oxide content in red and drab sediments *

Sediment type	Colour	Percentages		$Fe^{3+} : Fe^{2+}$
		Fe_2O_3	FeO	
Sand (UNB)	Pale yellowish-gray (5 Y 8/2)	1.53	0.35	4.37
Sand (UNB)	Very light olive gray (5 Y 7·5/1)	1.41	0.39	3.62
Siltstone (UNB)	Yellowish-gray (5 Y 7/4)	3.99	0.71	5.61
Siltstone (UNB)	Yellowish-gray (5 Y 7/4)	4.21	0.22	19.14
Sandstone (LNB)	Light brown (5 Y R 5/4)	4.28	0.32	1.34
Claystone (UNB)	Moderate reddish-brown (10 R 4/5)	5.61	0.46	12.20
Claystone (LNB)	Moderate reddish-brown (10 R 4/5)	5.84	0.28	20.86
Claystone (UNB)	Moderate reddish-brown (10 R 5/5)	8.19	1.42	5.77
Claystone (UNB)	Moderate reddish-brown (10 R 4/6)	7.18	1.03	6.97

* Chemical analyses by A. PELCZAR; UNB = Upper Nemegt Beds, LNB = Lower Nemegt Beds.

CLAY-GRADE SEDIMENTS

All claystones of the Nemegt Beds contain an admixture of grains of silt- and/or sand-grade, belonging chiefly to quartz and feldspar. The rocks are relatively hard and non-fissile.

In thin sections, the clay minerals appear as agglomerations of a brown-coloured substance, consisting usually of finely crystalline aggregates. Larger oriented flakes up to 50 microns long, of a "monocrystalline type" are frequent. According to CAROZZI (1960) these latter indicate slow deposition from suspension. Agglomerations of iron hydroxides are frequent.

The claystones contain small (1—8 mm) agglomerations of a black substance, irregular in shape and randomly dispersed. These contain a relatively high content of manganese (about 3 per cent). The substance has been identified as psilomelane.

Lower Nemegt Beds

The claystones, as a rule, contain an admixture of silt-grade grains. The rocks are moderately reddish-brown (10 R 4/5, 10 R 4/6). The content of calcium carbonate ranges from 4·04 to 5·75 per cent (3 analyses). Small concretions of calcium carbonate are very rare.

Upper Nemegt Beds

Besides sandy and silty claystones, nearly pure claystones are present. The rocks are usually moderately reddish-brown (10 R 4/6), but some beds or parts of them are yellowish-grey (5 Y 7/4) or light-grey (10 Y 6/1).

A diffractogram of a light-grey claystone indicated the presence of chamosite, thuringite and chlorite, while two diffractograms of moderately reddish-brown claystones proved the presence of haematite. The presence of montmorillonite, illite and kaolinite was indicated by all three diffractograms.

The claystones often contain small calcium carbonate concretions (see p. 166). The diameters of these range up to 50 mm, shapes are irregular, and the boundary with the suronding rock is always indistinct. The concretions are light-coloured, usually light brownish-grey (5 Y 7/1). The concretions are irregularly distributed, occurring abundantly in the upper part of beds (Pl. XXIX, Fig. 2).

Barite concretions occurring in silty claystones were found in two outcrops. The concretions are 20—35 mm long, oval in shape and light-coloured, with a distinct concentric structure.

SILT-GRADE SEDIMENTS

In these sediments, the grains of silt-size are accompanied by various amounts of fine- and very fine-sand grains and clay minerals. Feldspar grains are common.

Lower Nemegt Beds

The siltstones are non-fissile and usually unlaminated. Their colours belong always to the red group, and most frequently are light-brown (5 YR 5/4).

Upper Nemegt Beds

Siltstones and silts occur in the Upper Nemegt Beds. The siltstones are moderately hard and non-fissile and may be either laminated or unlaminated; the silts differ only in their lower degree of consolidation. Both are usually yellowish grey (5 Y 7/4, 5 Y 7/2, 5 Y 8/2). The lamination is related to the occurrence of larger grains (0.04—0.18 mm in diameter). Mica flakes are present on lamination planes, and sometimes the coarser laminae are impregnated with iron hydroxides. The content of calcite cement ranges up to 10 per cent in the coarser varieties.

SAND-GRADE SEDIMENTS

Lower Nemegt Beds

Fine-grained and very fine-grained sandstones occur almost exclusively in the Lower Nemegt Beds. Medium-grained sandstones are rare, and coarser varieties occur quite exceptionally. Loose sands are very rare. As a rule, the sediments are light-brown (5 YR 5/4).

Among the detrital grains (without detrital matrix, 5 analyses) quartz forms 69—80 per cent, feldspars 18—28 per cent, while grains belonging to other mineral constituents form 1—4 per cent. The quartz/feldspar ratio ranges from 2.42 to 4.44. The matrix, forming usually about 20 per cent of the rock consists of aggregates of clay minerals, with a small admixture of silt-size grains. In one case (very fine sandstone), the observed content of clay amounted to 67 per cent. It seems probable that this high value is caused by the presence of larger detrital grains of clay minerals, not easily recognizable in a thin section (see ALLEN, 1962*a*). The content of calcite cement ranges from 1 to 15 per cent. The grains of the detrital framework often display the presence of a brown-coloured coating of clay minerals or trivalent iron compounds.

In the Eastern Sayr of the Nemegt locality, large (1—4 m long), spheroidal concretions occur in the sandstones. The content of calcium carbonate in these cementation concretions amounts to about 35 per cent.

Upper Nemegt Beds

Very fine-grained to very coarse-grained sandy sediments occur in the Upper Nemegt Beds, but fine- and medium-grained sediments distinctly predominate. The greater part of sediments consists of poorly consolidated sands (Text-fig. 4*A*). The only difference between the sands and the sandstones is the presence of calcite cement (see p. 166) in the latter.

Table 2

Composition of detrical framework in sandy sediments of Upper Nemegt Beds

Grade	Very coarse-grained (4 samples)	Coarse-grained (4 samples)	Medium-grained (10 samples)	Fine-grained (8 samples)
Quartz				
mean	29.8	47.0	61.8	69.3
minimum	15.0	40.5	51.0	61.5
maximum	51.5	54.5	81.0	75.0
Feldspars				
mean	17.3	25.0	30.9	27.7
minimum	11.0	16.0	18.0	21.5
maximum	29.0	40.0	40.5	38.0
Source rocks				
mean	5.9	4.3	2.3	1.6
minimum	3.5	2.0	1.0	0.5
maximum	7.0	6.5	6.5	3.5
Intraformational rocks				
mean	46.0	22.5	3.9	0
minimum	23.6	16.0	0	0
maximum	68.5	37.5	20.0	0
Other grains				
mean	1.1	1.2	1.1	1.4
minimum	0.5	0.5	0.5	0.5
maximum	1.5	1.5	1.5	1.5
Quartz/feldspar ratio				
mean	1.76	2.12	2.15	2.61
minimum	1.24	1.15	1.62	1.54
maximum	2.51	2.73	4.50	3.49

Single siltstone pebbles are common in the sandy sediments, irrespective of their grain size. With increase in the number of such pebbles, the sediments pass gradually from sands to intraformational conglomerates (p. 164). Large pebbles of exotic rocks (diameters ranging up to 10 cm) are sporadically distributed in the sands.

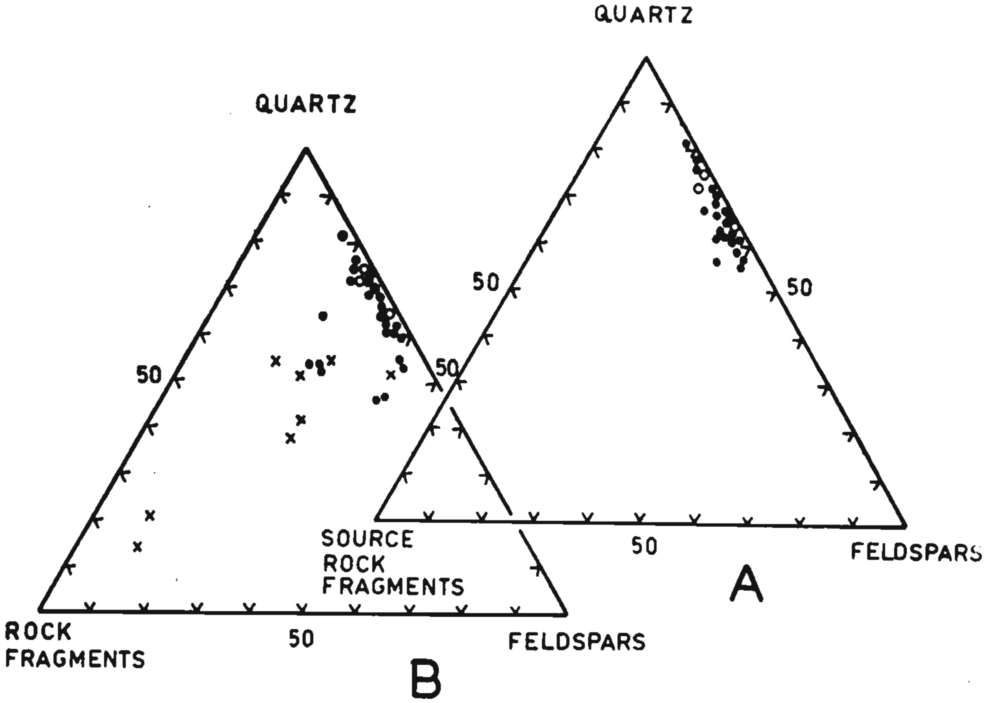

Fig. 5

Triangular diagrams showing composition of sandy sediments: *A*—petrogenetic diagram (intraformational clasts not included), circles — Lower Nemegt Beds, dots — Upper Nemegt Beds; *B*—petrographic diagram (rock fragments include both source rock fragments and intraformational clasts), circles — Lower Nemegt Beds, dots — Upper Nemegt Beds, fine- to medium-grade sandy sediments, crosses — Upper Nemegt Beds, coarse- to very coarse-grade sediments.

Yellowish-grey colours predominate in the sediments (10 YR 7/2, 10 YR 7/4), commonly with an orange shade (10 YR 7/6). Rarely a light grey colour is present (5 Y 7·5/1). A minor part of the sediments has colours of the red group (usually moderate light-brown, 5 YR 5·5/4, more rarely moderate reddish-brown 10 R 4/6); yellowish-brown (10 YR 6/4) sediments with red bands are more common. The grains of the red-coloured sediments have coatings consisting of aggregates of a brown anisotropic substance, or such a substance fills pits in the surface of grains. A chemical analysis of a red sand indicated the presence of 3·99 per cent of Fe_2O_3 and of 0·71 per of FeO, but in the diffractogram, the peaks of oxides and oxide hydrates of iron are absent.

The composition of the detrital framework (without matrix) in various sandy sediments of the Upper Nemegt Beds is shown in Table 2 and in Text-fig. 5. Because of the varying degree of cementation, the percentages of the constituents were determined in thin sections (15 samples) and in grain mounts (11 samples). The sources of error lie in the difficulties of discrimination between grains of intraformational rocks and matrix in some thin sections, and of determination of some grains in loose grains mounts. However, the mean values indicate a high percentage of fragments of intraformational rocks in coarse- and very coarse-grained sediments, and a distinct increase in the value of the quartz/feldspar ratio with decreasing mean grain diameter.

The content of detrital-clay matrix usually does not exceed 5 per cent. Only in some fine- and very fine-grained sandstones, the content of matrix reached 22—50 per cent. The content of calcite cement ranges from 3 to 42 per cent (see p. 166).

GRAVEL-GRADE SEDIMENTS

Lower Nemegt Beds

Gravel-grade sediments are represented by intraformational conglomerates and occur quite sporadically. They consist of pebbles of sandy claystone and fragments of calcareous concretions (see Table 3). In two cases, pebbles of source rocks were found (see p. 167). The diameters of pebbles usually do not exceed 20 mm. The pebbles are embedded in a sandy matrix, the content of which makes up more than 60 per cent of the rock. The conglomerates fill small, shallow pockets carved in erosional surfaces.

Upper Nemegt Beds

Conglomerates and intraformational gravels are common, and were seen in every outcrop. The conglomerates differ from the gravels only in the presence of calcite cement.

The gravels consist mainly of fragments of calcareous concretions, siltstones (often poorly unsolidated) and claystones. The percentage of pebbles of these different types is variable, but usually in the finer gravel grades, fragments of calcareous concretions predominate (Table 3). The diameters of the fragments of concretions range from a few mm to 3 cm. The size range of siltstone and claystone fragments is similar, but occasionally they reach 20 cm in diameter

Table 3

Composition of pebbles in intraformational conglomerates and gravels

Sample Nos.	Predominating diameter of pebbles (in mm)	Percentage		
		Calcareous concretions	Siltstone and claystone pebbles	Source rock pebbles
Upper Nemegt Beds:				
139/64 *	2—4	24	76	0
118/64 *	2—4	96	4	0
124/64 *	2—4	77	22	1
67/65 *	8—16	79	10	11
218a/65 *	8—16	93	7	0
218/65 *	16—32	73	27	0
36/65 **	16—32	76	24	0
101a/65 **	32—64	12	88	0
52/65 **	64—128	0	100	0
Lower Nemegt Beds:				
20a/65 **	16—32	26	74	0
233/65 **	16—32	32	18	40

* Pebble count on polished surface. ** Pebble count in outcrop.

and exceptionally boulders with diameters of around 50 cm were observed. Both macroscopic and microscopic features of the pebbles are identical with those of the sediments of the Upper Nemegt Beds already described.

The gravels and conglomerates lie, as a rule, upon scoured surfaces (see p. 182). This fact, together with petrographic characteristics of the pebbles, indicate that the gravels are of penecontemporaneous origin with respect to sedimentation. The gravels and conglomerates are therefore intraformational, corresponding to the definition given by WALCOTT (1894, p. 192). The only exotic constituents in the gravel grade are certain pebbles, occurring sporadically and in small quantities (see p. 167).

The pebbles are embedded in a sandy matrix, the content of which usually exceeds 60 per cent of the rock. The diameter of the grains in the sandy matrix is variable, but usually lies within the fine or medium sand ranges.

The gravel-grade sediments are usually light-coloured, according to the colours of the pebbles and of the matrix. The overall colour is usually yellowish-grey (5 Y 7/4), or greyish-orange (10 YR 7/4) and sometimes light brown-grey (5 YR 7/1).

HEAVY MINERALS

The heavy minerals analyses were carried out by Dr. J. ŁOZIŃSKI (Department of Mineralogy and Petrography, Jagellonian University). Seven samples taken from various types of sediments and from various points of the profile of the Nemegt Beds, were analysed:

M 3/65 — very fine sand, Upper Nemegt Beds, locality Tsagan Khushu,

77/65 — fine sand, Upper Nemegt Beds, locality Altan Ula IV,

Table 4

Composition of heavy minerals

Sample Nos.	M 3/65	77/65	18/65	201/65	217/65	138/65	20/65
Weight percentage of the heavy minerals	0.24	0.60	0.25	1.04	0.93	0.01	0.63
Percentage of opaque minerals	46	48	42	54	74	34	51
Tourmaline	2	2	3	1	1	2	tr. *
Zircon	10	13	15	4	7	11	11
Garnet	10	14	7	5	9	6	5
Rutile	tr.	tr.	1	—	—	—	—
Anatase	—	—	—	—	—	tr.	—
Titanite	6	4	tr.	17	12	12	14
Staurolite	3	—	—	2	4	—	3
Kyanite	—	2	2	—	—	—	tr.
Epidote	69	59	71	71	65	69	65
Amphibole	—	1	2	—	2	—	tr.
Chlorite	—	—	—	—	tr.	—	—
Undetermined	—	2	tr.	tr.	—	tr.	—

* tr. = trace

18/65 — medium sand, Upper Nemegt Beds, locality Altan Ula IV,
201/65 — fine sand, Upper Nemegt Beds, locality Nemegt,
217/65 — sandy claystone, Upper Nemegt Beds, locality Nemegt,
138/64 — claystone, Upper Nemegt Beds, locality Nemegt,
20/65 — fine sand, Lower Nemegt Beds, locality Nemegt.

The samples were treated with hydrochloric acid, in order to remove the carbonates and iron oxides and hydroxides. The clay grade was removed by decantation. The heavy minerals were separated in bromoform from the grade with grain diameters less than 0.50 mm.

The results of the analyses are given in Table 4. Percentages of mineral species are given only for transparent grains. The undetermined grains are very rare; they have a high refractive index, and morphological features do not permit definite identification. These grains may be cassiterite or titanite.

Minerals of the epidote group always predominate among the transparent grains. They are represented mainly by pistacite, accompanied by clinozoizite and zoizite.

CEMENTATION

Wide variation in the degree of cementation in the sand- and gravel-grade sediments is a characteristic feature of the Upper Nemegt Beds. The thickness of the cemented beds of sandstone and conglomerate is small, ranging usually from 10 to 30 cm, and exceptionally exceeding 1 m. In vertical profile, such cemented beds are spaced at irregular intervals, ranging from about 1 m to several metres. In the profiles of outcrops, the sandstones form about 7 per cent of sand-grade sediments, and the conglomerates about 60 per cent of gravel-grade sediments.

In spite of the small thickness, the lateral extent of the cemented beds is relatively large (a dozen to several hundred metres). The cemented beds are, as a rule, nearly horizontal, and form characteristic shelves on the slopes. Denudation terraces are developed on such beds.

The cemented beds usually directly overlie the claystones or siltstones. The cemented sediments pass gradually upwards into unconsolidated sediments. Such a passage is usually independent of sedimentary structures, often running across one set of cross-strata. Zones of stronger cementation are also sometimes present around the bones of dinosaurs. Such zones are up to 30 cm wide. Outside the cemented zone, there is a gradual passage into unconsolidated sediment. Such cementation zones usually accompany those dinosaur specimens showing a low degree of disarticulation (see p. 208).

The cementation consists of partial or complete filling of pores between grains by calcite. A coarse mosaic of calcite crystals filling the voids is visible in strongly cemented sandstones and conglomerates. In moderately cemented sediments, the calcite crystals are developed only on the borders of detrital grains.

The observed maximum content of calcite cement amounts to 42 per cent in fine-grained sandstones, 34 per cent in coarse-grained sandstones and 26 per cent in conglomerates These. values correspond fairly closely to the porosity of freshly deposited sediments of the individual grades (TRASK, 1931; HAMILTON & MENARD, 1956). The absence of pebbles of sandstones and conglomerates among the intraformational clasts indicates that the cementation of the sediments of sand- and gravel-grade was a relatively slow process.

The calcareous nodules common in the claystones (see p. 161) are cementation concretions. The content of calcium carbonate in the concretions ranges from 68.42 to 75.70 per cent (6 analyses). These values correspond to the porosity of freshly deposited sediment of clay-grade (TRASK, 1931; HAMILTON & MENARD, 1956). In thin section, numerous detrital grains of the same size range as in the enveloping rock are visible, dispersed in crystalline calcite. The content of non-carbonate material increases progressively in all directions away from the central part of the concretions, so that concretions progressively blend into the host rock. However, there is no nucleus or internal structure in the concretions. Only a few concretions show a brecciated appearance, due to the presence of patches or veins of coarse-crystalline calcite.

The irregular distribution of the concretions in the host rock suggest that they are not syngenetic according to PANTIN'S (1958) classification. However, there is no doubt that they were formed shortly after the deposition of the claystones and are probably early diagenetic. This conclusion is supported by the occurrence of small irregularities related with the occurrence of concretions, observed frequently on the eroded upper surfaces of the claystones and the mass occurrence of concretions and their fragments in the intraformational conglomerates. Pebbles of claystones containing concretions are fairly common in these conglomerates.

The rapid formation of calcareous concretions in argillaceous deposits was described by COLEMAN and GAGLIANO (1965) on the Mississippi River deltaic plain. These authors observed incipient concentrations of soft, calcareous material in deposits, formed as recently as 30 years ago, while larger and more indurated concretions were present in somewhat older deposits.

EXOTIC GRAVELS

Exotic gravels are rare. They are scarce in the Lower Nemegt Beds, and somewhat more common in the Upper Nemegt Beds, where they are, as a rule, dispersed in the intraformational conglomerates. Single, large pebbles were observed to occur sporadically within sandy sediments. The diameter of exotic pebbles usually ranges from 4 to 10 cm, reaching a maximum value of 16 cm.

Larger collections were made at the following localities: Tsagan Khushu (from one bed of intraformational conglomerate) Altan Ula (three beds) Nemegt (two beds), N part of Naran Bulak (one bed), and in the Lower Nemegt Beds in the E part of the Nemegt locality (from two pockets). The composition of these collections is presented in Table 5.

The following characteristics of rock types represented as exotic pebbles in the Upper and the Lower Nemegt Beds is based chiefly upon microscopic observations of 68 thin sections.

Granites and related vein rocks

Alaskites and their pegmatoidal and granophyric equivalents are present. Microcline predominates among the feldspars. The majority of rocks display epidotisation and chloritisation. Cataclastic deformation is common, and mylonitisation was observed in some cases.

Porphyries and porphyrites

The porphyries are characterized by small amounts of quartz, with spherolitic and felsitic structures in the groundmass. Plagioclases predominate among the phenocrysts, some orthoclase is also present. Porphyrites are represented by varieties both with and without quartz; plagioclases prevail among the feldspars, while orthoclase is present in small quantities. Propilitisation (formation of chlorite pseudomorphs after mafic minerals) and sericitisation are common.

Syenites

Quartz syenites, with orthoclase contents greatly exceeding that of plagioclase, are present.

Table 5

Composition of exotic pebbles

Rock type	Upper Nemegt Beds: Tsagan Kshushu	Upper Nemegt Beds: N Naran Bulak	Upper Nemegt Beds: Altan Ula IV	Upper Nemegt Beds: Nemegt	Lower Nemegt Beds: E Nemegt
	percentages				
Granites and related vein rocks	10	13.3	11.2	10.9	14.4
Porphyries, porphyrites	7.5	13.3	9.2	6.5	16.4
Syenites	—	—	2	2.2	—
Orthophyres	2.5	—	2	2.2	7.3
Pyroclastic rocks	22.5	20	33.7	15.2	21.7
Arkoses	35	26.7	18.4	30.5	20
Gneisses	12.5	13.3	14.3	13.0	7.3
Jaspers	7.5	—	2	6.5	1.8
Quartzites	—	6.7	4.1	4.3	1.8
Other rocks	2.5	6.7	3.1	8.7	9.1
Number of pebbles	40	15	98	46	55

Orthophyres

Orthophyres are represented by types with a trachitic structure of the groundmass. The feldspars belong mainly to the plagioclase group and are often altered. One of the specimens was impregnated with opaque minerals, and contained rare orthoclase phenocrysts with only a small amount of quartz.

Pyroclastic rocks

This group comprises lava agglomerates, tuff breccias and tuffs. The lava agglomerates are related to the porphyrites. The tuff breccias are composed of fragments of various volcanic rocks, displaying various degrees of alteration. Weathering of the components of the breccias is often indicated by stains of iron hydroxides. The tuffs are lithoclastic. Welded tuffs are common and lapilli tuffs are also present. They are considered to be dacitic-andesitic lavas. All rocks belonging to this group have a greenish-grey or reddish colour. Epidotisation and silicification are common and strongly marked.

Arkoses

The arkoses are most often greenish-grey or reddish in colour. They are very hard, owing to silicification. The grain size ranges from very fine to very coarse. Rock fragments and mineral grains are angular or subrounded. The arkoses are polymictic and usually rich in feldspars. Rock fragments are represented by various volcanic rocks, claystones, carbonate rocks, cherts and quartzites. In some pebbles, plagioclase predominates among the feldspars, while in others, K-feldspars are most aboundant. Matrix is relatively scarce, consisting of silt-clay ground mass, often with an admixture of volcanic ash.

Gneisses

Rocks of this group are represented mainly by muscovite-microcline gneisses, with a high quartz content. Another variety are gneisses with a hornfels structure and a high content of quartz, the latter which is accompanied by muscovite, microcline and plagioclases. Slightly metamorphosed arkoses, containing appreciable amounts of epidote besides quartz and feldspars were also noted.

Jaspers

Only red jaspers were observed. Microscopic observations reveal the presence of indistinct outlines of organisms, probably radiolarians.

Quartzites

These rocks consist almost exclusively of quartz grains with sutured contacts. In one specimen, small amounts of sericite were observed.

Other rocks

This group includes dark, strongly silicified rocks (probably cherts), and greenish-grey rocks, probably silicified and epidotized tuffs or arkoses, which were not determined in detail.

It follows from the above, that the exotic pebbles are represented only by rocks highly resistant to abrasion.

According to the opinion of Prof. T. WIESER, who examined all the thin sections, the exotic material permits the following conclusions to be made on the composition of the source area of the clastic material. The basement of the area was built of alaskite granites, with their pegmatoidal and granophyric equivalents. The contact zone is represented by hornfelses and hornfelsic gneisses (with plagioclases). The lack of biotite in the contact rocks indicates that the country rocks did not contain argillaceous minerals. The plutonic rocks were overlain by a sedimentary-volcanic series, consisting mainly of volcanoclastic arkoses, with grains poorly sorted and poorly rounded. The volcanic series consisted of palaeo-lavas: porphyries, porphyrites and orthophyres. Their pyroclastic equivalents comprise the lava agglomerates, tuff breccia, lapilli tuffs and welded tuffs. The epidotization and propilitization were probably related to sub-volcanic processes. This is indicated by the occurrence of rocks usually forming dykes, such as granophyres. Tectonic movements within the source-area are indicated by the frequent occurrence of cataclasis and mylonitisation of granites, gneisses and sedimentary rocks. The cataclasites and mylonites, although strongly altered and fragmented were preserved, owing to a strong secondary petrification in sub-aerial conditions (mainly silicification).

Arid climatic conditions with concomitant deep weathering probably prevailed in the source area. A thick layer of regolithe is related to marked differences in relief. All detrical rocks containing an admixture of volcanic ash and the tuffs were subjected to an intense silification, associated with hydrolisis of the vitreous particles.

GRANULOMETRIC COMPOSITION

The granulometric composition of the sediments was investigated by means of two methods: sieve analysis (30 sand samples, 5 gravel samples) and microscopic (point-counter) analysis (19 thin sections of sandstones, siltstones, and conglomerates). The grades finer than

0.0625 mm were analysed in 5 samples by hydrometric methods. The cumulative curves of grain size distribution were drawn on logarithmic probability paper and the parameters of the distribution were computed from formulae of Folk and Ward (1957). Sediment properties defined by values of the parameters introduced by the above authors *(l. c.)* are considered valid in this paper.

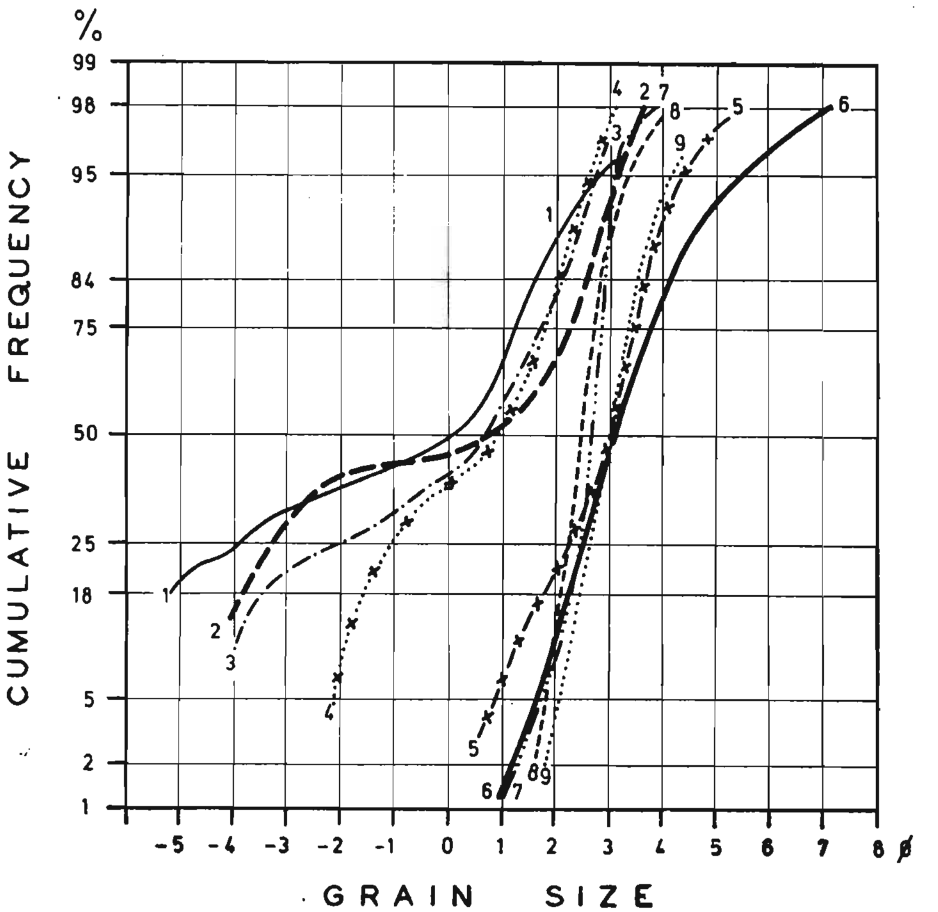

Fig. 6
Grain-size distribution based on mechanical analysis for sediments belonging to the Nemegt Beds. Upper Nemegt Beds: pebbly sands *(1, 2, 3, 4)*, sands with large-scale trough cross-stratification *(8, 9)*, sands with large-scale tabular cross-stratification *(7)*, sands with climbing-ripple structures *(6)*. Lower Nemegt Beds: sands with small-scale cross-stratification *(5)*.

A relatively large error is inherent to the results of the individual analyses based on either of the two methods. The sieve analyses of sediments containing fragments of poorly consolidated rocks (gravel samples, some sand samples) were analysed by a composite method. The rock fragments were first picked and measured, and the remaining part of the sample was sieved mechanically. In the case of microscopic analysis, the limited size of thin sections made impossible the obtaining of fully representative results for rocks containing larger pebbles. Therefore the results of analyses should be regarded as being only approximate. However, as the granulometric composition of the various types of sediments shows marked differences, the results obtained are sufficient for a general characteristics of these sediments.

The results of the granumetric analyses are:

1) Sorting of the sediments of the Nemegt Beds ranges from very poor (3.20) to good (0.38). The sorting is distinctly dependent on mean grain size (Text-fig. 10);

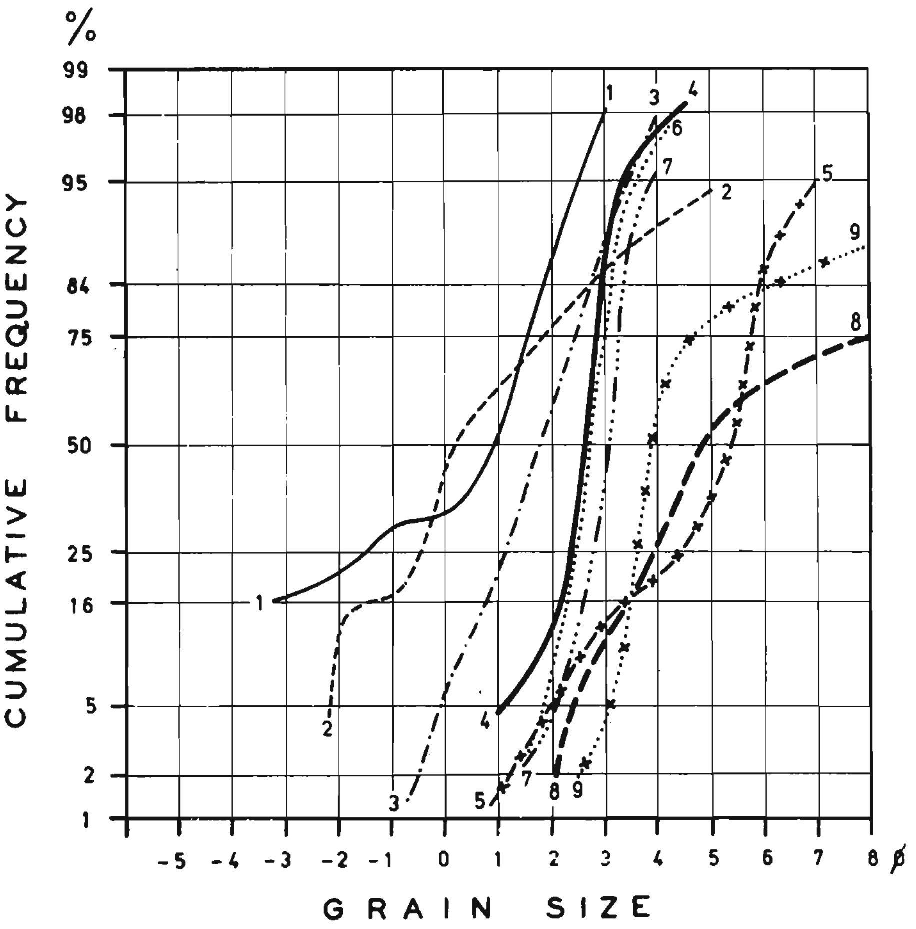

Fig. 7

Grain-size distributions based on thin section analysis for the Nemegt Beds. Upper Nemegt Beds: pebbly sandstones *(1, 2)*, sandstones with large-scale trough cross-stratification *(4, 6)*, sandstone with large-scale tabular cross-stratification *(7)*, siltstones *(5, 8, 9)*. Lower Nemegt Beds: structureless sandstone *(3)*.

2) Sediments of the fine-sand grade show the best sorting, being as a rule moderately to well sorted. The sediments of coarser and finer grades show poorer sorting. The high values of sorting of sediment with mean size (Mz) values smaller than phi 1 are related with the presence of intraformational gravel, and in sediments with values of mean size larger than phi 4 are caused by the presence of an admixture of sand grains in silts and clays;

3) Sediments with values of mean size smaller than phi 1 are polymodal or bimodal with one peak within the sand grade, and remaining peaks within gravel grades. The modal grain sizes vary from sample to sample both for sand and for gravel.

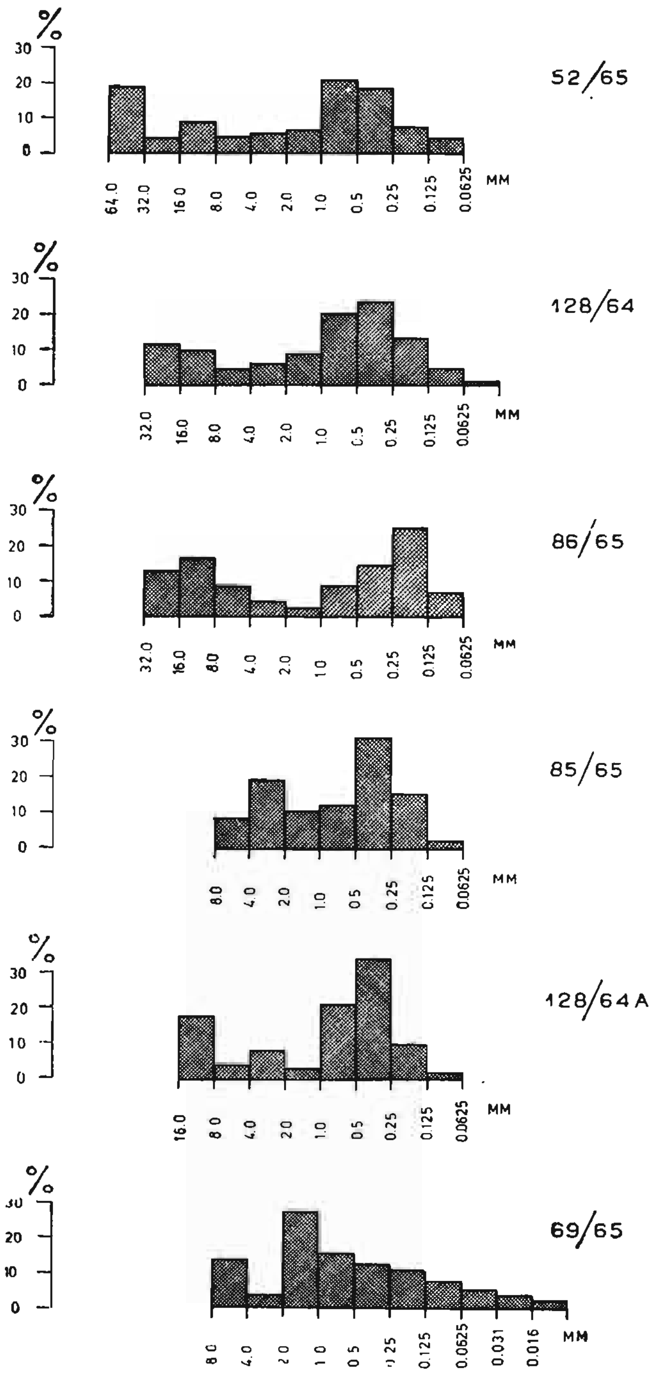

Fig. 8
Histograms showing grain-size distribution of intraformational conglomerates and pebbly sands from the Upper Nemegt Beds. Number of samples from the author's collection are given on the right-hand margin.

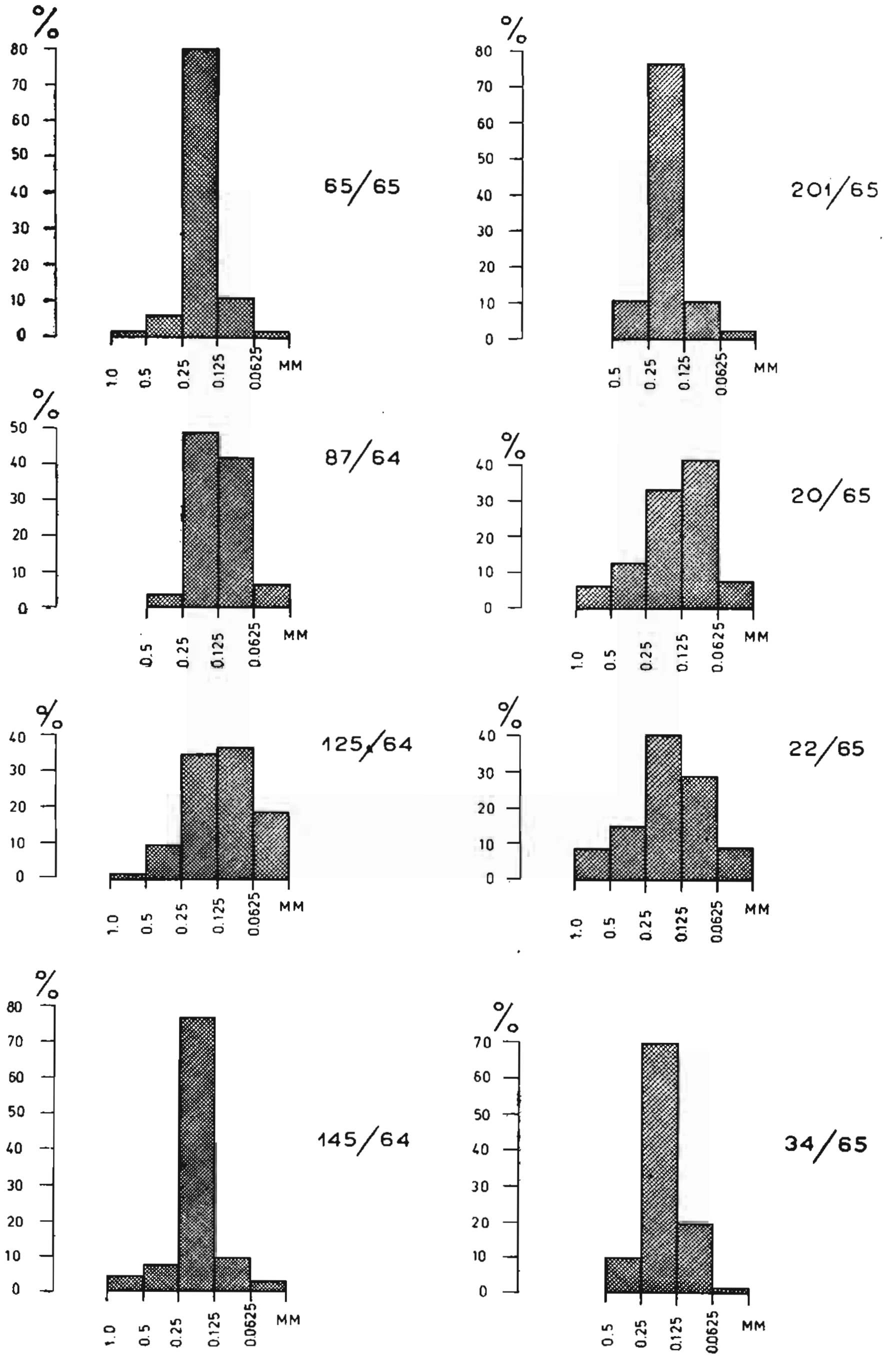

Fig. 9
Histograms showing grain-size distribution in sands. Lower Nemegt Beds: samples 20/65 and 22/65. Upper Nemegt Beds: all remaining samples.

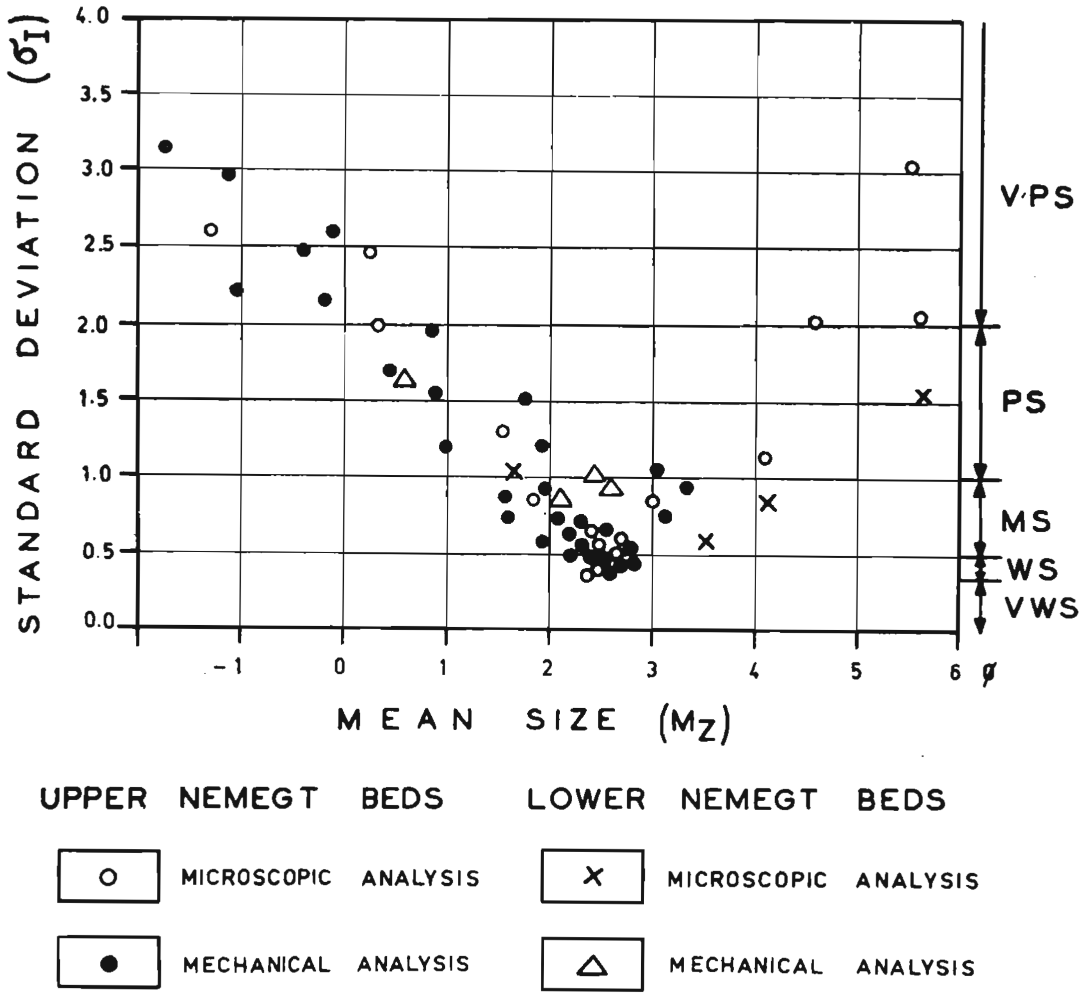

Fig. 10

Scatter plot of mean size against standard deviation (sorting). Letters along the left-hand margin correspond to sorting classes: *VWS*—very well sorted, *WS*—well sorted, *MS*—moderately sorted, *PS*—poorly sorted, *VPS*—very poorly sorted.

ROUNDNESS AND SHAPE

Grains

The roundness and sphericity of grains were determined for the grades 0.25—0.3 mm, 0.5—1 mm and 1—2 mm, by visual comparison with the standard table published by Krumbein and Sloss (1963, Fig. 4—10, p. 111). The determinations were carried out for 10 samples of sand. The parameters were determined separately for 100 grains of quartz and feldspar in each grade; in some of the samples 50 grains were determined for the coarsest grade. Histograms of roundness and sphericity of two representative samples are presented in Text-figs. 11, 12.

The results and the observations of other samples and of thin sections indicate that low values of roundness of grains is a characteristic feature for the sediments of the Nemegt Beds. In all grades, the rounding of feldspars was higher than the rounding of quartz. Moreover,

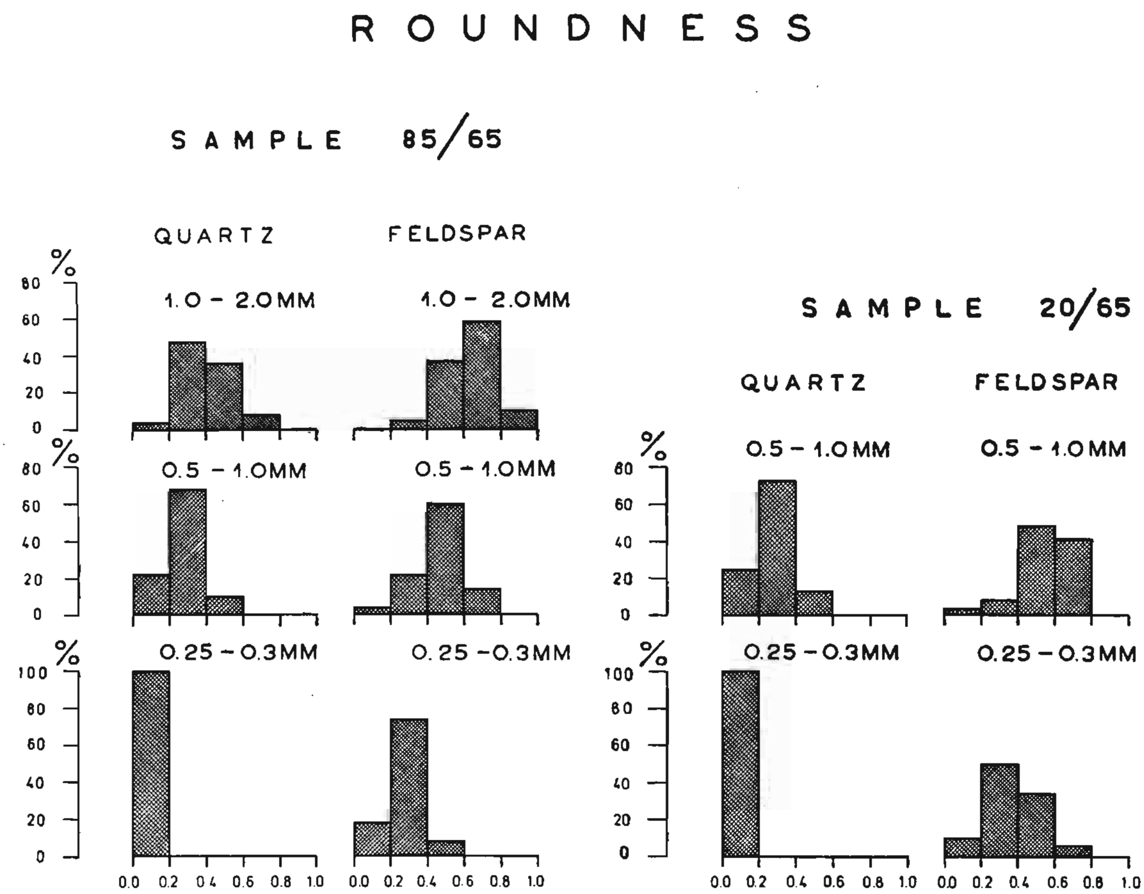

Fig. 11
Example of differences in roundness of quartz and feldspar grains for different grades of the same sample. Sample 85/65 — sand, Upper Nemegt Beds, sample 20/65 — sand, Lower Nemegt Beds.

Table 6

Roundness and sphericity of grains (mean values of 10 samples)

Grain diameter (in mm)	Roundness		Sphericity	
	quartz	feldspar	quartz	feldspar
0.25—0.3	0.11	0.28	0.51	0.63
0.5 —1.0	0.22	0.53	0.57	0.69
1.0 —2.0	0.34	0.67	0.68	0.75

especially in the fine grades, the feldspar grains show a great variation of roundness, ranging from angular to rounded. The occurrence of angular feldspar grains is probably the result of fracturing of rounded grains along cleavage planes during transportation (KRYNINE, 1950).

Exotic gravels

A systematic observation of the relationship of size and roundness amongst the exotic gravels was undertaken for 83 pebbles of granites, volcanic rocks, silicified arkoses and pyroclastic rocks, quartzites and jaspers. Only the arkose pebbles show a distinct increase of roundness with increasing diameter, and a similar relationship is less distinct for granite pebbles. Pebbles of other types of rocks are subangular, subrounded or rounded regardless of their size.

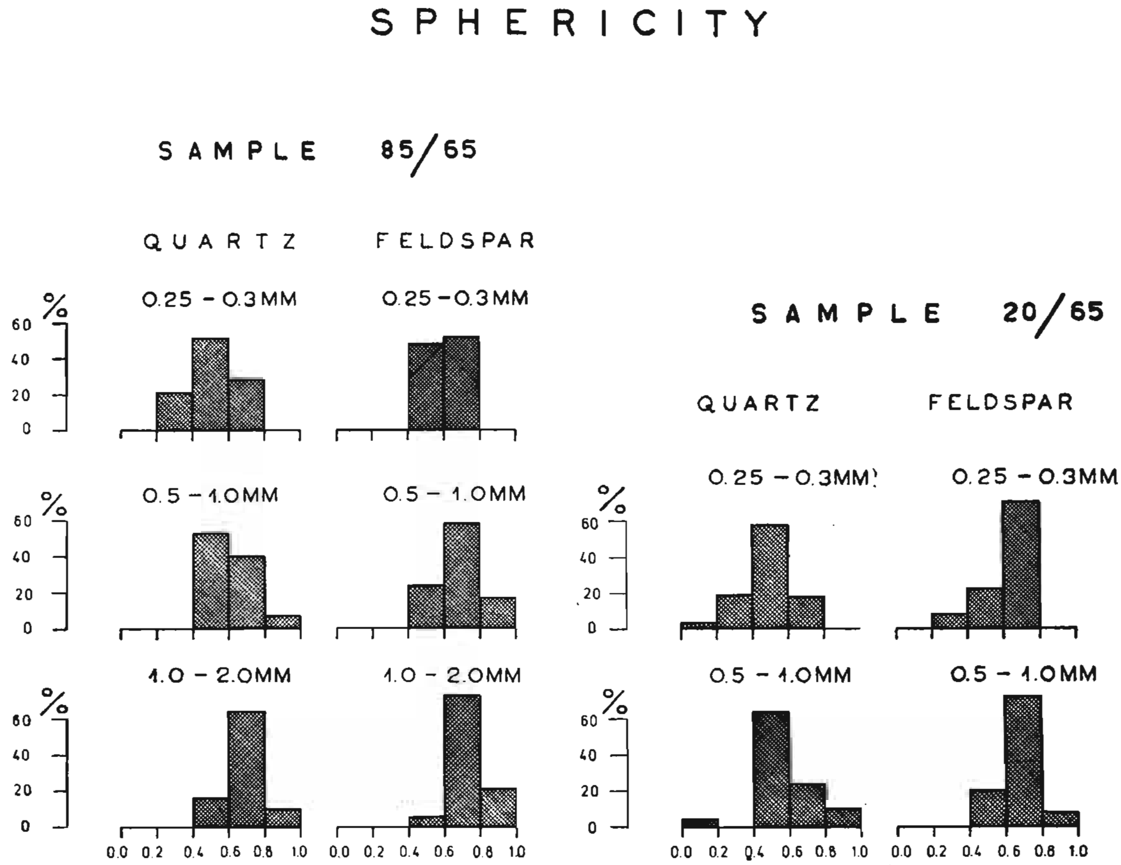

Fig. 12
Example of differences in sphericity of quartz and feldspar grains for different grades of the same sample. Same samples as in Fig. 11.

Intraformational gravels

Pebbles of siltstones and claystones vary considerably in shape and roundness. Small pebbles ranging in diameter from a few mm to 20 mm are predominantly discoidal and more rarely spherical or bladed. Among pebbles with larger diameters, spheroidal and discoidal shape prevails. Typical mud-balls are rare, but they predominate in some conglomerate layers. Roundness varies from subangular to well rounded, the greatest variation being seen in the grade 5—25 cm.

Pebbles consisting of calcareous concretions are usually spheroidal and subrounded, or more rarely, rounded.

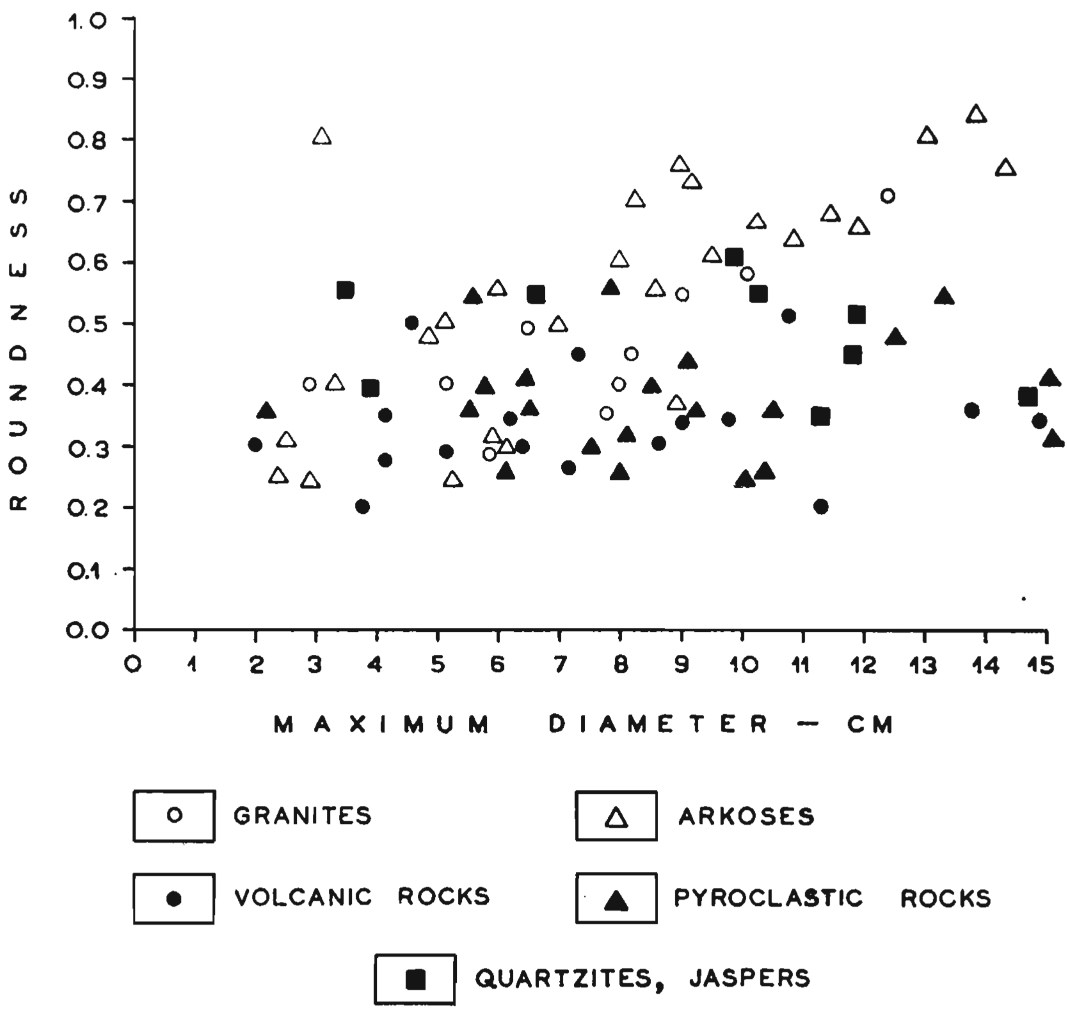

Fig. 13
Roundness of exotic pebbles plotted against maximum diameter.

PETROGRAPHIC CONCLUSIONS

Comparison of the mineral composition of sediments with the types of rocks represented by exotic (source-rock) pebbles in the conglomerates indicates that both mineral grains and pebbles were supplied from the same source area. Acid and intermediate volcanic rocks occurring in this area (porphyries, porphyrites and orthophyres) and related pyroclastic rocks were probably the main source of K-feldspars. Feldspars were also supplied by acid, plutonic rocks, gneisses and probably also by arkoses, occurring commonly among the source-rock pebbles. It should be stressed that a distinct epidotization was recorded in the majority of the investigated source-rocks pebbles. Furthermore, epidote is one of the principal heavy minerals present in the sediments of the Nemegt Beds, and occurs both in fine-grained and medium-grained sediments. The relation of the mineral composition and the exotic material is also indicated by the presence in the sand grade of rock fragments, similar in type to the exotic pebbles.

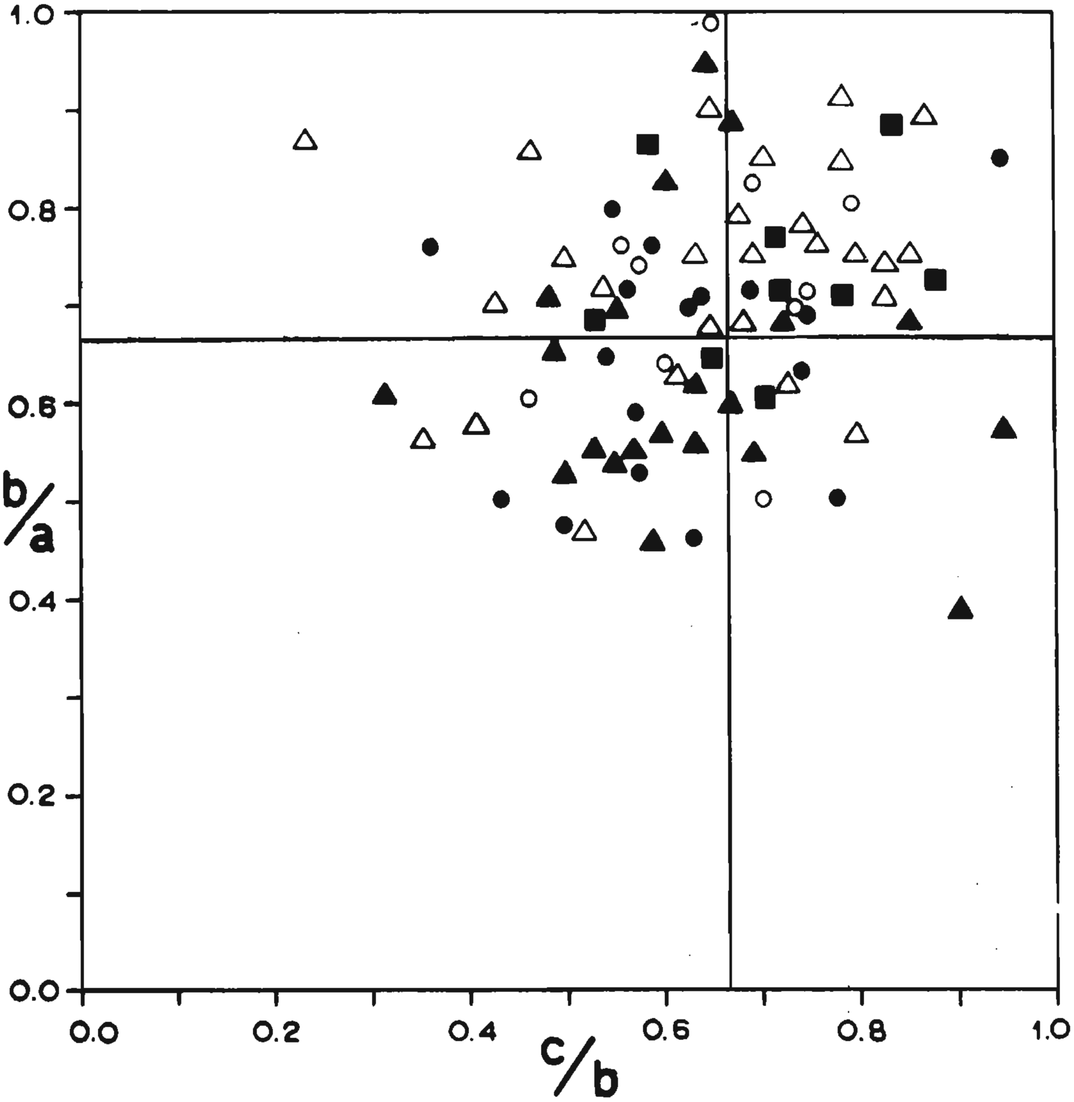

Fig. 14
Axial shape coefficients for exotic pebbles (method after Zingg, 1935): *a* long axis, *b* intermediate axis, *c* short axis of pebble. Same pebbles as in Fig. 13.

The presence of a large amount of feldspars in sediments is considered to be the result of rapid erosion of a source area built of acid igneous rocks followed by rapid deposition (REED, 1928; KRYNINE, 1935). Arkosic sediments are usually contemporaneous with large-scale block faulting (KRYNINE, 1948). In Mongolia and neighbouring regions, such processes occurred in late Jurassic time (BERKEY & MORRIS, 1927; LEE, 1962; VASILEV *et al.*, 1959). The marked differences in relief, caused by faulting, created conditions favourable for the rapid erosion of the elevated horst, from which the Jurassic rocks were removed. The Jurassic is represented in Mongolia by a thick series of clastic rocks, mainly arkoses and conglomerates, with numerous intercalations of pyroclastic rocks and effusive and intrusive igneous rocks, chiefly porphyries, porphyrites, syenites and orthophyres (BERKEY & MORRIS, 1927; MARINOV, 1957; VASILEV *et al.*, 1959). It should be added, that according to MARINOV (1957, p. 149), the pyroclastic rocks of Jurassic age are often silicified. The close petrographic similarity between exotic pebbles in the Nemegt Beds and the Jurassic rocks leads to the conclusion, that the latter were probably the main source of the clastic material of the formation described. However, a part of the exotic pebbles may be derived from Lower Cretaceous rocks (see MORRIS, 1936).

The decrease in the value of the quartz/feldspar ratio with increasing grain diameter observed in the sandy sediments of the Nemegt Beds (see Table 2) can be explained by the presence of a relatively high amount of large feldspar phenocrysts in the volcanic rocks. A high degree of rounding of feldspar grains (see Text-fig. 11) indicates, that the process of fracturing of the feldspar grains along cleavage planes suggested by KRYNINE (1950) was not the rule, although it certainly operated to some extent, as the degree of rounding of the feldspar grains show a large variation in the individual grades (Text-fig. 11). Higher roundness values for feldspar than for quartz grains are explained by the smaller resistance of the former to abrasion (KUENEN, 1959*a*).

The presence of a certain number of subrounded and well rounded quartz grains in the coarser grades of the investigated sandy sediments may be explained in the light of the experiments of KUENEN (1959*a*, 1959*b*, 1960) by the assumption that these grains are derived from older sedimentary rocks.

Pebbles of hard rocks are present exclusively in the exotic gravels. This indicates selection of the gravel material supplied. The elimination of unresistant rocks during river transport is accomplished on a distance of a few tens of kilometres (see, for instance, PLUMLEY, 1948; UNRUG, 1957). Among the exotic pebbles of the Nemegt Beds, only the arkoses, the relatively less resistant, show a distinct positive correlation between diameter and degree of rounding. The absence of this relation in other types of exotic rocks can be explained by specific conditions of transport. The dispersion of the pebbles in the sandy sediments indicates that they were transported with large amounts of sand. The experiments of KUENEN (1956) proved that, in such conditions, the intensity of the abrasion of pebbles is greatly reduced.

Large variability of sorting of the sediments from well sorted to very poorly sorted (Text-fig. 10) is a characteristic feature of the formation described, especially of the Upper Nemegt Beds. In the case of conglomerates and, to some extent, sands, the poor sorting is the result of the presence of an admixture of fragments of basin rocks. Sorting is therefore related to the conditions existing in the area of deposition and not to the granulometric composition of material transported from the source area.

The Nemegt Beds are considered as typical red-beds on account of continental facies, red colour, predominance of arkosic sandstones and generally poor sorting. Other features of the Nemegt Beds similar to those of other red-beds formations will be discussed later.

Investigations of red-beds proved (for references, see VAN HOUTEN, 1961) that the red colouration is due to the presence of trivalent iron, occurring chiefly in the form of haematite. According to a number of authors (REED, 1929; KRYNINE, 1935; RAYMOND, 1942, VAN HOUTEN, 1961), the haematite was formed in red upland soils of the source area, in tropical or subtropical conditions. High seasonal precipitation and large variation of the water table (savanna-type climate) are considered as being especially favourable for the formation of haematite. According to this hypothesis, the haematite is transported to the area of deposition as very fine detritus, and therefore is present chiefly in the argillaceous sediments and as coatings on sand grains. According to KRYNINE (1935, 1949), intense incision of valleys in the source area results in simultaneous transportation of fresh clastic material with the weathered red soil. VAN HOUTEN (1961) suggested that a warm and humid climate predominated also in areas of deposition of red-beds, although seasonal droughts possibly also occurred. It should be added, however, that T. R. WALKER (1967) proved that authigenic haematite may be formed after deposition in a dry climate. According to this author, the haematite pigmentation of some red-beds, especially of those associated with evaporites and aeolian sediments was formed in this way.

The intense red colour is distinctly associated with fine-grade sediments in the Nemegt Beds. The red claystones are characterized by a high content of trivalent iron compounds and high values of the Fe^{3+}/Fe^{2+} ratio (Table 1) as compared with coarser sediments. These facts suggest transportation of the red pigment from the source area to the sedimentary basin, in the form of fine detritus. On the other hand, the fineness of grains of trivalent iron compounds is indicated by the presence of relatively small peaks of haematite in the differactograms and the absence of peaks of hydrohaematite, goetite and lepidocrocite. The presence of red claystone pebbles in drab intraformational conglomerates precludes the possibility of secondary formation of the red pigmentation in these rocks. In coarser red-coloured sediments, the pigmentation is seen as coatings on grains or as fillings of pits on grain surfaces by a red substance. Only in rare instances, the possibility of secondary formation of the red colouration cannot be excluded.

On the assumption that the bulk of the trivalent iron compounds is derived from the source area, it may be stated that the sediments of the Nemegt Beds were deposited in an oxidizing environment.

SEDIMENTARY STRUCTURES

BEDDING

In the Nemegt Beds, the distinction between sediments of various lithological types is sometimes obscure. However, owing to variable resistance to erosion, bedding is relatively distinct in weathered vertical sections. This permits the distinction of stratification units. In the present paper, such a unit is termed "bed". This term corresponds to a "stratum" according to the definition given by PAYNE (1942, p. 1742, p. 1742) and is somewhat wider in application than the term "bed" in the sense of McKEE and WEIR (1953); some beds described here correspond to "sets" and "cosets" (in the sense of McKEE and WEIR, *l. c.*). The thickness classification of beds used in the present paper is based on the scale of INGRAM (1954).

As the dip of the whole complex of the Nemegt beds is very small, the author uses, for the sake of simplicity, the adjective "horizontal" referring to beds parallel to the principal surface of accumulation of the formation. In reality, such beds dip SSW at an angle of 1—2°.

Lower Nemegt Beds

Medium- and thick-bedded sandstones predominating in this member often alternate with very thin- and thin-bedded, sandy siltstones. Beds of very thin- to medium-bedded silty claystones occur at vertical intervals of a few m. The limits of beds are indistinct and related to gradual changes in lithology. Most beds are horizontal and display great lateral persistence. Sometimes, individual beds can be traced for at least 100 m and frequently over much larger distances, limited only by the size of exposures. However, wedging out of individual beds is fairly common. Complexes of beds several m thick, displaying large-scale inclined stratification (p. 197), occur occasionally in the Lower Nemegt Beds.

Upper Nemegt Beds

In the sediments of the Upper Nemegt Beds, the conglomerates are usually thin-bedded, sands are thin- to very thick-bedded, siltstones are very thin- to thick-bedded and claystones occur in medium to very thick beds. Individual beds show large changes of thickness and a variable, but usually small, lateral persistence. These changes in thickness and the lateral disappearance of beds are either depositional features or are due to erosion following deposition. As a result of these two processes, the lithological variability, both lateral and vertical, is very large in the Upper Nemegt Beds. Lithological profiles of the same exposure, spaced a few tens of metres apart, are often entirely different.

The claystones exhibit the greatest lateral persistence. In vertical profile, claystone beds occur at intervals of several metres. Thick claystone beds are parallel and horizontal. Many of them can be traced over a distance of 200 m, and often for larger distances limited only by the dimensions of exposures. The most extensive of the observed beds exposed in the cliffs in the central part of the Central Sayr at the Nemegt locality was traced over an area of 750×2300 m. The lateral limit of this bed is visible only on the SE side, where it is truncated by a large erosional channel.

The bedding surfaces of thick claystone beds are considered by the author to be planes parallel to the principal surface of accumulation of the Upper Nemegt Beds. These surfaces have been used for the determination of the dip and strike (see p. 156).

Besides the claystones, only some conglomerate beds show a lateral persistence in the order of a few hundred metres. Such conglomerate beds are related to widespread horizontal, erosional surfaces (scoured surfaces of ALLEN, 1962*b*).

Other conglomerate beds, sand beds and the majority of siltstone beds can be traced in the exposures for several metres or at the most for several tens of metres. Wedging out of beds, erosional truncation and gradual lateral passages from one lithological type to another are common. Bedding surfaces of most beds are usually inclined slightly with respect to the principal surface of accumulation of the formation. Complexes of sand/siltstone beds several metres thick displaying large-scale inclined stratification are frequently observed (see p. 193).

SCOURED SURFACES AND CHANNELS

Lower Nemegt Beds

Erosional structures are rare in the Lower Nemegt Beds. Relatively small erosion channels were observed only in a few exposures. In transverse section, the channels are 6—40 m wide and 1—4 m deep. The channel index defined as width/depth ratio (BLUCK & KELLING, 1962) ranges from 6 to 10. The even bottoms of the channels are concave upwards, with a regular shape. In the marginal parts of the channel, these surfaces become flat and gradually pass into horizontal bedding surfaces, showing no traces of erosion. A composite channel, consisting of two superposed channels (see BLUCK & KELLING, *l. c.*), was observed only in one exposure.

The sediments filling the channels are usually identical to those in which the channel is incised. Within the channel, beds lie concordantly on its bottom and are thickest along the axis of the channel. At the margins of the channels, these sediments pass continuously into the overlying horizontal beds.

Rare exceptions are provided by thin (ca. 10 cm) lenses of intraformational conglomerate, found in some shallow pockets. Pebbles of exotic rocks were present in two such pockets.

Upper Nemegt Beds

Erosional structures are common in the sediments of the Upper Nemegt Beds and can be observed in every outcrop. The most frequently occurring type consists of a sharply marked erosional surface, covered by intraformational conglomerate, or by sandy sediments with incorporated fragments of basin rocks. Such surfaces truncate beds of fine-grained, often argillaceous sediments. Erosional structures with similar features were termed scoured surfaces by ALLEN (1962*b*).

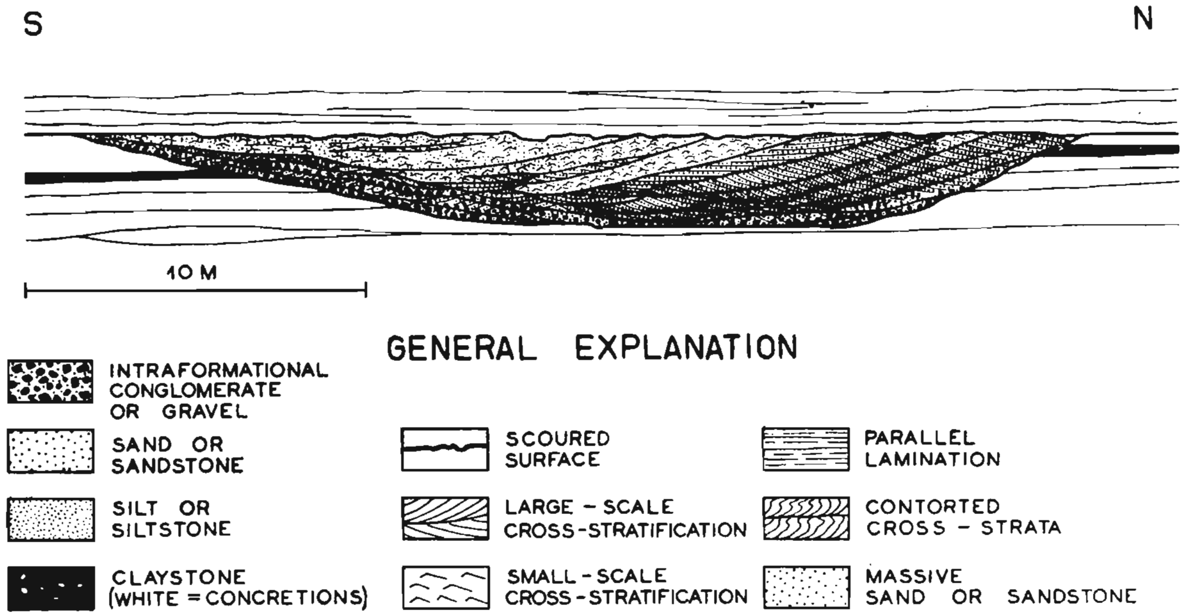

Fig. 15

Transverse, vertical section of an erosional channel of medium size, slightly schematized. Lithological character and sedimentary structures limited to sediments within the channel. Upper Nemegt Beds, locality Altan Ula IV, Eagle Sayr.

Large, nearly horizontal scoured surfaces are very characteristic for the Upper Nemeg. Beds. In vertical profiles, they are spaced a few metres apart. Usually, the whole surface is flatt Many horizontal scoured surfaces can be followed without change in two perpendicular directions over a distance of several hundred metres. A gradual disappearance of the erosional character of such surfaces is, however, common.

In many exposures, margins of scoured surfaces were observed. In such occurrences, the scoured surface rises within a vertical section for distances of a few up to several metres and either is truncated by a higher horizontal scoured surface or flattens and passes gradually into a bedding surface, without distinct traces of erosion. In both cases, such margins of a scoured surface represent the outer limits of an erosion channel. It should be added, that in some exposures, both margins of an erosional channel with a nearly flat horizontal central part were observed. The sediments filling such channels are identical with the sediments overlying the large scoured surfaces (see p. 203). All these observations indicate that each of the horizontal scoured surfaces can be regarded as a fragment of the bottom of an erosional channel, of local, though occasionally wide lateral extent.

Erosional channels with the entire cross-section visible are common among large-scale erosional structures. The width of channels observed ranged from several m to 130 m, while the depth ranged up to 7 m. Channels in the order of a dozen m wide usually exhibit sections concave-upwards, while the wider ones are nearly flat in the axial parts of the bottom. Both have asymmetrical margins, and the inclination of the steeper margin usually amounts to 15—20°, but may reach up to 40° The majority of channels are filled with a layer of intraformational conglomerate, overlain by a set of sand layers. Siltstone intercalations also occur. The channel-fill sediments usually display large-scale inclined stratification.

Some of the horizontal scoured surfaces and channel bottoms described above are smooth or gently undulating. Others have variable relief. The largest of these irregularities in relief are about 60 cm deep and are related to the presence of secondary erosional structures. The largest and the most characteristic of these have the shape of downward-facing bulges, asymmetrical in section. The upcurrent wall is noticeably steeper than the other, and sometimes nearly

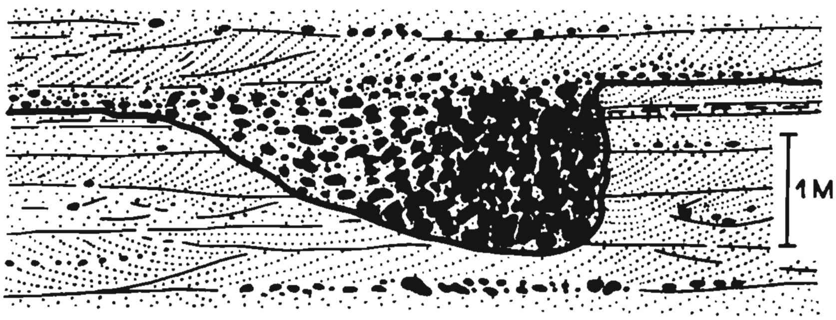

Fig. 16
Erosional bottom form of plunge-pool type, slightly schematized. Upper Nemegt Beds, locality, Altan Ula IV Eagle Sayr.

vertical (Pl. XXXVII, Fig. 1). Large bulges are up to 2 m wide and up to 3 m long. The shape of the bulges resemble the bottom (bed) forms of rivers described as plunge pools (NORDIN, 1964).

A more detailed elaboration of the features of structures associated with small-scale irregularities of the scoured surfaces is not possible because of the weakly cemented nature of the filling sediments. There is no doubt, however, that these forms represent scour markings of various types. Some of the scour markings occur in groups and are asymmetrical in vetrical cross-section. It seems probable that such forms are the flute markings described by many authors (among others, CROWELL, 1955; DŻUŁYŃSKI & SANDERS, 1962). If the scoured surface truncates claystones containing calcareous concretions, then shallow depressions are present around the concretions. Probably these are forms of current crescents (PEABODY, 1947, MCKEE, 1954).

Besides horizontal scoured surfaces and erosional channels, a third type of large-scale erosional structure is present in the Upper Nemegt Beds. These are relatively deep (up to 2 m) but short and narrow depressions (Text-fig. 16). In cross-section, they are markedly asymmetrical, the steeper margin being often nearly vertical. These forms are nearly entirely filled with siltstone and claystone fragments ranging in diameter up to 40 cm. Moreover, non-stratified sands, with irregularly dispersed pebbles, are present at the downcurrent ends of such forms. These depressions are closely similar to relatively small plunge pools described from the river channel of Puerco Rico (NORDIN, 1964). According to the author cited, the plunge pools are formed during periods of low and intermediate flow, and filled chiefly during periods of high flow (see also SIMONS *et al.*, 1965, pp. 45—46, Figs. 14, 15).

PARALLEL LAMINATION

The term parallel lamination is used for laminae lying concordantly one upon another, parallel to the lower surface of bed.

Lower Nemegt Beds

Parallel lamination, similarly as other internal structures, is observed rarely in the Lower Nemegt Beds, occurring in siltstones and sandstones. The laminae are horizontal though often indistinct and discontinous.

Upper Nemegt Beds

Parallel lamination occurs most often in horizontal or slightly inclined siltstone beds. The lamine are even or slightly wavy and often discontinuous. Beds with parallel lamination very often cover pre-existing bottom forms. Deposition was presumably the result of relatively slow setting from suspension in quiet water or in a current, which had a velocity insufficient to produce ripple marks in sediment (see HARMS & FAHNESTOCK, 1965; SIMONS & RICHARDSON, 1965, p. 52, fig. 21).

Parallel lamination occurs in sands much more rarely than do other structures, and can be seen only in certain exposures. Horizontal laminae occur usually immediately above gravels, which contain large (up to 40 cm in diameter) blocks of siltstone or claystone (Pl. XXXIX, Fig. 1). The laminated sands pass upwards into cross-stratified sediments, or are covered by structureless layers of intraformational conglomerate. Experimental studies (see, for example, SIMONS & RICHARDSON, 1963; SIMONS *et al.*, 1965) and observations of recent sediments (HARMS *et al.* 1963; HARMS & FAHNESTOCK, 1965) indicate that horizontally laminated sands are deposited in conditions of the upper flow regime. In the case of horizontal lamination occurring in the sands of the Upper Nemegt Beds, the existence of such condition is suggested by the occurrence of the described structures immediately over coarse gravels.

CLASSIFICATION AND TERMINOLOGY OF INCLINED STRATIFICATION

The term "inclined stratification" is used in this paper to define stratification of primary origin, inclined to the principal surface of accumulation of a formation. This term is used in its general and purely descriptive sense (see also POTTER & PETTIJOHN, 1963, p. 69).

The term "cross-stratification" is used to denote a particular type of inclined stratification. It is limited to structures confined to a single sedimentation unit (in the sense of JOPLING, 1964). A set of cross-strata forms "the smallest and most basic group unit" (MCKEE & WEIR, 1953, p. 383). Thus a continuous series of cross-strata is inclined to the lower bounding surface of this set. However, this surface may display various attitudes with respect to the principal surface of accumulation of a formation (see Text-fig. 17). The term "coset" is used here in the sense of ALLEN (1963*b*, p. 98), to denote an assemblage of vertically adjoining sets, which are essentially similar in type of cross-stratification. The descriptions and classifications of cross-stratified structures are based chiefly upon the geometric features of the latter. The terminology used here is based on that of MCKEE & WEIR (1953). The modifications concern criteria and descriptive terms listed below:

1) Magnitude of set (see ALLEN, 1963*b*): small-scale (< 5 cm), large-scale (> 5 cm),
2) Grouping of sets (see ALLEN, 1963*b*): solitary, grouped,

3) Shape of lower bounding surface of set (simplified after ALLEN, 1963*b*): planar, trough, irregular,

4) Relation of cross-strata to the lower bounding surface of set (after ALLEN, 1963*b*, with the "concordant" type omitted): angular, asymptotic (tangential),

5) Relation between the lower bounding surface and the stratification of the underlying set (simplified after CROOK, 1965): parallel, non-parallel.

The classification of cross-stratified structures based on geometric criteria facilitates without genetic implications the compilation of a detailed inventary of the structures present in the formation studied.

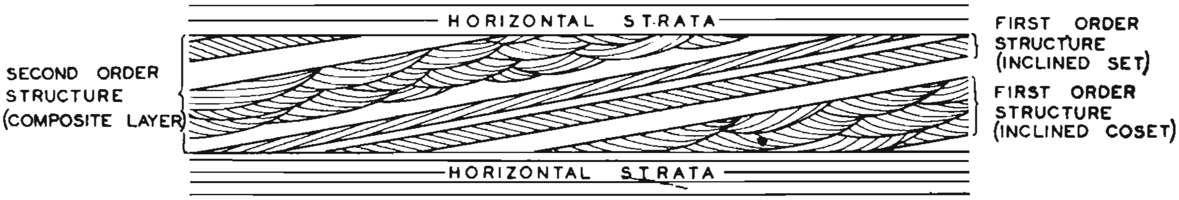

Fig. 17
Schematic diagram showing orders of structures with inclined stratification.

Existing terminology for inclined stratification is usually limited to cross-stratification. Other structures with inclined stratification are large-scale phenomena, frequently neglected. The latter are characteristic for sediments, such as these of deltas, spits and bars and lateral accretion deposits (see POTTER & PETTIJOHN, 1963, p. 69).

In the Upper Nemegt Beds, the latter structures are common and their presence is one of the characteristic features of this formation. All such structures are termed here "large-scale inclined stratification". In many cases, relatively smaller structures of cross-stratification type occur within the inclined strata. Such composite structures, shown diagrammatically in Text-fig. 17, are termed here "composite inclined stratification".

Structures of composite, inclined-stratification type are classified hierarchically. The whole complex of inclined strata is regarded as an inclined stratification structure of the second (higher) order. The individual sets or cosets of such a complex, which form single layers are regarded as first (lower)-order structures. The hierarchy in which the basic structures are assigned to the lowest order of magnitude is based on an analogy with stream orders (HORTON, 1945).

CROSS-STRATIFICATION IN THE UPPER NEMEGT BEDS

GENERAL

Flume experiments and studies of structures formed in recent sediments (for examples and references see SIMONS & RICHARDSON, 1961; SIMONS *et al.*, 1965; BRUSH, 1965; HARMS & FAHNESTOCK, 1965; ALLEN, 1963*c*, 1965*a*) indicate that most cross-stratified structures are related to the migration of bottom forms and are produced in the lower flow regime.

The migrating ripples, which predominate in the lower part of this regime, form small-scale sets, while dunes (large ripples) which are characteristic for the upper part of this regime give rise to large-scale sets (ALLEN 1963*a*; HARMS & FAHNESTOCK, 1965). However, cross-stratified structures of various sizes may be formed also by aggradation to a profile of equilibrium. Examples of such "delta-type" structures and the mechanism of their formation is presented in papers of JOPLING (1963*a*, 1963*b*, 1965, 1966). Structures formed in this way are assigned by JOPLING (1966) to "aggradational" structures, while those formed by the movement of ripples or dunes are termed "form-drag" structures.

SMALL-SCALE CROSS-STRATIFICATION

Small-scale cross-stratification is abundant in the Upper Nemegt Beds, occurring in the majority of siltstone beds, and in many beds of very fine and fine sands. Three principal types of small-scale sets of cross-stratification can be distinguished, according to their arrangement within beds. It should be stressed, however, that gradual passages between the types described below are fairly common.

Trough cross-stratification (small-scale)

In the Upper Nemegt Beds, structures of this type occur chiefly in sands, usually well sorted and, more rarely, in coarse siltstones. They consist of grouped sets of trough type. The individual sets are directly superposed. The bounding surfaces of sets are erosional. The cross-laminae are concave upwards and always tangential to the lower surface of the set. The maximum angle of dip of the laminae is small and rarely exceeds 20°. In a vertical section at right angle to the direction of the current, the cross-laminae are trough-shaped (festooned, see KNIGHT, 1929, Fig. 24). In horizontal sections, features described as "Schrägschichtungsbögen" (GÜRICH, 1933), "rib and furrow" (STOKES, 1953) and "arcuate bands" (DŻUŁYŃSKI & ŚLĄCZKA, 1958) occur. In a longitudinal section, the individual sets usually form troughs. The observed ranges of sets are 1·5—5 cm in thickness, 8—25 cm in width, and 5—45 cm in length. Usually neighbouring sets have similar dimensions.

Within a given bed, structures of the type discussed occur separately or are accompanied by other types of small-scale cross-stratification described below. Sometimes they are associated with large-scale cross-stratification (p. 192). The type of structure described has features identical with the structures described by HARMS *et al.* (1963, pp. 575—576) from a modern point bar in the Red River. It displays also great similarity to structures described by HAMBLIN (1961) as "micro-cross-lamination". Structures of this type are known to occur in sediments deposited in various environments, but they are especially common in fluvial sediments (MCKEE, 1939; BOTVINKINA *et al.*, 1956; BOTVINKINA, 1962; LANE, 1963; ALLEN, 1965*a*; HARMS & FAHNESTOCK, 1965; VISHER, 1965).

Small-scale trough cross-stratification is related to the rippled bottom form (HARMS & FAHNESTOCK, 1965). This association was recognized previously by WURSTER (1958), HAMBLIN (1961), ALLEN (1963*a*), HARMS *et al.* (1963) and others. Various explanations of the mechanism of the formation of small-scale, trough-shaped sets and their relations with various types of ripples were proposed. ALLEN (1963*a*) considered their formation as being related to the migration of trains of linguoid ripples, while HARMS *et al.* (1963) envisaged the infilling of scours on the lee side of lunate ripple forms (see also HAMBLIN, 1961). According to HARMS *et al.* (1965, p. 103), an important factor leading to the formation of these structures is the development of spoon-shaped depressions connected with the formation of linguoid ripples. Such scours may be filled by avalanching from the faces of either linguoid ripples or lunate ripples. Horizontal sections suggest that most small-scale trough-shaped sets were formed by the migration of lunate ripples (see DŻUŁYŃSKI & WALTON, p. 175, Fig. 116).

Flaser structure

This type of structure is characterized by the presence of solitary, small-scale cross-stratified sets, composed of relatively coarse material (fine- or very fine-grained sand, coarse silt) and separated partly or completely by intercalations of distinctly smaller grain diameter. These intercalations are usually structureless, but sometimes parallel lamination is present.

In a section parallel to the current direction, the sets are usually irregular in shape. Their lower surfaces are concave-up or wavy. The upper surfaces are convex, concave or wavy. Cross-laminae are partly or completely sigmoidal. Between cross-laminae fine-grained intercalations, merging upwards and downwards into the sediment separating the individual sets, are fairly common.

In sections oriented at right angle to the current direction, the lower surfaces of sets are usually concave-up. The cross-laminae are nearly parallel to the lower bounding surface. However, the cross-laminae are sometimes seen to pinch and swell, producing a pattern of superposed lenses.

The observed ranges of dimensions of sets are following: 3—20 cm in length, 3—20 cm in width and a few mm to 3 cm in thickness. Flaser structures occur in the Upper Nemegt Beds in sandy and silty sediments, usually in the upper part of sand layers passing gradually into siltstones.

Structures very similar or identical with those elaborated above have been described from some environments characterized by alternating in deposition of sandy and muddy sediments. They are known from Recent tidal flats ("Flaserschichtung" or "flaser bedding", HÄNTZSCHEL, 1936; REINECK, 1960, 1967) and fluvial sediments (BOTVINKINA *et al.*, 1956; BOTVINKINA, 1962; HARMS & FAHNESTOCK, 1965, Pl. 6).

The formation of flaser structures is related to alternating phases of current activity and pauses in current activity (HÄNTZSCHEL, 1936; REINECK, 1960*a*, 1960*b*, 1967). Coarser-grained material is deposited from a current as ripples (see p. 186). When current activity ceases, mud is deposited from suspension and either completely covers the ripples, or covers only part of the ripple troughs.

Typical lenticular structures are produced when isolated ripples are formed on a muddy bottom, during phases of current activity and are then covered by mud deposited from suspension, (REINECK, 1960*a*, 1967). Typical examples of these structures were not observed in the Upper Nemegt Beds, while passage forms from flaser to lenticular structure are present.

Climbing-ripple structure

Characteristic structures described in the literature as "ripple-drift bedding" (SORBY, 1908), "ripple-drift cross-lamination" (WALKER, 1963), "climbing ripple lamination" or "climbing ripple structures" (MCKEE, 1965, 1966) occur fairly commonly in the Upper Nemegt Beds. They are present only in fine and very fine sands, well sorted or moderately sorted.

Climbing-ripple structures are visible only in sections parallel to the current direction. The grouped sets are separated by pseudobedding surfaces (MCKEE, 1939) inclined in the up-current direction. These latter are usually imaginary surfaces defined by changes in the attitude of cross-laminae. In such cases, the cross-laminae are continuous across these surfaces from one set to another. Sometimes the cross-laminae are preserved only on the lee side of ripples and then the overlying pseudobedding surface is erosional. Both kinds of structures are present sometimes in one coset, and gradual passages between them were seen.

The lamination of the ripples is related to small changes in grain size. Often the laminae are defined by accumulation of mica flakes or red colouration of the fine-grained layers (Pl. XXXVIII, Fig. 2). The thickness of laminae on the lee-side ranges from 1 to 3 mm. Within a given lamina, the grain size is larger as a rule on the lee-side than in the trough and on the stoss-side.

The dimensions of ripples and the angles of their cross-laminae usually vary within a given set. In the majority of cases, the ripples of the lower part of a coset have low amplitude and wavelength; the laminae are inclined at a low angle. Towards the upper part of the coset, the values of these parameters increase gradually (Pl. XXXVIII, Fig. 2). This causes an increase in both thickness of individual sets and angle of inclination of pseudobedding surfaces. In such a case, the lower bounding surface of a coset is usually almost entirely flat. An upward decrease in the values of parameters of climbing ripples is rare.

As a rule, the ripples of climbing-ripple structures are asymmetrical. The observed maximum angle of inclination is 24° for laminae on the lee-side and 16° for stoss-side laminae. The usual values of these angles are lower by a few degrees, especially in the case of the stoss-side. Wave-lengths are up to 16 cm, amplitudes up to 4 cm and the ripple index ranges from 4 to 10.5. The angle of inclination of the pseudobedding surfaces is up to 22°.

The climbing-ripple structures occur in cosets ranging in thickness from 25 cm to 50 cm. They often form intercalations consisting of a several grouped sets within beds with small-scale trough cross-stratification or with flaser structures. In such cases, both lateral and vertical passages between types of structures are present.

In sections oriented at right angles to the current direction, the cross-laminae of climbing-ripple structures form patterns of superposed lenses. This seems to indicate that the climbing-ripple structures occurring in the sediments of the Upper Nemegt Beds were formed as a result of migration and superimposition of asymmetric ripples with non-straight crests.

McKee (1939, 1965, 1966) and R. G. Walker (1963) expressed the opinion, that this structure is formed by comparatively weak currents in conditions of a aboundant supply of sand or silt permitting an upward and forward growth of the rippled surface (McKee, 1966, p. D 101). According to McKee (1965, 1966), climbing-ripple structures are a characteristic indicator of environments involving considerable, rapid accumulation of sand. Floodplains are areas in which this type of structure might be expected to form. In the Mississippi River delta, climbing ripples are abundant in natural levees, rare in stream-channel deposits and unrecorded in other sedimentary environments that do not involve overbank flow (Coleman *et al.*, 1964; Coleman & Gagliano, 1965).

R. G. Walker (1963) has defined three morphologically distinct types of ripple-drift cross-lamination. The first type is characterized by erosion of the stoss-sides of ripples, the third type is without erosion of the stoss-side and the second type is intermediate between the two. Walker suggested that the first type is formed in fluvial and shallow water environments, while the third type is formed by deposition from a turbidity current. The second type was thought to form in intermediate hydraulic conditions. Observations of the present writer contradict Walker's conclusions. All three types of climbing-ripple cross-lamination are present in the Upper Nemegt Beds, and they often occur together within one bed.

LARGE-SCALE CROSS-STRATIFICATION

Large-scale cross-stratification occurs in the Upper Nemegt Beds in most sand beds and in some conglomerates. These sediments range from well sorted to very poorly sorted (see Text-figs. 6, 7).

Trough cross-stratification (large-scale)

Trought-type structures are the most common among large-scale cross-stratified structures occurring in the Upper Nemegt Beds. The sets are generally grouped and separated by concave-up erosional surfaces. The widths of troughs range usually from 0.5 to 2 m, exceptionally reaching 4 m; the length is usually 2 to 4 times as much. The maximum thickness of a set varies in the range 20—50 cm.

The cross-strata are tangential to the lower surface of the set. The maximum angle of inclination of the cross-strata ranges up to 18°—25° reaching exceptionally around 30°. The thickness of cross-strata ranges from a few mm to 25 mm. Numerous exposures permitted measu-

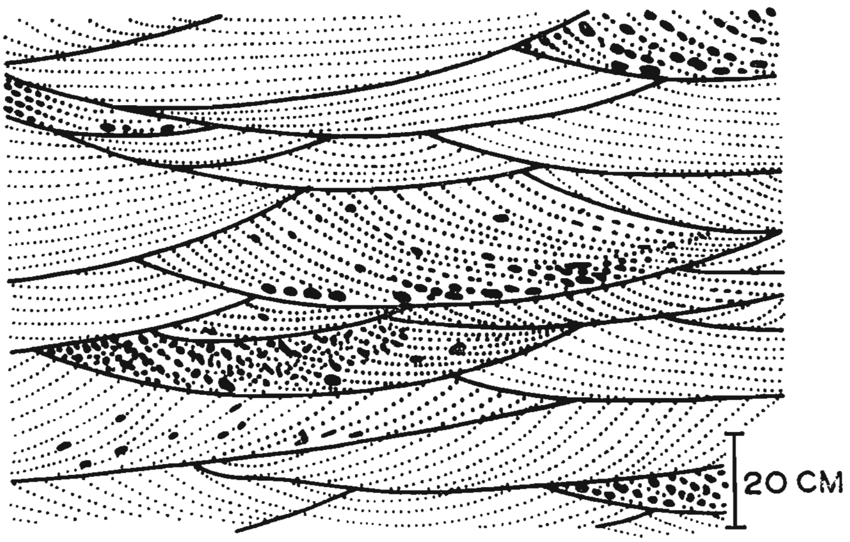

Fig. 18
Large-scale trough cross-stratification. Section perpendicular to trough axis. Note differences in grain size in the individual sets. Slightly schematized. Upper Nemegt Beds, locality Altan Ula IV, Central Sayr.

rements and observations in three dimensions. The general features of large-scale, trough-cross-stratified structures are:

1) Within a given coset, the trends of long axes of troughs are similar and show a relatively small dispersion, usually not exceeding 25°;

2) The lines of intersection of cross-strata with the horizontal plane are always concave downcurrent;

3) The troughs are often filled asymmetrically. In a horizontal section, the lines of intersection for cross-strata are at an angle to the long axes of the troughs; in sections perpendicular to the axis, the infilling cross-strata are progressively displaced laterally. In extreme cases, the discrepancy between the trend of the long axis of trough and the direction of maximum dip of infilling cross-strata reaches 45°.

4) Neighbouring troughs are either filled symmetrically or are characterized by varying degrees of asymmetry. In the latter case, the directions of maximum dip of cross-strata in individual sets within a coset show a large dispersion (up to 60°).

The sediments filling the trough-shaped scours often contain siltstone fragments ranging in size from a few mm to 5 cm, and showing variable shape and roundness. Usually they are flat and subrounded. In many sets, single pebbles are dispersed throughout the sandy material filling the troughs, while in others, numerous pebbles are concentrated in individual cross-strata. In both cases, pebbles usually lie flat on the surface of cross-strata, but some of them have long-axes inclined either upstream or downstream (Pl. XXXVIII, Fig. 1). Usually the number of pebbles is greatest in the lower part of a set. In such sets as well as in sets filled exclusively with sand, the bottom of the trough is often covered by a thin layer of pebbles. Sets containing pebbles and sets entirely devoid of them may occur fairly frequently within a given coset (Text-fig. 18).

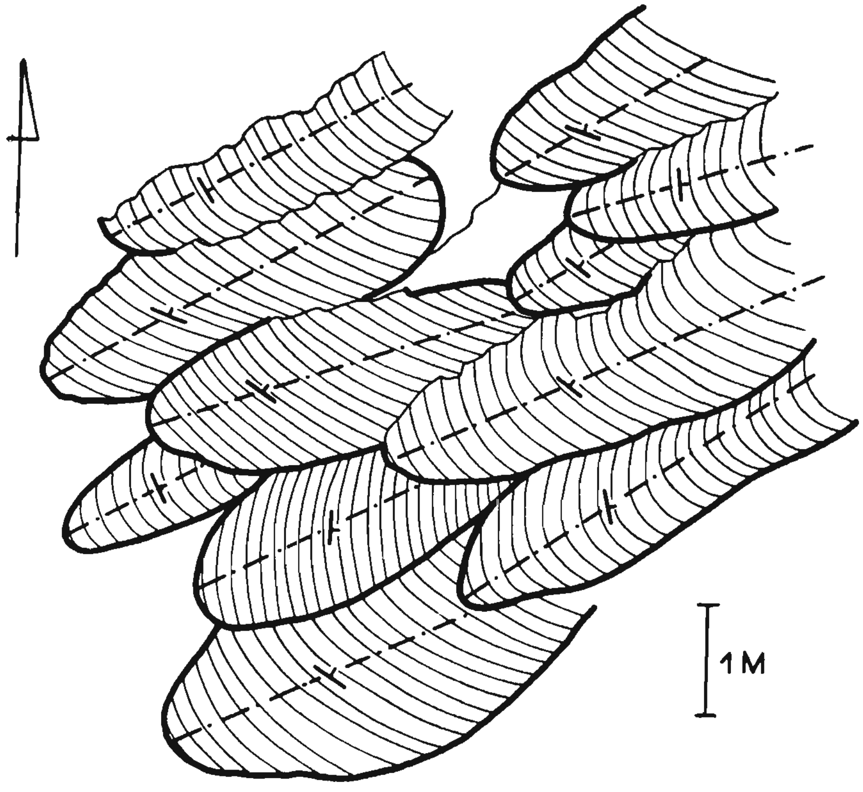

Fig. 19
Plan of horizontal surface with visible sections of troughs filled with cross-strata. Axes of troughs and dip directions of cross-strata are marked. Upper Nemegt Beds, Nemegt locality, Central Sayr.

Pebbles of poorly consolidated siltstones were undoubtedly eroded not far from the site of deposition. They were transported together with sand within the same bed filling the trough-shaped scours. An increase in the number of pebbles in the lower part of cross-strata is probably the results of avalanching (ALLEN, 1965*b*). In the case of layers of pebbles covering the bottoms of troughs filled with pure sand, the former may have been deposited before the infilling of the trough by cross-stratified deposits. Such pebble layers may represent lag material.

It is generally accepted that large-scale trough cross-stratified sets are formed by filling of scoured depressions by the avalanching of bottom load down slip faces, shortly after the formation of these depressions (see e.g. HARMS *et al.*, 1963). The flow regime, mechanism of scouring and position of scoured depressions in relation to the avalanching faces are poorly known. FRASIER & OSANIK (1961) assume that the depressions are migrating "pockets" in the river bottom and are formed immediately downstream of large sand waves. ALLEN (1963*a*) accepts a direct relationship with the migration of linguoid or lunate dunes. HARMS *et al.* (1963)

and HARMS & FAHNESTOCK (1965) expressed the opinion that the depressions are eroded by vortices not closely linked in space to the lee faces of sand dunes. In the case of structures observed by the author in the sediments of the Upper Nemegt Beds, the features of many trough-shaped sets (see points 3 and 4 above) support the last of the above explanations.

Large-scale trough cross-stratification occurs in sediments of a variety of environments (near-shore marine, beach, aeolian), but is especially common in river channel deposits. Examples of such structures from fossil river sediments are given, among others by MCKEE (1954), BOTVINKINA *et al.* (1956), POTTER & GLASS (1958, p. 18), ALLEN (1962*a*), STEWARD (1961) and FRIEND (1965). Studies of Recent river sediments by FRASIER & OSANIK (1961), HARMS *et al.* (1963) and HARMS & FAHNESTOCK (1965) showed that in point-bars, large-scale trough-cross-stratification is the most abundant and characteristic sedimentary structure.

Tabular cross-stratification (large-scale)

The adjective "tabular" is used by the author to define cross-stratified sets, which are not bounded by trough-shaped erosional surfaces and which display lateral persistence over areas large in comparison with the thickness of sets. In the Upper Nemegt Beds, many sets characterized by the above features have planar, parallel bounding surfaces of limited lateral extent, which are seen elsewhere to be irregular, wavy or convergent.

The tabular-shaped sets usually consist of well sorted, fine-grained sands (see Text-figs. 6, 7). Pebbles of basin rocks occur only exceptionally within the cross-strata. Large pebbles are present, sometimes occurring at the base of solitary sets. In some cases, such pebbles are imbricated and inclined upstream. Thin (about 10 cm), tabular-shaped sets are sometimes present in the intraformational conglomerates.

The majority of tabular sets are 10—50 cm thick. Such sets are usually grouped. Thick, solitary sets, 1—2 m thick are fairly common. The dimensions of tabular sets, although relatively large, are always limited in lateral extent. In the marginal parts, sets are usually truncated by scoured surfaces of various types, but wedging out of sets is also frequent. The lateral extents of sets are variable and are usually proportional to the thickness. The width of sets 50 cm thick is usually on the order of 10 m, while the length is 2—3 times greater. The lateral extent of thick sets only exceptionally exceeds 60 m.

The cross-strata range in thickness from a few mm to 30 mm. In thicker cross-strata, an upward grading from fine to coarse in a direction perpendicular to the inclined plane (vertical grading, ALLEN, 1965*b*, see also BOERSMA, 1967, pp. 229—230) is sometimes observed. In sections parallel to the current direction, the cross-strata are often straight, and only in the lower part flatten out and extend tangentially to the lower surface of set. Curvilinear cross-strata and exceptionally cross-strata convex-downcurrent also occur.

A bottomset layer with small-scale, cross-stratified structures (Text-fig. 20) is present sometimes in the lower part of the set. These structures gradually pass into the overlying cross-strata, but sometimes are distinctly separated. The cross-laminae in the bottomset layer often dip in a direction opposite to that seen in the overlying cross-strata. Climbing-ripple structure is common there.

The structures described above display features identical with those described by BOERSMA (1967) from probably Recent sediments of the Rhine. According to this author, the structures in the bottomset layer are formed at low current velocities, accompanied by large supply of sediment from suspension and their orientation depends on the distribution of currents in front of a megaripple. According to BOERSMA (*l. c.*), the structures described by him were formed in the upper part of a point bar.

In horizontal sections, the intersection lines of cross-strata in individual tabular-shaped sets are either straight or slightly wavy. Observations in three-dimensions suggest that in such sets, the attitudes of cross-strata do not depend directly upon local irregularities of the lower surface of the set.

The observations described above suggest that the majority of tabular-shaped sets occurring in the sediments described were deposited as bottom forms, which had the following features: 1) straight or sinusoidal crests of the avalanche side, 2) relatively steep avalanche sides and flat, nearly horizontal upper surfaces, 3) relatively long crests of limited extent (several to several tens of metres), 4) downstream migration, burying local irregularities of the bottom.

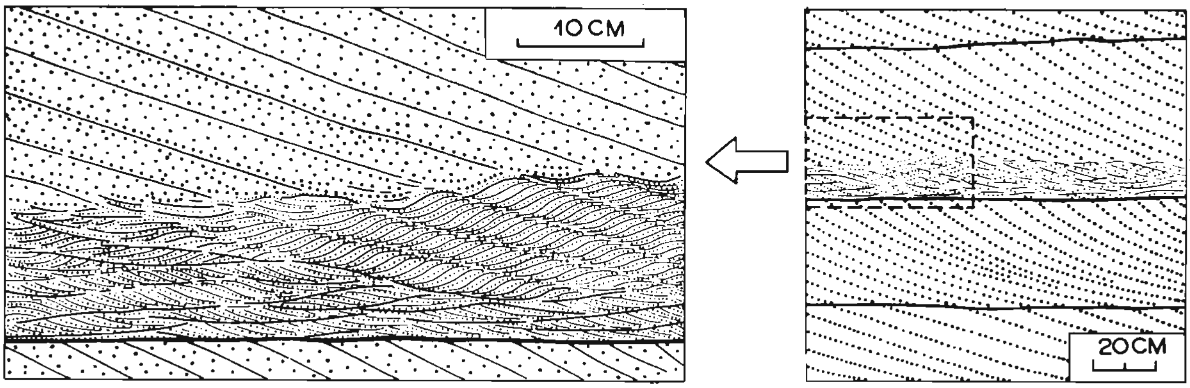

Fig. 20
Schematic diagram (right-hand side) showing relationship between large- and small-scale cross-stratification and detail (left-hand side) from bottomset layer. Upper Nemegt Beds, locality Tsagan Khushu, Tent Hill.

Forms with such features are known from Recent fluvial sediments. They are described as "bars" (HARMS & FAHNESTOCK, 1965. p. 92), "transverse bars" (SUNDBORG, 1956, pp. 208, 271—272), or collectively as "sand waves", "dunes" or "large-scale ripples" (for examples and references, see LEOPOLD *et al.*, 1964, pp. 194—226). On the basis of studies of Recent sediments of the Rio Grande HARMS & FAHNESTOCK (1965) concluded that the migration of bars results in the formation of tabular-shaped sets. These authors noted that the sandy material, which forms the cross-strata on the avalanche side, is transported on the even, upper surface of the bar by ripples. As a result of this mode of transport, the sand is usually better sorted in the tabular-shaped sets than in the trough-shaped sets.

According to JOPLING (1966), local depressions of the bottom are often filled by aggradation to a profile of equilibrium. A solitary set of cross-strata, with a regular and nearly horizontal upper surface, results from this process.

Thus, summarily, it may be noted that large-scale, tabular cross-stratification occurs in different environments. The structures of the type present in the Upper Nemegt Beds show features well known in fluvial sediments.

CROSS-STRATIFICATION IN THE LOWER NEMEGT BEDS

Cross-stratification occurs sporadically in the Lower Nemegt Beds (see p. 170) in medium- and fine-grained sandstones. Both the cross-laminae and the bounding surfaces of these structures are usually indistinct. Large-scale trough cross-stratification is relatively the most common.

The thickness of sets ranges from 10 to 15 cm, while that of cosets reaches 50 cm. The maximum dip of cross-strata amounts to 20°. Structures probably of the tabular-planar type were noted in three beds. Steep faces of exposures precluded the possibility of more detailed observations. The sets are solitary, 30—50 cm thick, extending horizontally for 15—20 m. Small-scale cross-stratification of flaser-structure type is rare, occurring usually in the upper part of fine-grained sandstone beds.

COMPOSITE INCLINED STRATIFICATION

Composite inclined stratification is a very common large-scale structure in the Upper Nemegt Beds. It is nearly always present in sediments overlying the relatively widespread horizontal scoured surfaces or filling various erosive channels.

The thickness of a complex of strata displaying composite inclined stratification ranges from 1 to 8·5 m. Each complex of this type consists of successive inclined beds. Cross-stratification is present within the majority of such inclined beds. Thus, the complexes described constitute inclined stratification of the second order (see p. 185 and Text-fig. 17). For the sake of simplicity, such complexes are termed here "composite layers".

The inclined beds forming composite layers consist of sands and siltstones. In vertical section perpendicular to the strike of inclined beds, the latter make asymptotic contact with the lower surface. If the upper part of the composite layer is not truncated, then the inclined beds flatten out laterally and gradually pass into the overlying series of horizontally lying, fine-grained sediments. In such cases, the shape of the inclined beds in vertical cross-section is usually fully sigmoidal. The maximum angle of dip for the inclined beds is usually small, usually in the order of 5°—10°. Values of around 20° were observed only near the margins of channels.

A composite layer usually rests on a layer of coarse-grained sediment, consisting of intraformational conglomerate and pebbly sand. Such a coarse-grained layer rests directly upon a scoured surface and often is nearly horizontal. It clearly forms a separate element transgressively covered by the complex of inclined beds. However, interfingering of the coarse-grained sediments with the sediments of the inclined beds, or passages between the two are fairly common.

In general terms, the inclined beds are regularly disposed within the composite layer. However, the individual inclined beds often swell, bifurcate or wedge out at various levels in the composite layer. Local wash-outs occur. In some composite layers, deformations of several neighbouring inclined beds are seen (Text-fig. 25*c*). The mode of occurrence of the deformed beds indicate that the deformations were contemporaneous or penecontemporaneous with sedimentation.

The majority of composite layers consist of alternating beds of sand and sandy siltstone, but often several beds of sand lie directly one upon another. In the central part of the composite layer, the thickness of siltstone beds ranges from a few cm to 30 cm and the thickness of the sand beds from 20 cm to 80 cm. Most frequently, the sand beds pass gradually upwards into the overlying siltstones. On the other hand, the bases of the sand beds overlying the siltstones are usually sharply marked and often bear traces of erosion.

An upward decrease of grain size is a general characteristic of the composite layers. It is marked by: 1) a gradual decrease of grain size up-dip in individual inclined beds, 2) an increase in the thickness of siltstone beds up-dip and decrease of thickness of sand beds in this direction.

Often the grain size also decreases laterally in the down dip direction. This feature is especially common in sediments filling relatively small, erosional channels (Text-fig. 15).

Relatively small-scale, sedimentary structures are always present in the inclined beds constituting a composite layer. Large-scale, trough cross-stratification predominates in the sand beds, especially in the lower part of the composite layer. Small-scale, trough cross-stratification and climbing-ripple structures are also present. Some of the inclined sand beds have the

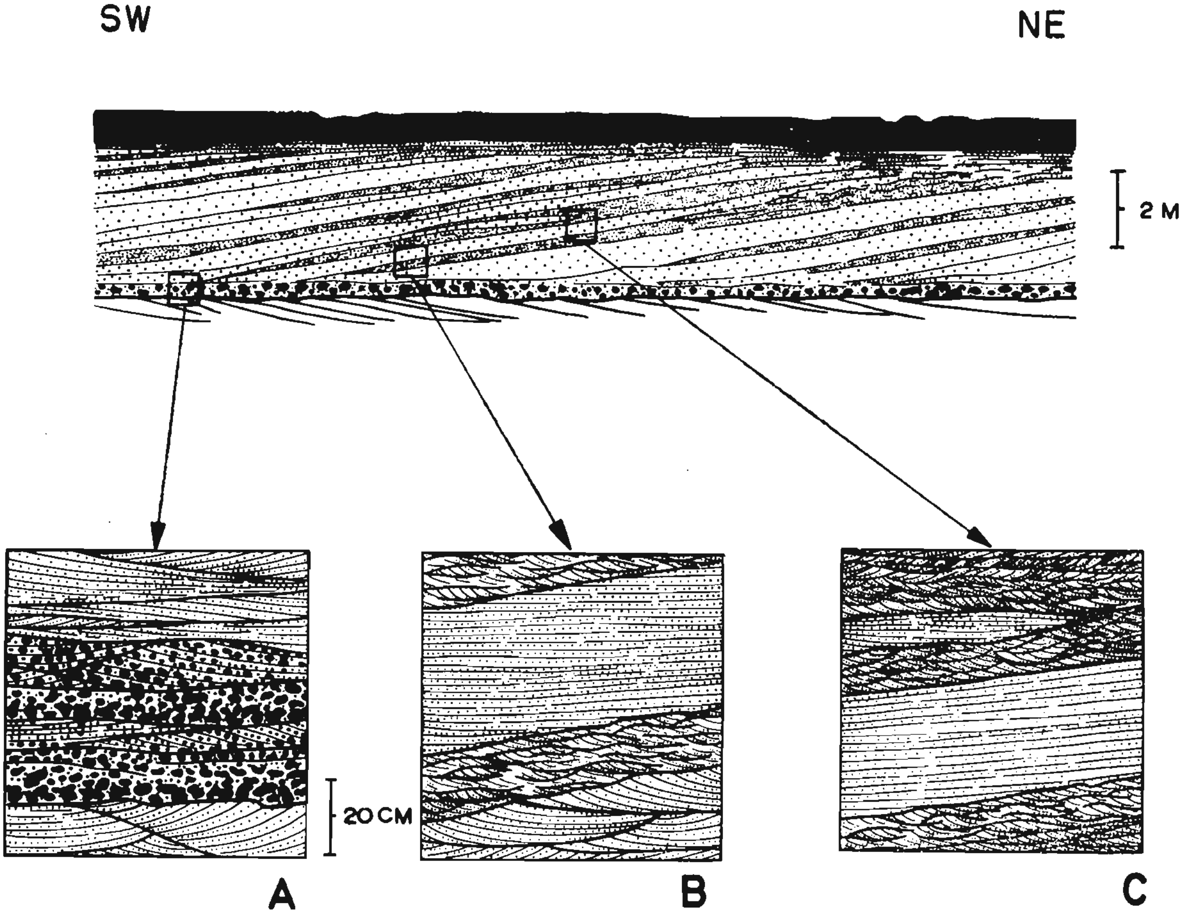

Fig. 21
Top: vertical section of a composite layer (parallel to direction of dip of inclined beds) and of overlying horizontal sediments. Internal sedimentary structures omitted. *A, B, C* — fragments of composite layer with sedimentary structures marked. Upper Nemegt Beds, locality Altan Ula IV, Eagle Sayr. For general explanation, see Fig. 15, p. 182.

shape of tabular sets of cross-strata. Within the siltstone beds, small-scale trough cross-stratification and flaser structures are common. Sometimes an indistinct lamination, parallel to the lower surface of the inclined bed, is present.

The composite layers occurring above horizontal scoured surfaces are tabular or wedge-shaped and are characterized by considerable lateral persistence. Some layers of this type can be traced for several hundreds of metres in two directions at right angle, before being lost through lack of exposure. Some layers terminate horizontally in the direction of dip of the inclined beds, being truncated by an erosional channel, while others die out gradually. In the latter case, the angle of dip decreases and the composite layer passes indistinctly into a complex of sediments with horizontal or irregular bedding. Margins of composite layers comprising inclined beds were also observed, frequently in the form of boundaries of erosional channels.

The inclined beds of different composite layers dip in various, frequently opposite directions. In large exposures, where several superposed composite layers are visible, this produces a "herringbone effect" (compare DUNBAR & RODGERS, 1958, p. 104; WRIGHT, 1950, p. 611; see also Text-fig. 22).

Observations of many tens of composite layers indicate, that the dip of inclined beds differs considerably from that of the first-order, cross-stratified structures present within these beds. Systematic measurement were carried out in 19 composite layers at the localities: Nemegt (12), Altan Ula IV (5) and Tsagan Khushu (2). In each of these points, the structures were observed in three dimensions, and measurements were taken of: a) the directions of dip for 10 adjacent or neighbouring inclined beds, b) the directions of dip for 10—20 large-scale, cross-stratification structures, occurring within these inclined beds (dip direction of cross-strata in the a-c plane, see POTTER & PETTIJOHN, 1963, p. 70, Fig. 4—2). In seven composite layers, the measurements were taken in several stations spaced 50—200 m apart, in the remaining layers only in one station.

The result of the measurements can be summarized as follows:

1) The dip directions in consecutive neighbouring inclined beds are nearly identical;

2) Within the same composite layers, the dip direction of inclined beds gradually changes; in two stations situated at a distace of 250 m a discrepancy of 50° may occur;

3) The large scale cross-stratified structures, which occur within the inclined beds show a wide variation of directions, ranging from 50° to 130° within one station. The mean direction of these structures is oblique to the dip direction of the inclined beds, forming an angle of 75°—125°. Typical examples of distributions of current directions for inclined beds and cross-stratified structures are given in Text-fig. 22.

Thus the composite layers were formed in successive phases, characterized by varying hydrodynamic conditions, as indicated by variation both in lithology and in sedimentary structures of the consecutive inclined beds. The surfaces between the inclined beds represent the bottom relief in consecutive phases in the formation of the composite layer. The direction of dip of the inclined beds indicates the direction of horizontal accretion of the sediments forming the composite layer. On the other hand, the dip of cross-strata occurring within the inclined beds records the directions of currents depositing the sediments. Horizontal accretion of the sediment bodies was transverse to the direction of currents responsible for cross-stratified structures. The structural features of composite layers indicate formation by lateral sedimentation (see VAN STRAATEN, 1954, pp. 26—27, Fig. 3). Deposition of this type is related to the lateral migration of channels, during which the erosion of receding banks is accompanied by deposition on the prograding banks. Processes of this kind are common in the fluvial environment and on some tidal flats, while in other environments they are extremely rare.

The migration of river channels is most regular in meandering rivers. Lateral accretion of sediment on the prograding bank of a meander point bar is more or less transverse to the axis of the adjacent sector of the channel (see WOLMAN & LEOPOLD, 1957; LEOPOLD & WOLMAN, 1960). Accretion of the point bar results in the formation of a tabular-shaped sediment body, extending within the zone of migration for the channel responsible for its formation. The base of such a sediment body is formed by the erosional bottom of the migrating channel and the top is the upper surface of the prograding bank. The sediment body so formed consists of lithologically diversified sediments. This is caused by seasonal changes of river stage, during which sediments of various textures are deposited on the surface of the prograding bank (see

MACKIN, 1937, p. 827, Fig. 2*a*). According to LEOPOLD & WOLMAN (1960, p. 783), contacts between these sediments are more or less parallel to past surface profiles of the prograding bank. On the cross-section of a channel and point bar of Watts Branch, published by these authors (LEOPOLD & WOLMAN, *l. c.*, p. 782, Fig. 6), the contours of the successive surfaces of the point bar are seen to be nearly sigmoidal.

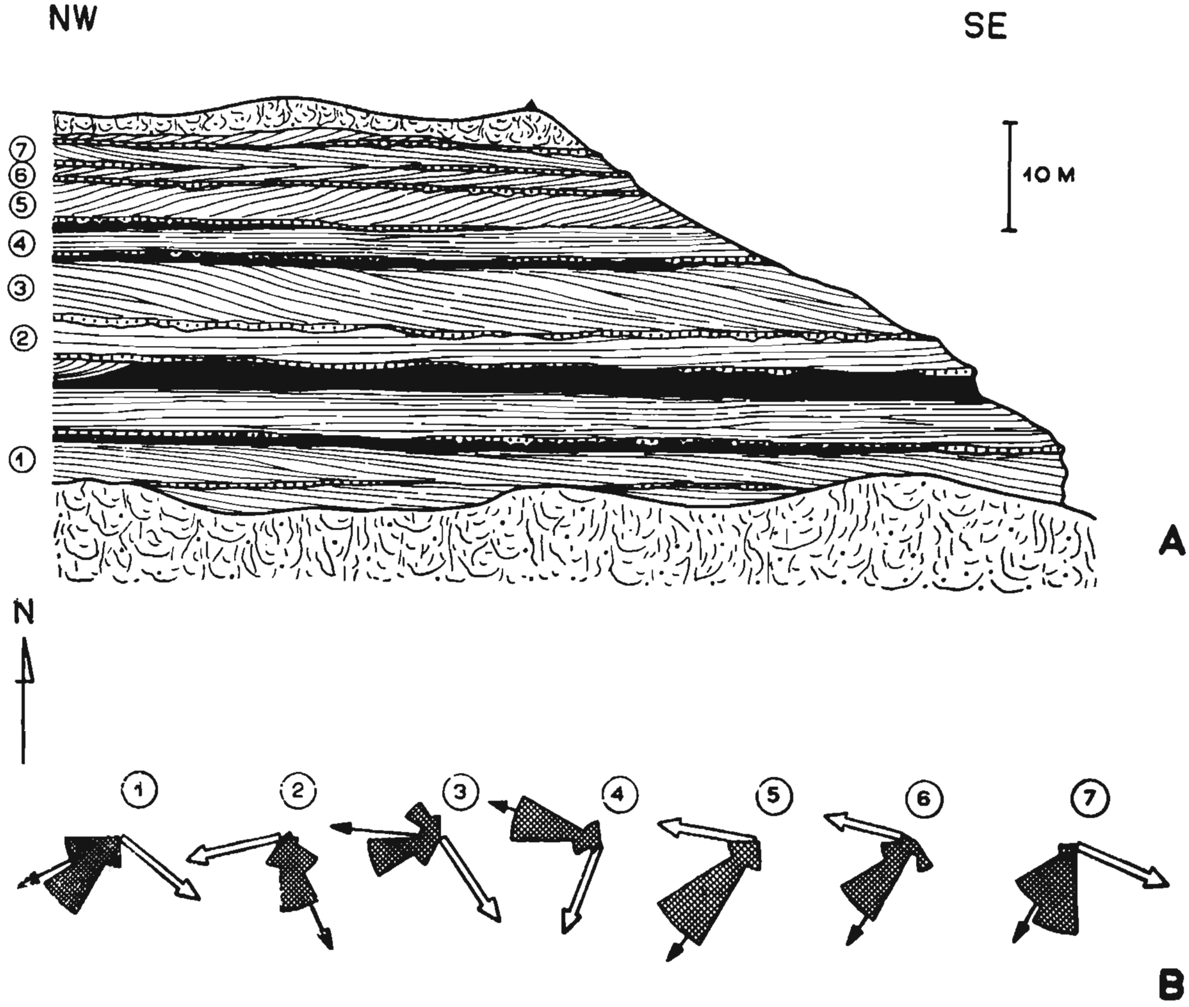

Fig. 22
Top: Composite layer exposed on SW slope of Reconnaissance Hill (Upper Nemegt Beds, Nemegt locality). Intraformational conglomerates and pebbly sandstones marked by dots, sands and siltstones — white, claystones — black, weathered debris at top and base. Structures within the inclined beds not marked. Bottom: dip directions of inclined beds (white arrows) in the individual composite layers, and mean dip directions of cross-strata (black arrows) in large-scale cross-stratification structures present within the inclined beds. Rose diagrams show the distribution of dip directions of the cross-strata. For detailed explanation, see text, p. 195.

The directions of currents depositing the clastic material on a point bar is recorded by relatively small-scale sedimentary structures. Investigation of the distribution of flow in a natural meander (for examples and references, see LEOPOLD & WOLMAN, 1960; LEOPOLD *et al.*, 1964) indicate that at the surface of the prograding bank, a distinct transverse component of velocity is directed towards this bank. According to LEOPOLD & WOLMAN (1960, p. 782), cross-channel currents must play an important rôle in the mechanism of point-bar building. The sediments of a point bar may thus contain large-scale cross-stratification, in which the cross-strata dip in a direction transverse to the axis of the channel, towards the prograding bank. Structures with such directions are known from Recent point bars (HARMS *et al.*, 1963, p. 573, Fig. 7; POTTER & PETTIJOHN, 1963, p. 81, Figs. 4—9).

Structures similar to the composite layers occurring in the Upper Nemegt Beds have been described from Old Red Sandstone of Anglesey by ALLEN (1965*a*). This latter author called these structures "epsilon cross-stratification" and interpreted them as the product of lateral sedimentation in meandering river channels.

The migration of tidal channels and gullies also causes the formation of sets of inclined beds. Structures of this type were described from Recent sediments of the Wadden Sea by TRUSHEIM (1929), HÄNTZSCHEL (1936), VAN STRAATEN (1954). REINECK (1958) described similar structures as "longitudinale Schrägschichtung". Sets of inclined beds formed on tidal flats are usually no greater than 1 m in thickness and display relatively small lateral persistence. Thus a review of the literature cited above suggests that large-scale cross-stratified structures are absent from the inclined beds. Moreover, in tidal flat environment, marine fossils always occur abundantly in the basal part of the inclined beds.

As exclusively continental sediments of late Cretaceous age occur in Mongolia and in adjacent areas of Central Asia (LEE, 1952; MARINOV, 1957; VASILEV *et al.*, 1959), tidal flats may be excluded as the environment in which composite layers of the Upper Nemegt Beds were formed. It is emphasized that these structures possess features characteristic for sediment bodies formed by lateral deposition in migrating river channels.

LARGE-SCALE INCLINED STRATIFICATION OF "DELTA-TYPE"

Besides the composite layers described above, large-scale, inclined stratification of "delta-type" is present in the Upper Nemegt Beds. Each „delta-type" structure consists of a complex of inclined beds ranging in thickness from 1 to 4 metres. The maximum inclination of the inclined beds is usually between 8° and 12°. The inclined beds are either tangential to the lower surface of the complex, or more frequently, pass longitudinally into a horizontal "substratum" (Text-fig. 23, left part). The inclined beds are usually composed of sandy sediments, with rare intercalations of siltstones. The boundaries of the individual beds are indistinct and marked by a gradual change in lithology. The sediments of the inclined beds appear to be structureless, or display poorly defined lamination or small-scale cross-stratification. Large-scale cross-stratification is observed extremely rarely. In both of the last mentioned cases, the inclination of the cross-laminae is usually in agreement with the direction of dip of the inclined beds. This indicates that the directions of currents depositing the sediment coincided essentially with the direction of accretion of the complex of inclined beds.

The inclined beds dip in various directions in the individual complexes of beds displaying the features of delta-type, large-scale, inclined stratification. Horizontal zones, in which dip directions of inclined beds converged within a sector of 135° (Text-fig. 23) were observed at the Nemegt locality. Such an arrangement of inclined beds is interpreted as the result of filling of a scoop-shaped depression, with accretion advancing from the rounded end towards the centre of the depression. Though it was not possible to ascertain the dimensions of such depressions, their width in cross-section was usually not less than 100 m.

In the depressions described, the central parts are filled with sandy beds, which are covered by fine-grained, argillaceous sediments. The latter are in turn overlain by alternating sandy and silty layers, with intercalations of claystones. Ball-and-pillow structures are, as a rule, present in these layers. It seems that the depressions described are not typical erosional channels, but were formed between large-scale accumulation forms.

The depressions filled with sediments characterized by "delta-type" structures are most common in the lower part of the Upper Nemegt Beds (the Passage Series of GRADZIŃSKI *et al.*, 1968/69). Structures of this type occur also in the upper part of the Upper Nemegt Beds at the

Fig. 23
Large-scale inclined stratification of "delta-type" and overlying sediments in the central part of the depression. Dip directions of the inclined beds shown at the top. Upper Nemegt Beds, Passage Series, Nemegt locality, northern part of Central Sayr. For explanation, see Fig. 15, and text, p. 197.

localities Nemegt, Altan Ula and Tsagan Khushu, where however, they are not as common as composite layers. Large-scale inclined stratification of "delta-type" occur only rarely in the Lower Nemegt Beds. The thickness of complexes of inclined beds there ranges up to 8 m. The structures of the type described are poorly visible, because of the homogeneous character of the sandstones in which they occur.

STRUCTURELESS SEDIMENTS

The major part of the rocks of the Lower Nemegt Beds and nearly all claystones and some sands of the Upper Nemegt Beds are apparently devoid of internal structures. The structureless character of the sediments can be attributed either to deposition under uniform conditions, or to destruction of primary structures by the action of organisms (see PETTIJOHN, 1957, p. 164; MCKEE, 1964, p. 293). In the case of the claystones, both possibilities seem highly probable. The coarser sediments are apparently without structures. However, it is likely that these are merely obscured by homogeneity of grain-size. HAMBLIN (1962, 1965) proved, using X-ray photography, that nearly all seemingly homogeneous sandstones from various formations in the USA possess lamination (chiefly micro-cross-lamination).

MUD CRACKS

Typical cross-sections of mud cracks were noted at only eight stations in the Upper Nemegt Beds (Text-fig. 24). However, it should be stressed that according to PETTIJOHN (1957, p. 193), mud cracks are usually preserved in sediments as casts on the lower surfaces of sandstone beds. The lithological character of the sediments belonging to the Upper Nemegt Beds created unfavourable conditions for observations of such surfaces. It is probable therefore, that mud cracks are much more common in the formation described than might be judged from the small number of observations. This possibility is also suggested by the abundant occurrence of intraformational clasts of mud-pellet type in gravel- and sand-grade sediments. The mud pellets occurring in intraformational conglomerates are regarded (see PETTIJOHN, 1957, pp. 193, 277) as redeposited clay flakes, produced by dessication and formation of mud cracks (see also ALLEN & NICHOLS, 1945).

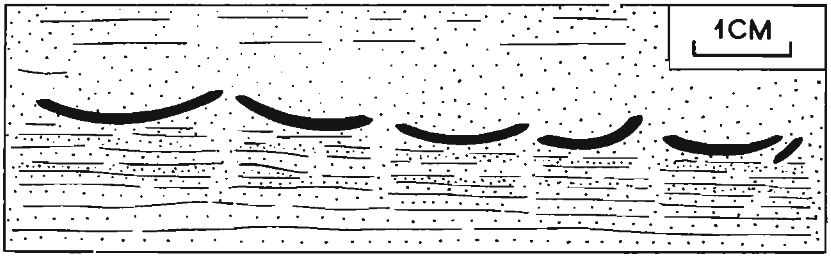

Fig. 24
Vertical section of mud cracks. Upper Nemegt Beds, locality Altan Ula II, sayr near Dragon's Grave.

DEFORMATIONAL STRUCTURES

Deformational structures are common in the Nemegt Beds as a whole and display particularly wide diversity of type in the Upper Nemegt Beds. In the latter formation, load casts are the most common deformation structure. They are usually present at the base of sandy deposits, which overlie horizontal beds of claystones. Some load casts have shapes resembling erosional depressions (see p. 183), while other are irregular (Pl. XXXVII, Fig. 2) in shape. In vertical profile, the depths of the load casts usually vary from 20 to 60 cm. The sandy material filling load casts often contains intraformational clasts and, as a rule, displays considerable deformation of laminae. Claystone tongues protruding into load pockets and isolated contorted claystone lenses occurring within the latter, are common. Load casts developed in the top parts of sandstone beds, overlain by intraformational gravels, are of sporadic distribution. Ball-and-pillow structures (SMITH, 1916) are of rare occurrence in horizontal beds of siltstones and very fine-grained sandstones. They are seen mainly in strata of Lower Nemegt Beds type, found within the Passage Series (see Text-fig. 23).

Some beds of cross stratified sand of the Upper Nemegt Beds show deformations with narrow, steep anticlines (Text fig. 25*A*). The cores of such anticlines are, as a rule, filled with structureless sand. Cross laminae deformed in varying degrees are preserved in the remaining part of the bed. Often, a few neighbouring "anticlines" are separated by broader "synclines". Very similar deformations were described by DOTT & HOWARD (1962) from non-graded sequences of the western USA, JONES (1962) from the Bima Sandstone of Nigeria (equivalent of the "Continental Intercalaire" of the French geologists) and SELLEY *et al.* (1963) from the red facies in the Torridonian sandstone of Skye and Raasay. In the Upper Nemegt Beds, stuctures of this type are usually present in very thick tabular-shaped sets. They are sometimes accompanied by pseudo-nodules (see MACAR, 1948), and intraformational recumbent folds.

Intraformational recumbent folds (described also as "overturned cross-strata" (POTTER & GLASS, 1958) are also observed in other cross stratified sets (Text fig. 25*B*; Pl. XLI, Fig. 3). Structures of this type often occur in several superimposed sets, and gradually die out laterally, passing into undisturbed cross-laminae.

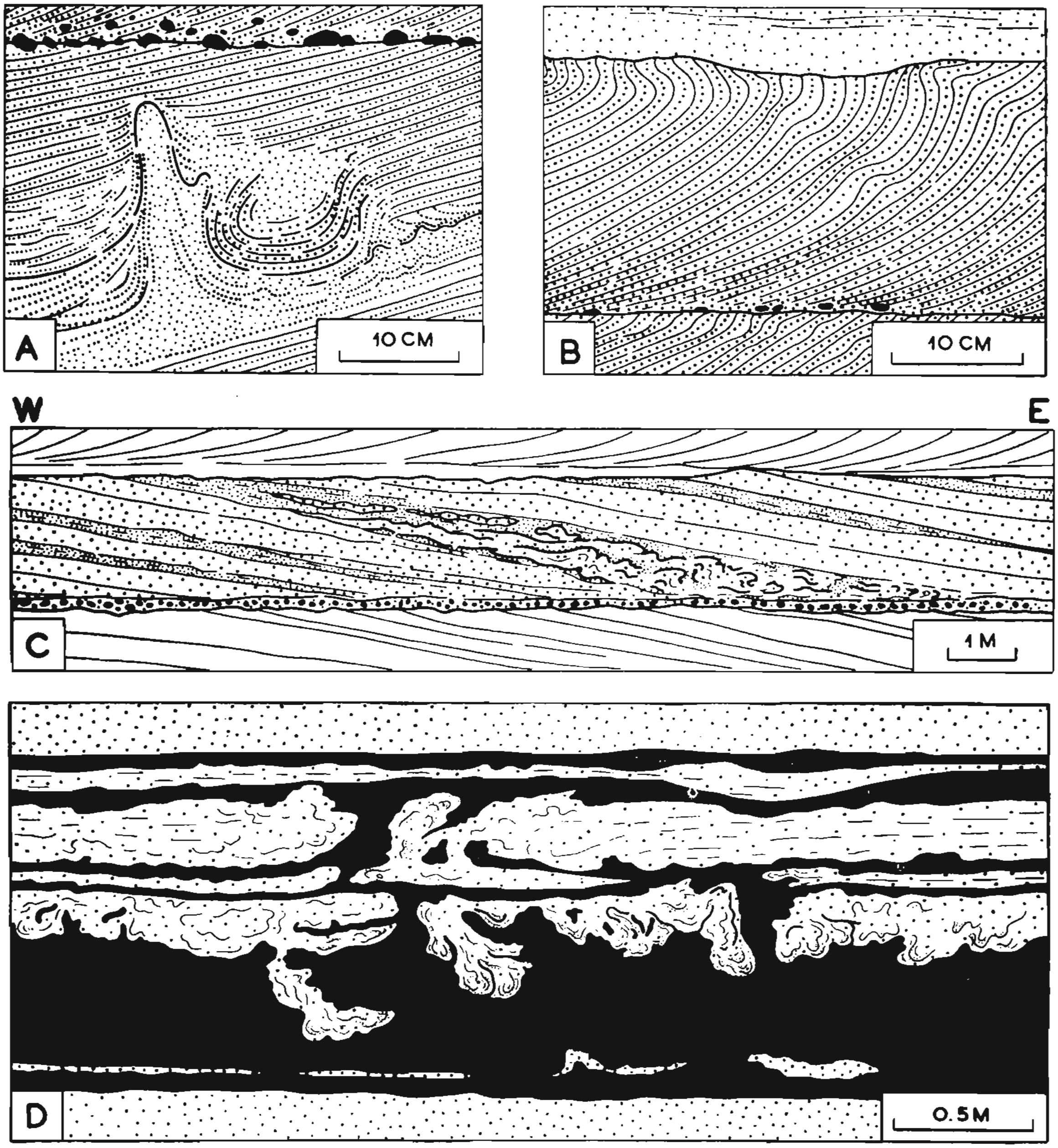

Fig. 25
Examples of deformational structures observed in the Nemegt Beds: *A*—"anticline" and pseudo-nodule in cross-stratified sands, Upper Nemegt Beds, locality Altan Ula IV, Central Sayr; *B*—recumbent folds in cross-stratified sands, Upper Nemegt Beds, Central Sayr; *C*—slump structure in composite layer (internal structures within inclined beds not marked), Upper Nemegt Beds, Nemegt locality, Western Sayr; *D*—fragment of horizontal zone of deformed layers, Lower Nemegt Beds, Nemegt locality. For general explanation, see Fig. 15, p. 182.

The deformational structures observed in the Lower Nemegt Beds usually comprise a few consecutive thin to medium sandstone beds separated by claystone intercalations. The set of deformed beds, as a rule, overlies a thicker, horizontal claystone bed (Text-fig. 25*D*). The sandstone beds are corrugated or folded and sometimes rolled up. The deformations die out gradually upwards. The zone of deformation has uniform thickness and can be traced laterally over a distance of at least 100 m, within the limits of the exposures. In an exposed vertical profile, an alternation of contorted and non-contorted zones is often observed.

Typical slump structures are fairly frequently seen in sediments exhibiting large-scale inclined stratification (see Text-fig. 25*C*). It is evident that deformations were contemporaneous or penecontemporaneous with sedimentation. With the exception of the slump structures mentioned above, deformations of sediments observed in the Nemegt Beds do not display any evidence of large scale, lateral movement. They represent different types of deformation, which arose more or less in situ, either in freshly deposited, plastic and cohesive sediments, or in secondarily liquified sediments (compare SELLY *et al.*, 1963; DŻUŁYŃSKI, 1966; BOGACZ *et al.*, 1968).

Types of deformational structures, represented in the Nemegt Beds, have been described from sediments deposited in various environments (for references, see POTTER & PETTIJOHN, 1963). The only exception is provided by the recumbent folds in cross stratified sands, which according to McKEE *et al.* (1962, p. D 159) occur mainly in fluvial sediments. Recumbent fold structures have been observed in point-bar sand deposits of the Red River (HARMS *et al.* 1963, p. 577) and are reported as being common in bar, channel and levee sediments in the top-stratum of the Mississippi River delta (COLEMAN & GAGLIANO, 1965, p. 136).

TRANSPORT DIRECTIONS

The abundance of cross-stratified structures in the Upper Nemegt Beds permits the determination of the regional direction of transport of clastic material. The author carried out 1321 measurements of the azimuth of maximum dip of cross strata at 89 stations. The measurements were taken only in such parts of the exposures, where three-dimensional observations of the large-scale cross-stratified structures were possible. Up to 30 measurements were taken at a given station, either in one coset of cross-strata or in a few neighbouring beds. One measurement per set was taken. The stations were selected with a view to obtaining a uniform coverage for the vertical profile of an exposure and for the area of the system of exposures in a given locality.

The mean directions for stations were obtained by graphical vector summation (see CURRAY, 1956; PINCUS, 1956). The consistency ratio (CURRAY, 1956), or length of the resulting vector to the number of vectors representing single measurements was used in the evaluation of the variance of the current directions.

The variance of directions within one station is usually small, as the values of the consistency ratio range from 0.80 to 0.95. However, in some cases, the variance is greater, and the values of the consistency ratio are as low as 0.42—0.50. In the vertical profile of an exposure, the mean directions for several stations usually show great differences (see for example Text-fig. 22). Also the mean directions for stations situated within one group of exposured show considerable dispersion.

The irregular distribution of exposures within the Nemegt Basin prevented the construction of moving average to obtain regional transport directions (compare PELLETIER, 1958). Therefore the author constructed the mean transport directions for several neighbouring stations (usually for 3—7 stations) situated on an area of ca. 1 sq. km. These mean directions are marked by arrows in Text-fig. 26. They show a marked dispersion, but all are grouped in the

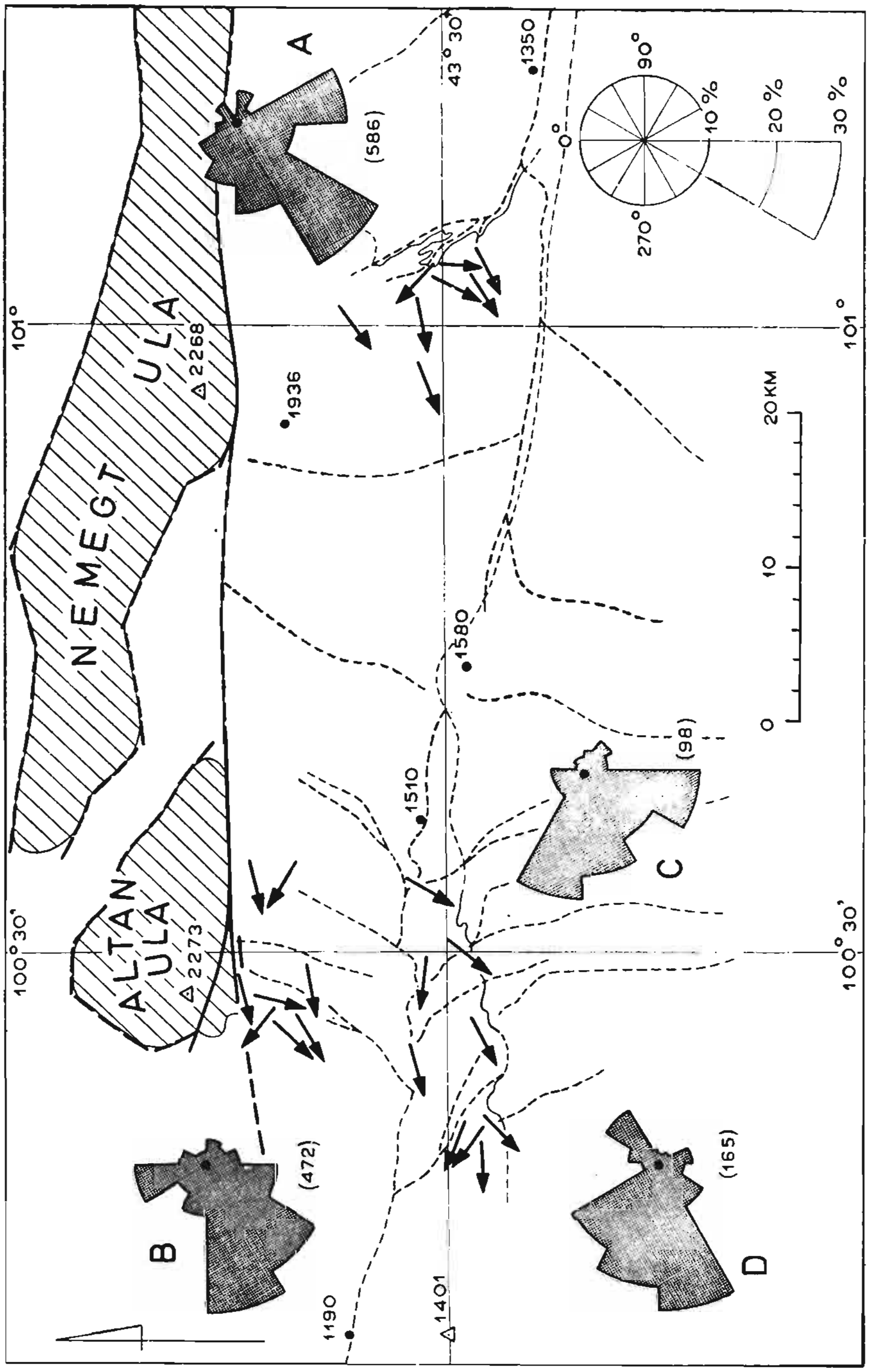

Fig. 26
Map of the Nemegt Basin, showing mean transport directions in Upper Nemegt Beds. Rose diagrams show distribution of measured directions of dip of cross-strata: *A*—locality Nemegt, *B*—localities Altan Ula II, III and IV, *C*—exposures in the Ekhin Dzooganay Gol area and in the northern parts of localities Naran Bulak and Ulan Bulak, *D*—locality Tsagan Khushu. Numbers of measurements in brackets. For detailed explanation, see text, p. 201.

sector 190°—310°. There are no great differences between mean directions for individual groups of exposures in the various localities within the Nemegt Basin. This indicates that in the whole profile of the Upper Nemegt Beds, the regional direction of transport of the clastic material was to WSW.

Measurements of maximum diameters for exotic pebbles, occurring sporadically in the sediments, did not display any decrease of diameter in the general direction of transport.

REPETITIVE STRATIFICATION

Vertical repetition of fixed sequences of different lithological types is observed in all exposures of the Upper Nemegt Beds (see GRADZIŃSKI *et al.*, 1968/69, Text-figs. 3, 5, 7). The base of each sequence is a scoured surface. Above these scoured surfaces, an overall, vertical decrease in grain size is characteristic. Sequences, in which the sediments pass from gravel-grade in the lower part to clay-grade in the upper part, are relatively common (see Text-fig. 27 *B*, *D*). Four divisions may be distinguished in such sequences. The characteristics of the divisions are presented in Table 7. Less complete sequences, usually consisting of divisions 1 and 2 only are also common, and in such sequences the top of division 2 is, as a rule, truncated by the overlying scoured surface.

Repetitive stratification, with vertical decrease in grain size above scoured surfaces, occurs commonly in sediments of fluvial origin and is observed both in Recent and ancient sediments (for examples and references, see SUNDBORG, 1956; ALLEN, 1962*d*, 1965*c*; POTTER & BLAKELY, 1967). Sequences showing such features were termed "fining-upwards cycles" by ALLEN (1965*c*). According to the latter author, a fining-upwards cycle consists of two principal "members": a lower, coarse grade member and a upper, fine grade member. The lower member consists of sediments deposited within river channels (channel or substratum deposits, according to ALLEN, 1965*d*), mainly as point bars and channel bars. The upper member consists mainly of overbank deposits, deposited on flood plains. In the case of the Upper Nemegt Beds, divisions 1 and 2 can be considered as representing the coarse grade member, and divisions 3 and 4 as representing the fine grade member. In the terminology of DUFF & WALTON (1962), the common sequence 1—2 is the modal cycle, while 1—2—3—4 is the composite cycle.

Division 2 is nearly always the thickest division in a given cycle of the Upper Nemegt Beds (see Table 7). Thickness measurements of the divisions in 38 cycles of composite type indicate that division 1 forms 5.63 per cent of the total thickness of the cycles, division 2 — 80·39 per cent, division 3 — 4.98 per cent, and division 4 — 13.98 per cent.

LEOPOLD & WOLMAN (1957) show that sedimentation by overbank flow plays only a small rôle in the formation of Recent alluvial sediments. This applies especially to the sediments of meandering rivers. According to LEOPOLD & WOLMAN *(l. c.)* and many others (for example, MACKIN, 1937, 1948; BERSIER, 1959; VISHER, 1965*a*, 1965*b*) sediments forming an alluvial plain in profile consist mainly of channel deposits. The thicknesses of individual divisions observed in the Upper Nemegt Beds can be considered therefore as typical for a fluvial sedimentary environment.

Thus the formation of fining-upwards cycles in fluvial sediments is chiefly due to the lateral migration of river channels. According to BEERBOWER (1964, p. 41), "natural alluvial plains will tend to develop an internal cyclicity independent of any external factors", although the latter may modify the effects of cyclic mechanisms of sedimentation. The sediments of the

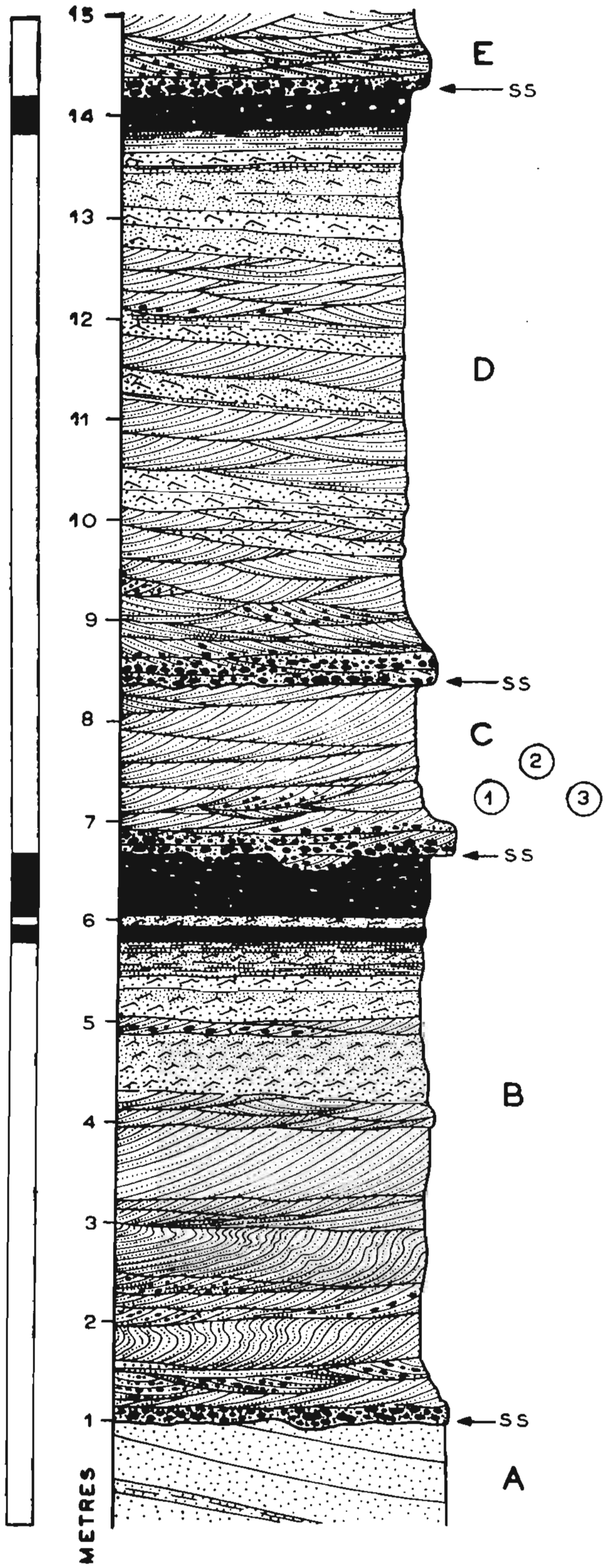

Fig. 27

Typical example of repetitive stratification in the Upper Nemegt Beds. Profile of the wall near the site of excavation of *Tarbosaurus* sp. (Nemegt, No. 1). The wall is shown on Plate XLIII, Fig. 3. Colours of sediments marked in column on left-hand margin: white — drab sediments, cross-hatching — red sediments. ss — scoured surfaces, occurring at the base of each of the fining-upwards cycles *(B, C, D, E)*. For general explanation, see Fig. 15, p. 182.

Table 7

Divisions making up composite, fining-upwards cycle

Division	Lithology	Thickness of division	Sedimentary structures
4	Claystone	A few cm to 2.5 m	Structureless, indistinct horizontal lamination occurring very rarely
3	Siltstone with occasional intercalations of fine sand	A few cm to 1 m	Small-scale cross-stratification dominant, horizontal lamination
2	Sands or sands alternating with silt-grade sediments	1—8 m	Large-scale inclined stratification common; large-scale trough cross-stratification predominate in sands, associated with large-scale tabular cross-stratification, small-scale trought cross-stratification, climbing-ripple structure, flaser structure, parallel lamination rare; small-scale cross-stratification predominates in silt-grade sediments, parallel lamination also occurs
1	Intraformational conglomerates and gravels, pebbly sandstones ,and sands	A few cm to 0.4 m	Structureless or with large-scale cross-stratification; occasionally parallel lamination in sand-grade sediments
Base:	Scoured surface		

Upper Nemegt Beds are relatively thick, but the character of repetitive stratification is essentially the same throughout. It can be assumed therefore, that during deposition of the Upper Nemegt Beds, a high rate of aggradation was probably caused by continued subsidence of the basin floor. The inferred mechanism of sedimentation and the lithological character of the sediments do not display significant changes with time and this suggests an absence of distinct climatic changes or irregularities in uplift of the source area, during the deposition of the Upper Nemegt Beds.

DEPOSITIONAL ENVIRONMENT

All sediments of the Nemegt Beds in general terms show marked similarity in petrology. However, the Lower and Upper Nemegt Beds display strikingly different assemblages of sedimentary structures. This suggests that the two formations represent different depositional environments. The dinosaur-bearing Upper Nemegt Beds, which form the main subject for the present study have a richer and more diagnostic assemblage of structures. For this reason, they are considered first.

Sedimentary features of the Upper Nemegt Beds are, without exception, known from fluvial sediments. In the sediments studied, particularly common are the following structures characteristic for the fluvial environment : scoured surfaces and associated intraformational conglomerates or gravels, channels, composite inclined stratification, large-scale trough cross-stratification, as well as climbing-ripple structures. The whole assemblage of sedimentary structures, the lithological character of the sediments and repetitive stratification of fining-upwards type permit an interpretation of the Upper Nemegt Beds as sediments deposited in a fluvial environment. In the opinion of the present author, scoured surfaces represent the bottom of the river channel. Intraformational conglomerates or gravels resting upon such surfaces are channel lag deposits (*sensu* ALLEN, 1965*d*). Most sand-grade sediments and a large proportion of the silt-grade sediments were deposited as point bars and channel bars. Overbank or top-stratum deposits (*sensu* ALLEN, *l. c.*) are represented by horizontally layered siltstones, sometimes with intercalations of fine sands, and by horizontally layered claystones. The latter were deposited from suspension onto surfaces of a flood plain, perhaps in ephemeral lakes (for example, in meander lakes, see WILHELMY, 1958; compare also SIOLI, 1957). Siltstone and claystone layers of limited lateral persistence might also have been deposited in swales between point bars or in abandoned channels.

The alternation of beds of sand and silt-grade sediments, often seen in composite layers, indicates frequent changes of hydrodynamic conditions within the channel. These changes resulted from frequent changes in river stage, which in turn suggest the existence of seasonal rains in the source area and perhaps also in the area of deposition. The widespread occurrence of siltstone pellets most probably arises out of the dessication of fine-grained, laminated sediment at the margins of channels in periods of lower river stages. Blocks and pebbles of siltstones and claystones were formed by erosion, mainly lateral, accompanying the migration of river channels.

The nature of sedimentary structures indicates that a large proportion of the sediments belonging to the Upper Nemegt Beds originated in hydrodynamic conditions referable to the lower flow regime. Conditions of upper flow regime probably existed only in periods of high river stage and were limited to certain parts of the channel. The occurrence of large exotic pebbles of sporadic distribution is genetically related to the periodic existence of upper-flow-regime conditions. On the basis of flume studies, FAHNESTOCK & HAUSHILD (1962) maintain that transport of such pebbles in a mass of finer-grained sediments may take place only in the upper flow regime. With deceleration of the current and passage into the lower flow regime, such pebbles are deposited. They next sink slowly in the underlying sandy sediments. In this way, the occurrence of large exotic pebbles in cross-stratified sands (see p. 167) may be explained.

The area of deposition was characterized by a high rate of aggradation, evidenced by repetition of fining-upwards cycles and fairly common composite cycles, made up of four divisions. The limited lateral extent of sediments comprising particular fining-upwards cycles, variable directions of transport for clastic material, usually seen in successive fining-upwards cycles, and "herringbone effect" evidence frequent changes in direction of lateral channel migration. Thus these features indicate bends in the channels.

The regular three-dimensional pattern frequently seen in composite layers permits the supposition that the channels responsible for the latter had meandering character. On the other hand, the occurrence of relatively narrow, erosional channels filled with sand, the frequently observed large, lateral variability in lithology of the sediments and considerable dispersion in current direction read from cross-strata within several successive beds (compare ORR, 1964) suggest a similarity to rivers of braided type. Studies of present-day rivers, as well as experimental work carried out by LEOPOLD & WOLMAN (1957, p. 73), suggest "that a given channel can change in a short distance from a braid to a meander or vice versa, that the divided channels of a braid may meander, and that a meandering tributary may join a braided master stream". Thus in the depositional area of the Upper Nemegt Beds, sediments characteristic both for meandering and braided rivers could have accumulated.

The depths of erosional channels seen in exposures and also the thicknesses of sediments making up composite cycles indicate, that channel depths were variable but probably never exceeded ten metres. In periods of low river stage, the depth of water in some channels must have been fairly low, in the order of decimetres, as indicated by the presence of plunge pools, filled with blocks and pebbles of fine-grained sediments at the bottom of these channels.

A more detailed description of climatic conditions in the depositional basin cannot be made on the basis of geological data alone. The absence of sediments of aeolian origin, evaporites and caliche-type sediments suggest that the climate was not arid. Most probably, seasonal rains and dry periods existed within the depositional area.

All observations suggest that the depositional area of the Upper Nemegt Beds was a broad, alluvial plain, with numerous river channels. Some of these channels, or at least certain parts of channels, were meandering, while others were of braided type. It is possible that the rivers of the depositional area were similar to present-day rivers described by GARNER (1966, 1967). Rivers of this latter type consists of numerous, anastomosing channels of varying widths (from several metres to several kilometres), differing in type from the majority of rivers of present-day continents. The depositional area was not limited to the Nemegt Basin, but probably extended far beyond its boundaries. In the area studied, rivers flowed towards West or South-West. The Upper Nemegt Beds were laid down in environmental conditions rather similar to those operative during the formation of other Upper Cretaceous dinosaur-bearing sequences in western USA and Canada (for references, see OSTROM, 1964; L. S. RUSSELL, 1966; see also D. A. RUSSELL, 1967*a*, 1967*b*).

The lithological character of sediments belonging to the Lower Nemegt Beds and assemblages of sedimentary structures observed in the latter do not permit such an exact determination of the depositional environment. The marked homogeneity of the sediments, the predominance of medium to very fine sandstones, considerable lateral persistence of certain beds, scarcity of cross-stratification, the rare occurrence of erosional channels, the absence of horizontal scoured surfaces and the extreme scarcity of intraformational conglomerates suggest the possibility of a lacustrine depositional environment. Thus the lowermost of the Upper Nemegt Beds constitute the first sediments of definitely fluvial type, resting conformably on a series of lacustrine sediments. The occurrence within the Passage Series of sandstone layers similar in type to the Lower Nemegt Beds, usually with large-scale inclined stratification of "delta-type", may be interpreted as having been deposited in fairly small depressions, forming the vestiges of a lake. It is necessary to emphasise that there is no definite proof for the supposition of a lacustrine origin for the sediments of the Lower Nemegt Beds and opposed to this view are occurrences of lizard remains in the sediments and also the absence of a typical lacustrine invertebrate fauna. It is also possible that the Lower Nemegt Beds, like the Upper Nemegt Beds, represent fluvial sediments.

ORGANIC REMAINS AND TRACE FOSSILS

DINOSAUR REMAINS

In the area studied, dinosaur bones occur almost exclusively in the Upper Nemegt Beds. Only a few small dinosaur bones and indeterminate fragments of bones were found in the Lower Nemegt Beds. Therefore, the following description does not apply to the latter formation.

The term "bone material" as used here refers in general terms to all fossil bones present in the sediments. The term "specimen" is used for skeletal material, articulated or disarticulated, belonging to a single individual. This material ranges from two or more bones to entire skeletons. The descriptions of specimens excavated by the Polish-Mongolian Palaeontological Expeditions are supplemented with locality name and number of specimen. Numbers correspond to those shown on planes and schematic profiles in the paper by GRADZIŃSKI *et al.* (1968/69). Only problems directly related to sedimentation are discussed in the present paper. Alterations of the bone material after burial in the sediment are considered only briefly.

The conclusions of the author are based mainly on the data gathered during the Polish-Mongolian Palaeontological Expeditions. Data obtained by the Soviet Expeditions could not be extensively used, since problems were treated by the Soviet authors in a very general way and only a few examples were described in detail (EFREMOV, 1954*a*, 1955).

MODE OF OCCURRENCE OF BONE MATERIAL

The bone material present in the Upper Nemegt Beds occurs in various forms, consisting of: 1) almost complete skeletons, 2) fragments of skeletons, consisting of several bones, 3) single bones and 4) bone fragments. The skeletons and fragments of skeletons show various states of completeness. They consist of articulated or disarticulated bones, which display a spatial distribution different from that, which normally existed at the time of death of the animal.

No important loss of bone material due to chemical decomposition after final burial was observed in the material occurring in situ in the rock. Therefore the conclusion is justified that the bones occurring in the sediments represent the state of completeness which existed at the time of final burial in sediment. This is also generally applicable to the spatial position of the bones. In many specimens (e.g. sauropod dinosaur, Altan Ula IV, No. 4, ornithomimid dinosaur, Tsagan Khushu, No. 3), deformation and fracturing of bones seem to be related to compaction of the enclosing sediment. Similar observations were made by EFREMOV (1955, p. 993). It seems therefore, that slight displacements of bones can be the result of post depositional processes in many cases.

The Polish Mongolian Expeditions excavated 34 specimens of dinosaurs from the Upper Nemegt Beds comprising: 6 nearly complete skeletons, 10 incomplete skeletons and 18 fragments of skeletons (skulls, pelvic girdles, sets of limb-bones etc.).

These numbers are based upon the amount of the skeletal material excavated and does not give a clear picture of the original state of completeness of the skeletal material occurring in the sediments. In some specimens, the missing bones and the rock enclosing them were destroyed by erosion. In other cases, the exposed parts of the bones were so strongly weathered that collection was impossible. In two instances, for practical reasons, only part of the bones exposed in a vertical cliff wall was collected.

Among the nearly complete skeletons, four belong to *Tarbosaurus* sp. (Tsagan Khushu, No. 2 and No. 4; Nemegt, No. 1 and No. 2), one is an ornithomimid dinosaur (Tsagan Khushu, No. 1) and one is a sauropod dinosaur (Altan Ula, No. 4). Only one skeleton (*Tarbosaurus* sp., Tsagan Khushu, No. 2) displayed nearly complete articulation. The position of bones corresponded to that of the original anatomic structure of that dinosaur (Text-figs. 28, 31; see also KIELAN-JAWOROWSKA & DOVCHIN, 1968/69, Pl. 2). The remaining specimens displayed various spatial arrangements of skeletal material. Some were largely articulated (*Tarbosaurus* sp., Nemegt, No. 1; *Tarbosaurus* sp., Nemegt, No. 2), while in others, disarticulation of bones prevailed. The displacement of bones in these skeletons was never marked and ranged from a few cm to a few tens of cm at the most. All skeletons, with the exception of the first one, were characterized by an arrangement of elements corresponding to vertical projection onto a horizontal surface.

The skeletons of the five bipedal dinosaurs were found in a similar position. In all specimens, the tail was strongly bent backwards, the neck, with head preserved in four specimens,

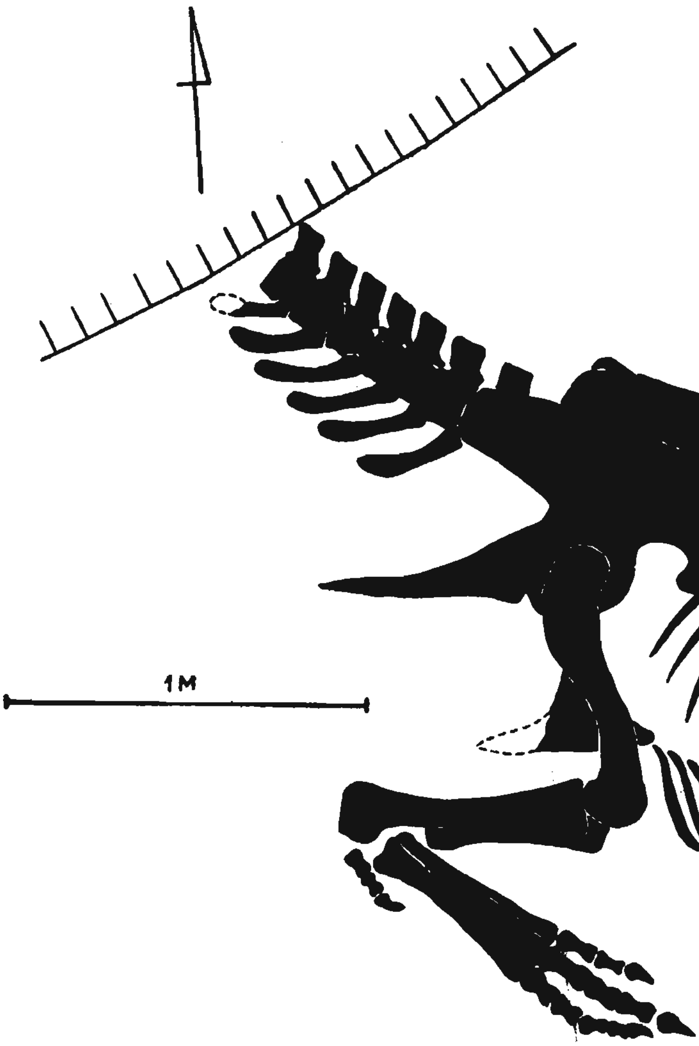

Fig. 28
Arrangement of bones making up skeleton of *Tarbosarus* sp. (Tsagan Khushu, No. 2), top view (compare Fig. 31, p. 213. Excavated bones marked in black. Erosional margin of the gorge marked in NW. Drawing by Dr. A. Sulimski.

was likewise bent and the hind limbs were contracted. All skeletons were largely articulated, although some bones (mainly ribs and limb bones) were disarticulated, and slightly displaced. The ribs were often strongly fractured. In one specimen (*Tarbosaurus* sp., Nemegt, No. 2), the neck was sharply bent twice and had a "Z"—shape. Four skeletons were found in a lateral position and one (ornithomimid dinosaur, Tsagan Khushu, No. 1) in a dorso-lateral position.

The skeleton of the large sauropod dinosaur (Altan Ula, No. 4) was found in a dorsal position (see Kielan-Jaworowska & Dovchin, 1968/69, Pl. 3) different from that of the bipedal dinosaurs. The bones of the vertebral column were appreciably displaced, while only slight displacements were observed in bones of the tail and hind legs. The ribs had a characteristic regular arrangement in a single horizontal plane. The cervical vertebrae of the sauropod have

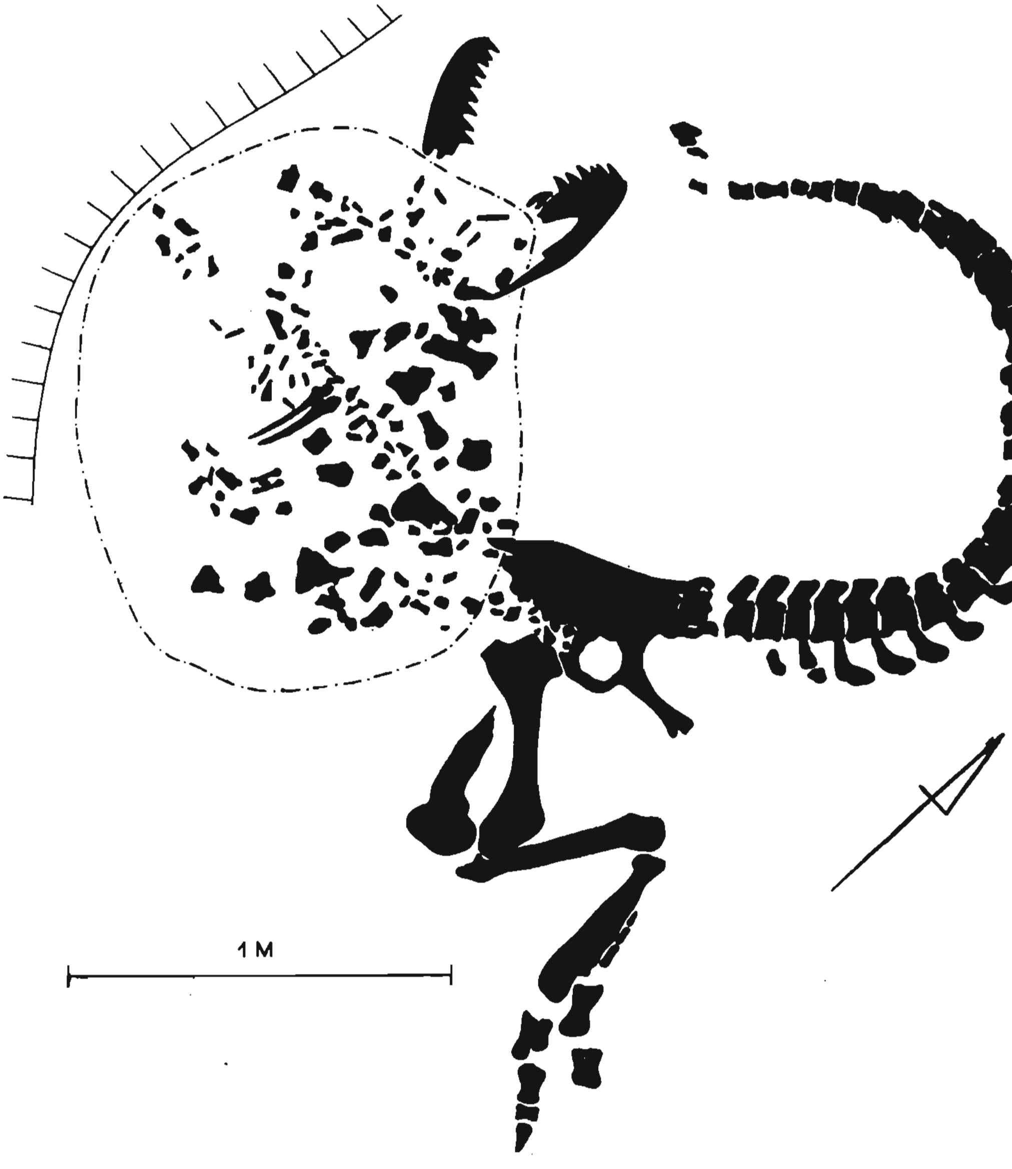

Fig. 29
Arrangement of bones of *Tarbosaurus* sp. (Nemegt, No. 1), top view. Broken line marks area in which the bones were lying at the surface or just below the surface of the denudation terrace. Margin of terrace marked in W (see also Plate XLII, Fig. 3). Drawing by Dr. A. SULIMSKI.

not been found. Possibly the neck was torn apart before burial in the sediment, or it was bent under the trunk. It will be possible to decide between these two possibilities after completion of the preparation of the bone material.

The incomplete skeletons are more diversified with regard to the spatial arrangement of bones. Some of these specimens are articulated in spite of their incompleteness, for example, *Tarbosaurus* sp. (Altan Ula III, No. 3), and *Tarbosaurus* sp. (Nemegt, No. 12). In the first case, the incompleteness is due to recent weathering, and in the second one only a part of the skeletal material has been excavated. Undoubtedly both these specimens were buried in sediment as complete skeletons, before the disarticulation of bones.

Other skeletons of this group of specimens has been found in a fairly advanced state of disarticulation. An advanced state of disarticulation is exemplified by the specimen of *Deinocheirus mirificus* (Altan Ula III, No. 2). The position of bones of this specimen is shown in Text-fig. 30 (see also KIELAN-JAWOROWSKA & DOVCHIN, 1968/69, Pl. 4, Fig. 1, and OSMÓLKA & RONIEWICZ, 1970, Text-fig. 1).

Fig. 30
Arrangement of bones of *Deinocheirus mirificus* (Altan Ula III, No. 2). Bones of the left and right sides of the skeleton separated by broken line. Erosional margin of denudation terrace marked in E.

The bones of the front legs and of the shoulders were dispersed over an area of 3.5 by 3.5 m. The skeletal material occurred within a hill cut by an erosional scarp. This suggests that the remaining part of the skeletal material was destroyed by erosion. The bones are entirely disarticulated, and apparently are chaotically dispersed. However, the bones of the two forearms occur separately. This suggests that the arrangement of bones in space is not due to transportation by water, but was effected by natural disarticulation of the skeleton at the place of burial. Even the small bones were not transported by water during burial of the skeleton.

The specimens belonging to the group of partial skeletons also display various states of disarticulation. In 11 specimens, the excavated bones were nearly fully articulated. Distinct disarticulation was found in three specimens. In the remaining four specimens, the original position of bones has been determined because of weathering and displacement resulting from recent erosion.

Only in the case of two specimens it could be stated with certainty that these fragments of skeletons were entirely isolated: the pelvis of a large quadrupedal dinosaur (Altan Ula IV, No. 1) and the tail of a carnivorous dinosaur (Altan Ula IV, No. 2). No bones have been found in the sediments around these fragments of skeletons in a radius of several m. In the case of other 16 specimens of this group, it cannot be excluded that the missing parts of the skeletons were destroyed by recent erosion.

Besides the 34 specimens mentioned above, isolated concentrations of strongly weathered bones were found in many places, mostly on the surfaces of denudation terraces. The number of bones and their anatomic features suggest that these concentrations represented entire skeletons or large fragments of skeletons originally buried in sediments and later exhumed by denudation. Single isolated bones or large fragments of bones were found rarely. It seems that mainly long bones of limbs, phalange bones and rib fragments occur in this manner. Other skeletal elements have been found occasionally: pelvic bones, shoulder girdles and others. It cannot be cluded that these are relicts of larger fragments of skeletons.

Casts of the skin of dinosaurs were found in one place only, at the Dragon's Grave (Altan Ula II), in the immediate neighbourhood of skeletons of *Saurolophus angustirostris* (see EFREMOV, 1955). The preservation of the casts is probably due to the occurrence of dinosaur skeletons within a bed of very strongly cemented sandstone, which is an extremely rare lithologic type in the Upper Nemegt Beds.

Fragments of egg shells, probably chiefly dinosaur eggs, are frequently encountered in the Upper Nemegt Beds and sometimes also in the Lower Nemegt Beds. The only specimen of a complete egg with long axis in a vertical position was found by the present writer in a sandstone bed at Altan Ula IV locality.

The conclusions concerning the excavated specimens of dinosaurs are:

1) At the time of final burial, most of the specimens had probably a greater degree of "completeness" than the excavated skeletal material. In many cases, the incomplete state of the skeletal material results from recent erosion.

2) The specimens show varying completeness, disarticulation and fragmentation of bones. These features are not distinctly related with taxonomic groups.

3) Most specimens show some disarticulation of bones.

4) The nearly complete skeletons of bipedal dinosaurs are, as a rule, characterized by a lateral position and, in most cases, a strong dorsal bending of the neck and tail.

DISTRIBUTION OF BONE MATERIAL

Both geological field observations and palaeontological data indicate that in the Upper Nemegt Beds a definite relationship exists between occurrence of dinosaur remains and lithological character of the enclosing sediment. Most bones occur in sand- and gravel-grade sediments. In siltstones, bones are rarely encountered and never are they found in claystones. The foregoing remarks apply to dinosaur skeletons showing varying degrees of completeness, as well as to single bones and bone fragments. Bone fragments most frequently occur in intraformational conglomerates, while skeletons are chiefly found in sandy sediments, which often contain admixtures of intraformational clasts (compare Table 8). Two examples showing the lithological character of the sediments enclosing specimens collected are given in Text-figs. 31, 32.

In general, it may be said that the bone material displays a relatively high degree of dispersal within the sediment. Both bone fragments and single bones occur sporadically. Bone breccias and bone beds are nowhere seen. Assemblages of bones belonging to particular skeletons are exceptionally found several metres or more apart. Even in such cases, it was nowhere confirmed that bones belonging to different specimens were mixed. The most pronounced grouping of dinosaur skeletons within a single layer was found during the 1948 Soviet Expedition in

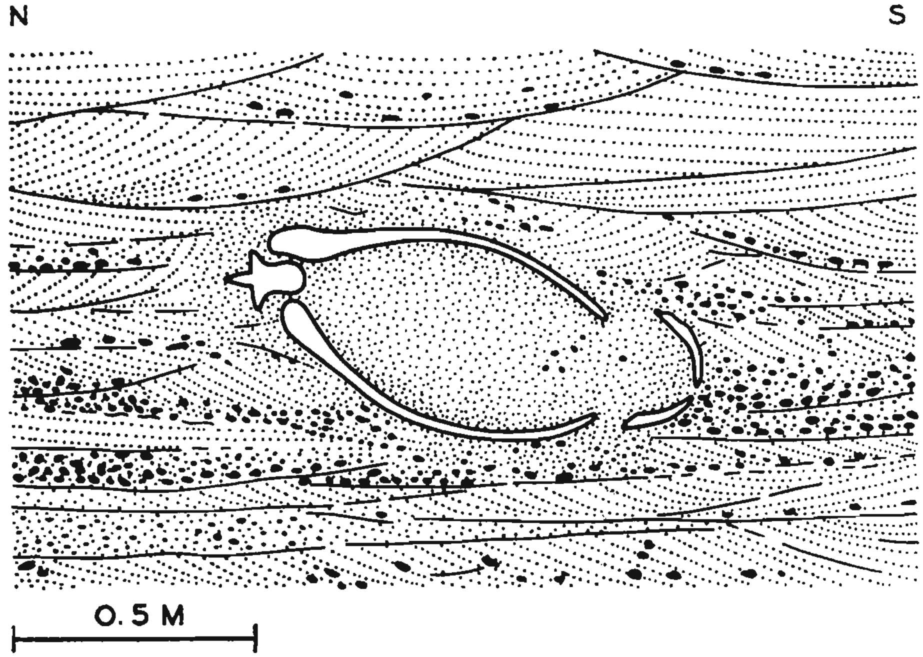

Fig. 31
Lithological character and sedimentary structures of sediments enclosing bones making up skeleton of *Tarbosaurus* sp. (Tsagan Khushu, No. 2). In immediate neighbourhood of bones, drawing is slightly schematized.

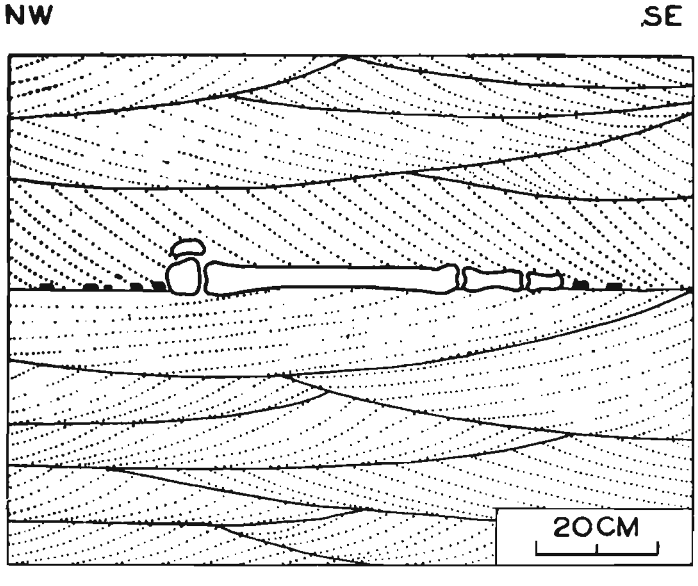

Fig. 32
Lithological character and sedimentary structures of sediments enclosing bones of ornithomimid dinosaur (Altan Ula IV, No. 8). Shapes of bones schematized.

the Dragon's Grave (Altan Ula II). From EFREMOV'S (1955, p. 799) account, it is seen that on a surface of area 700 m^2, seven skeletons of *Saurolophus angustirostris* were found. During the Polish-Mongolian Palaeontological Expeditions, relatively high concentrations of larger dinosaur remains were found in sediments exposed on the surface of an extensive denudation terrace in the northen part of the Central Sayr, Nemegt locality (Text-fig. 33). At the same locality, three partial skeletons of dinosaurs were found in close proximity within the Western Sayr. These are: a partially excavated skeleton of *Tarbosaurus* sp. (Nemegt, No. 12), the hind

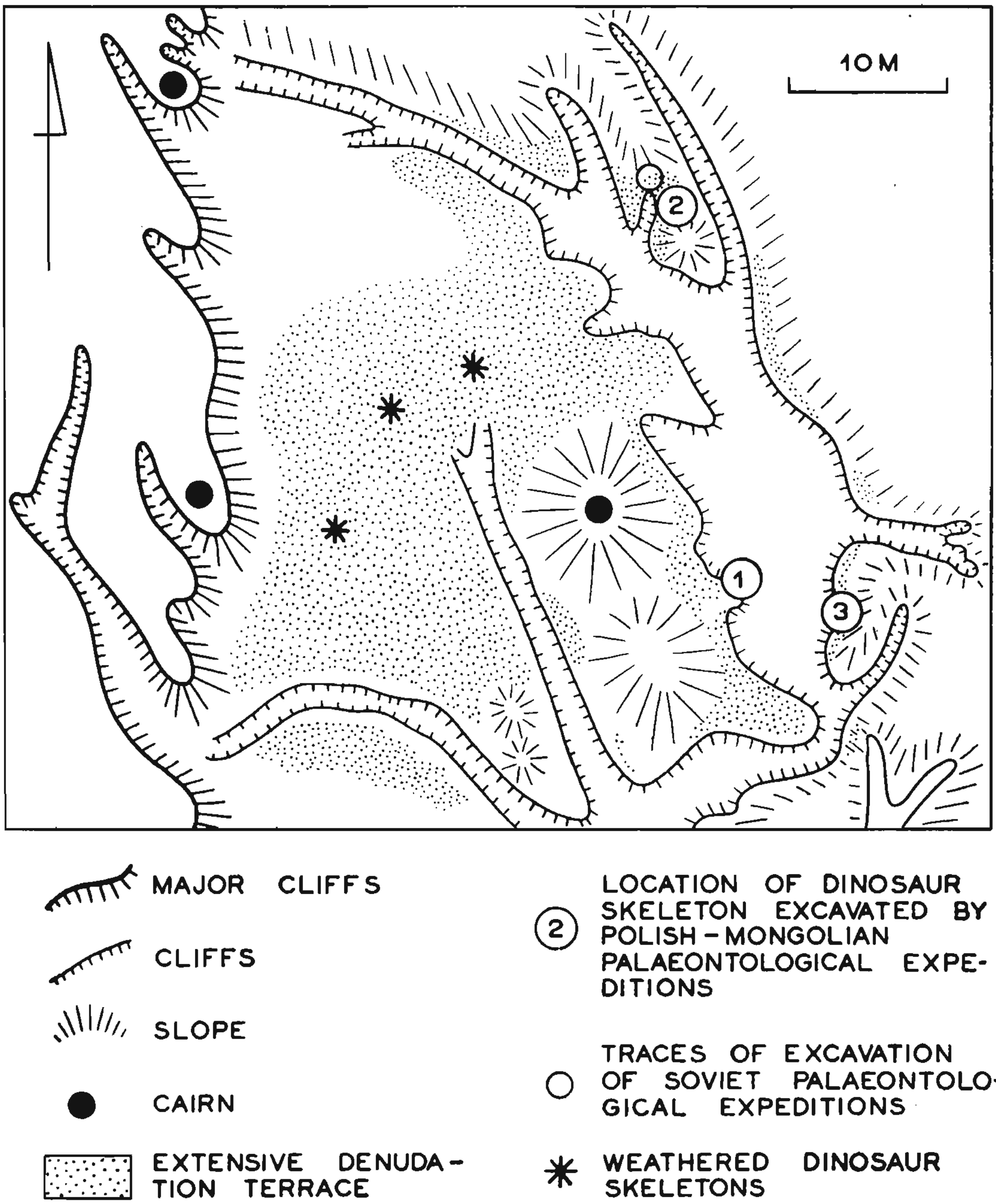

Fig. 33
Occurrence of larger dinosaur remains on extensive denudation terrace in northern part of Central Sayr, Nemegt locality.

limbs and incomplete tail of an ornithomimid dinosaur (Nemegt, No. 11) and the pelvic girdle of a large dinosaur (?*Saurolophus*). The first two specimens were ten metres apart, while the third specimen occurred a dozen or so metres from each of the other two. The larger dinosaur remains are relatively rarely seen in vertical exposures. They are not found in definite bone-rich horizons, but do tend to occur in complexes comprising layers of sand- and gravel-grade sediments. Sediments of these types usually occur above scoured surfaces (compare p. 203).

Table 8

Larger dinosaur remains excavated by Polish-Mongolian Palaeontological Expeditions and type of enclosing sediment

Dinosaur specimens	Intraformational conglomerates and pebbly-sandy sediments	Sands with intraformational gravel intercalations	Sands or sandstones	Sandy siltstones with intercalations of intraformational clasts	Sandy siltstones
Carnosaurian dinosaurs					
nearly complete skeletons	—	4	—	—	—
incomplete skeletons	—	4	—	1	—
parts of skeletons	5	3	—	—	—
Ornithomimid dinosaurs					
nearly complete skeletons	—	1	—	—	—
incomplete skeletons	2	1	—	—	—
parts of skeletons	2	2	1	—	—
Sauropod dinosaurs					
nearly complete skeletons	—	1	—	—	—
parts of skeletons	—	1	—	—	—
Unidentified saurischian dinosaurs					
incomplete skeleton	—	—	—	—	1
Ankylosaurid dinosaurs					
incomplete skeletons	1	1	—	—	—
parts of skeletons	1	1	—	—	—
Unidentified ornitischian dinosaurs					
incomplete skeleton	—	1	—	—	—
Total	11	20	1	1	1

These sediments are also exposed on the surfaces of almost horizontal denudation terraces. During the expeditions, dinosaur remains were sought and excavation work was concentrated chiefly in these places. For this reason, sites of exacavation of dinosaur specimens, marked in vertical profiles of exposures (see GRADZIŃSKI *et al.*, 1968/69), give the impression of the existence of definite bone-bearing horizons what is not necessarily the case.

Almost all of the larger dinosaur remains seen in the Upper Nemegt Beds occur in sediments with cross-stratification, usually of large-scale type (compare Text-figs. 31, 32). Detailed observations of sedimentary structures in the sediments making direct contact with the surfaces of the bones led to the following conclusions. In the case of single bones, as well as specimens, showing a marked degree of disarticulation, cross-laminae usually make contact with the surfaces of the bones (Text-fig. 34*A*, *B*). In some samples, the cross-laminae display deformations, most probably resulting from compaction of the sediments (Text-fig. 34*C*). On the other hand, in samples making contact with skeletons showing a low degree of disarticulation, no structures are seen. In these latter instances no structures were observed, even when X-ray photographic methods (procedures given by HAMBLIN, 1962, 1965) were employed. Probably the absence of structures is the result of vertical movements following burial of bones enveloped in soft tissues.

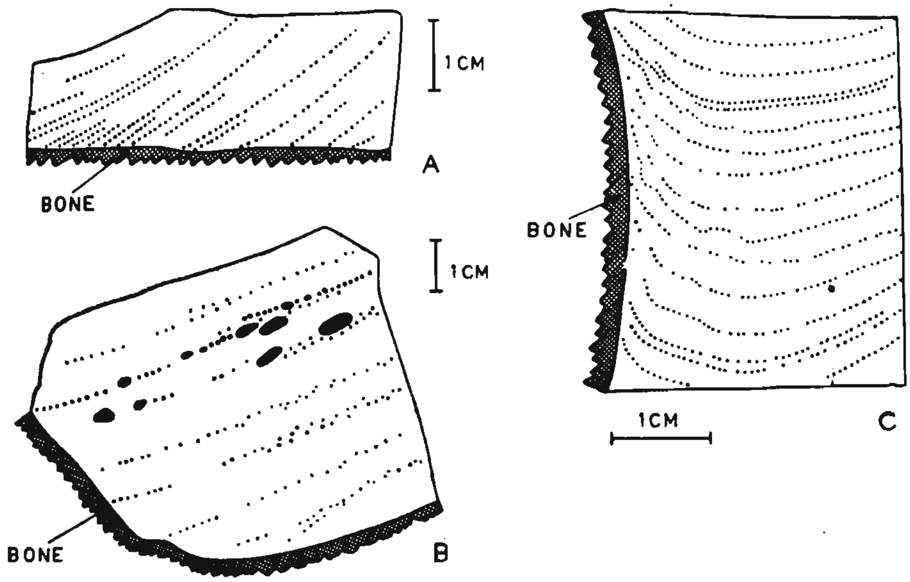

Fig. 34
Sedimentary structures of sediments in contact with dinosaur bones: *A*—cross-laminae in contact with surface of shoulder bone of sauropod dinosaur (Altan Ula IV, No. 4); *B*—cross-laminae in contact with surface of femur of sauropod dinosaue (specimen as above); *C*—deformed laminae near the contact with pelvis of an unidentified quadrupedal dinosaur (Altan Ula IV, No. 1). Drawing made from X-ray photographs *(A, B)* and during excavation *(C)*.

Only isolated, single bones display a definite orientation with respect to directional structures in the enclosing sediment. Elongated bones, occurring in this manner (for example long limb bones, rib fragments), are usually arranged either parallel or normal to the direction of maximum dip of cross laminae. Single, large bones (for example, large shoulder bones) and also whole skeletons or their distal elements, do not show any preferred orientation (compare Text-figs. 28—30). Fine bone fragments occurring in sediments with large-scale cross-stratification, like pebbles, normally lie on the surfaces of cross-strata.

STATE OF PRESERVATION OF BONE MATERIAL

The state of preservation of the bone material, as described in the present paper, comprises physical and chemical properties of the bones, such as chemical and mineral composition, colour, toughness, surface morphology of complete bones and their fragments etc. The chemical and mineral composition of bones is a problem beyond the scope of the present paper. Only problems related to the environment and conditions of deposition are here considered.

Thin sections of bones from several specimens were examined under a polarizing microscope. The original structure of the bone is usually very well preserved. As a rule, the original, dense bone material has been replaced by amorphous collophane. Nearly complete calcitization of the bone material was found in rare instances.

Histological investigations of one sample (phalange bone of a dinosaur) were carried out by PAWLICKI *et al.* (1966). The presence of collagenous material in the walls of the vessels was demonstrated by means of electron microscopy. Also JAWOROWSKI & PEŃSKO (1967) during studies of radioactivity of the bone material, confirmed the presence of organic substances in several samples of dinosaur bones from the Nemegt Valley. Microscopic observations carried out by the present author revealed the frequent occurrence of haematite and of manganese oxides and hydroxides. These substances either impregnate and coat the walls of the voids inside the bone (such as the Haversian channels) or fill them entirely. These voids are often filled with calcite. Larger calcite crystals sometimes fill the bone marrow holes.

The colour of the dinosaur bones largely depends on the kind of substance filling the internal voids. Dark brown or nearly black colouration of bones is due to the presence of iron and/or manganese compounds. Light-coloured bones (white, yellow) have empty voids or voids filled almost exclusively with calcite. Often in one bone, the parts with compact structure are light coloured, while the parts with spongy structure are distinctly darker.

Field observations indicate that brown or orange coloured bones occur within sediments having similar colouration, and containing relative large amounts of trivalent iron. In this case, the present writer's observations are in agreement with those of TCHUDINOV (1966) made at Bugin Cav.

Bones found loose on the surface or only partly embedded in sediments show the greatest differentiation of colour. In such cases, differences in colour were observed not only between the compact and spongy parts of the bone, but also between various sections of the same bone or between various parts of the skeleton. In the specimens excavated from sediments, there was no clear relationship between the colouration of the bones and the state of disarticulation, fragmentation of bones or taxonomic group, to which the skeleton belonged. It may be supposed that the colour of bones results mainly from processes, which operated after the burial of bones in sediments, that is, during fossilisation and also from recent weathering. Therefore the colour of bones cannot be regarded as an indicator of processes to which the bones were subjected prior to burial in sediment, as was assumed by EFREMOV (1955, p. 802).

The iron content in the bone material can be possibly used as an indicator of climatic conditions existing during the deposition of the embedding sediment. According to HOUSTON *et al.* (1966), a large mean content of iron in bones from a given formation is related to a humid and warm climate. However other factors, such as environment and micro-environment of the place of burial and weathering may cause large differences in iron content in bones of the same age and collected from the same exposure. Nevertheless, in the opinion of the above authors "the bulk of the iron in fossil bone is introduced after burial, during diagenesis" (HOUSTON *et al.*, *l. c.*, p. 11).

Only 6 chemical analyses of dinosaur bones from the Upper Nemegt beds have been carried out; the samples for analysis were selected from material, which did not show distinct changes due to recent weathering. The iron content in the bones varied from 2.2 to 8 per cent, with a mean value of 3.6 per cent. The comparison of these data with the results of HOUSTON *et al.* (1966) indicate a comparatively high content of iron. However, the small number of analyses and the lack of data from other formations of Mongolia for comparison, does not permit inferences on the palaeoclimatic conditions.

Dr. J. Łoziński of the Department of Mineralogy and Petrography, Jagellonian University, is investigating the rare-earths content in samples of dinosaur and tortoise bones from the Upper Nemegt Beds supplied by the present writer. The preliminary results of these investigations indicate that the concentration of these elements is relatively high (maximum content ca. 0.5 per cent). Preliminary chromatographic separation of elements indicate the predominance of yttrium or of yttrium earths. The characteristic concentration of rare earths in fossil bones is widespread, and noted, among others by Lavrov (1956) and Toots (1963). According to Lavrov *(l. c.)*, the secondary character of this process is beyond doubt, and the process operated very slowly during long periods.

Jaworowski & Peńsko (1967) described a relatively strong radioactivity of the bone material occurring in the Upper Nemegt Beds. According to these writers, the accumulation of parent uranium in the bones was post-depositional.

The bone material occurring in the Upper Nemegt Beds is characterized by a general lack of abrasion of bones (that is of crushing, chipping, cracking and grinding as defined by Kuenen, 1956). As a rule, the bones show only effects of breaking and splintering. Rounded bone fragments were not found.

Single isolated bones occasionally show a small loss of material, usually at the ends of the shaft in long bones. The fracture surfaces of single bone fragments also show small losses of material and some rounding of edges in parts with spongy structure, while the parts with compact structure always have sharp edges.

The fragility of some bones is related chiefly to recent weathering. The bones exposed at the surface or found under a thin cover of sediment are always strongly fractured and have a tendency to break and splinter. Bones excavated at greater depths were usually tough. No relationship was observed between the toughness of bones and the degree of disarticulation of the excavated specimens in such cases. Also the toughness of bones does not seem directly related to the type and degree of mineralization.

CONDITIONS OF BURIAL OF DINOSAURS

It has been demonstrated above that the Upper Nemegt beds were deposited in a fluvial environment with a strong tendency towards aggradation. Coarse-grained sediments, seen as intraformational conglomerates and sands, were deposited at high rates, accumulating piecemeal during seasonal floods. The deposition of these sediments created favourable conditions for the rapid burial of remains of dinosaurs. The burial of dinosaur remains in the sediments could be preceded by earlier processes such as natural decay of the body of the animal and the related disarticulation and weathering of bones, and transportation of the bone material.

The dinosaur bones displaying articulation were probably buried before the decay of the soft tissues. This conclusion is supported by observations of dead bodies of Recent large vertebrates carried out in various environments, among others by Weigelt (1927, 1930), Schäfer (1962), and Toots (1965). Among the excavated dinosaur skeletons, those which were characterized by an anatomic arragement of skeletal elements and articulation of the majority of bones (e.g. *Tarbosaurus* sp., Tsagan Khushu, No. 2; *Tarbosaurus* sp., Nemegt, No. 1; ornithomimid dinosaur, Tsagan Khushu, No. 1) were undoubtedly buried in the early stages of decay of soft tissues (see Schäfer, 1962; Toots, 1965).

A comparison of the stages of disarticulation of the skeletons represented by various specimens of dinosaurs indicates a strong similarity between the sequence of events in this process and the sequence of disarticulation of skeletons of Recent land-dwelling vertebrates (see Toots, 1965).

Displacement of bone material over a large distance may be caused either by traction transport by running water or by floating of bodies. In the opinion of the present writer, tractive transport of the bone material did not occur on an appreciable scale in the sedimentary environment of the Upper Nemegt Beds. This conclusion is based on the following observations: the large number of specimens with a high degree of completeness of the skeletal material, lack of mixing of bones belonging to various dinosaurs, and lack of distinct rounding of bone fragments. The number of single bones and bone fragments is small by comparison with the large amount of bone material represented by skeletons and parts of skeletons.

The incompleteness of skeletal material in some specimens excavated, and the fracturing of their bones cannot be regarded as being indicative of tractive transport. The incompleteness of the bone material could be caused by several other processes, such as strong dispersion of bones at the place of the disarticulation of the skeleton or partial burial (see Schäfer, 1962; Toots, 1965), the action of carnivorous animals and carrion feeders or by recent erosion and weathering. The fracturing of bones could be caused by primary weathering at the place of burial, by recent weathering, or by compaction of sediments. It seems very probable that the decomposition of a completely buried body of a dinosaur resulted in collapse of the covering sediment, which could cause the fracturing of bones.

The isolated single bones and bone fragments occurring rarely in the Upper Nemegt Beds were probably dispersed by local redeposition. This is indicated by the distinct relation of such bone material with the intraformational gravels and a great dispersion in the sediments.

No distinct features, indicative of long transportation of the bodies of dinosaurs by floating were found in the specimens excavated in the Upper Nemegt Beds. Observations of dead bodies of Recent vertebrates indicate that floated corpses assume a characteristic "passive position" after sinking (Weigelt, 1927; see also Schäfer, 1962). This position is characterized by a ventral or dorsal attitude, and by spread limbs, head and tail (if these were not separated earlier). In the case of strong bottom currents, the limbs are orientated, most often parallel (Weigelt, 1927; Müller, 1950, 1963).

The above set of features of the "passive position" was not observed in the six nearly complete skeletons excavated from the Upper Nemegt beds. Only one specimen of a sauropod (Altan Ula IV, No. 4; see Kielan-Jaworowska & Dovchin, 1968/69, Pl. 3) displayed some features of this position. Four specimens belonging to *Tarbosaurus* sp. were found in a lateral, position, and one (ornithomimid dinosaur) in a lateral-dorsal position. In all these five specimens, the hind limbs were contracted, while the neck and the tail were as a rule bent strongly dorsally.

Such a dorsal bending of the neck and tail is often observed in skeletons of fossil vertebrates. Various explanations of this phenomenon have been proposed (see Hennig, 1915) and now it is held to result from desiccation of the body (Weigelt, 1927; Müller, 1950, 1963).

Thus, burial of the mentioned skeletons of bipedal dinosaurs was probably preceded by at least partial dessication of their bodies. This process took place at the site of the burial or in its immediate neighbourhood. Any prolonged transport of the heavy and already stiff body without distinct traces seems impossible.

It cannot be excluded entirely that some dinosaur bodies were transported over small distances by floating in a river. However, such floating bodies were probably deposited on the shores or on sand bars where they were subject to decomposition and disarticulation in subaerial conditions.

All the data presented indicate that the overwhelming majority of dinosaur remains occurring in the Upper Nemegt Beds was buried at or near the site of death of the animals.

The area of sedimentation was undoubtedly flat and crossed by channels of a river or several rivers (see p. 207). On such an area, both amphibious and land-dwelling dinosaurs could live and the population could consist both of potential competitors (hadrosaurs, ankylosaurs, sauropods) and potential predators belonging to the Theropoda (see COLBERT, 1951; OSTROM, 1964). It seems that for such an area, definite boundaries of zones occupied by various groups of dinosaurs, as shown in the scheme of EFREMOV (1954*b*), cannot be accepted. Even if such zones were delimited, their areas were adjoining and interlocking, forming embayments and enclaves.

DISCUSSION

The opinion of the present writer on the transportation and deposition of dinosaur remains occurring in the Upper Nemegt Beds differ from the opinions previously expressed by EFREMOV (1950, 1954*a*, 1954*b*, 1955).

EFREMOV assumed that the bone-bearing sediments were deposited in a large lake or in an inland sea, within "subaqueous deltaic channels". The area of sedimentation was situated beyond the life zones of the dinosaurs (see EFREMOV, 1954*b*), possibly with the exception of the sauropod zone. According to EFREMOV (1950, p. 67), the fossiliferous sediments of the Nemegt Basin represent "relatively long-distance exportations of dinosaur remains" (sravnitelno dalnye vynosy ostatkov dinosavrov). The dinosaur remains reached their sites of burial by floating (chiefly hadrosaurs) or were carried by traction transport (mainly carnivorous dinosaurs). Following this line of reasoning, EFREMOV (1955) regarded the completeness of skeletons as resulting from transportation by floating and a considered poor state of preservation of the skeletons (incompleteness fracturing of bones) as indicative of traction transport over a large distance.

EFREMOV's assumptions concerning the lacustrine environment of deposition of the fossiliferous sediments (1950, 1954*a*, 1955) are not supported by geological evidence. The recognition of fluvial deposition of the Upper Nemegt Beds makes the assumptions of a long-distance transport of dinosaur remains either by floating or by traction along the bottom unnecessary.

EFREMOV (1950) stressed upon the poor state of preservation of skeletons as characteristic for predatory dinosaurs. The results of the excavations carried out by the Polish-Mongolian Palaeontological Expeditions indicate that this is not the rule. On the contrary, among six nearly complete skeletons, four belong to predatory dinosaurs and do not show traces of transport by traction.

It should be added that several conclusions of EFREMOV (1955) were based on comparisons of proportions of specimens representing various taxonomic groups excavated at different localities of the Nemegt Basin. However, these proportions were seriously changed by the excavation of new specimens in the same area by the recent expeditions.

OTHER ORGANIC REMAINS

In addition to dinosaur bones, the sediments of the Upper Nemegt Beds contain, besides fragments of dinosaur eggs, also remains of tortoises, crocodiles, fishes, pelecypods, phyllopods and ostracods. Plant remains are represented by calcified tree trunks and oogonia of Charophyta.

Tortoise and fish remains usually occur in sandy or gravelly sediments. Single bones of tortoises and fragments of shells are common and complete skeletons are also found. Abundant tortoise skeletons in one bed of very fine sand were reported from the locality Tsagan Khushu in an earlier note (see GRADZIŃSKI *et al.*, 1968/69, Text-figs. 8, 9). According to Soviet authors, the tortoises occurring in the Upper Nemegt Beds belong to the family Baenidae (see EFREMOV, 1955; KHOZATSKI, *in* MARINOV, 1957, p. 173) and to the family Trionychidae (see EFREMOV, 1954*a*, 1955). However, until now, no papers were published on the

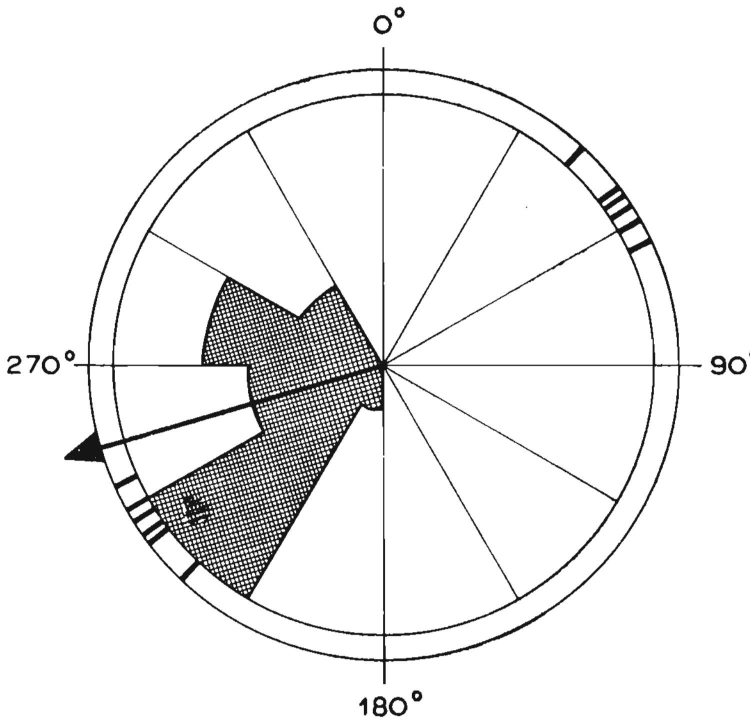

Fig. 35
Orientation of tree trunks (in outer circle). Rose diagram shows directions of maximum dip of cross-laminae in enclosing sediments; black arrow gives mean value of latter. Upper Nemegt Beds, locality Altan Ula II, Dragons Grave.

Cretaceous tortoise remains collected by the Soviet and the Polish-Mongolian Palaeontological Expeditions. According to Dr. M. MŁYNARSKI (personal communication), small tortoises, belonging to the family Dermatemydidae *(sensu lato)*, predominate in the material collected by the latter expeditions. Fish remains are common in the sediments described, but occur only as single vertebrae.

Rare crocodile remains were found by the Soviet Expeditions in sandy sediments at the Nemegt locality. KONZHUKOVA (1954) described *Paraaligator ancestralis* from this material, noting that this form lived probably in shallow water with sand banks.

Some conglomerate beds contain numerous and usually poorly preserved shells and internal molds of pelecypods. MARTINSON (1966, p. 63) reported specimens of *Pseudohyria* sp. (family Trigonioididae) found by members of the Soviet Expeditions at the locality Altan Ula (probably Altan Ula II, according to the present author).

The phyllopods found by the Soviet expeditions were described by NOVOZHILOV (1954*a*). The specimens were collected at the localities Tsagan Khushu and Altan Ula (II), in places called

Ikhe Khongol and Ula Shand. According to data given by NOVOZHILOV (*l. c.*, pp. 102—103), the phyllopods occurred in sands with flaser structure, in lenses of fine-grained sediments and in mudstones. According to the last-mentioned author, the phyllopods lived in the near-shore zone of a lake.

Calcified wood fragments are found as a rule in sandy sediments. They are numerous in exposures of the western part of the Nemegt Basin, and are rare at the Nemegt locality. Their lengths usually do not exceed 50 cm and their diameter ranges from a few to several cm. As a rule, such wood fragments are flattened. A few large trunks 5—8 m long with diameters ca. 30 cm. were observed in the immediate neighbourhood of the accumulation of *Saurolophus angustirostris* skeletons in the Dragon's Grave (locality Altan Ula II). These long trunks were nearly parallel to the current direction given by cross-stratification (Text-fig. 35).

Ferrugineous streaks, possibly representing plant detritus, are observed occasionally in sands and in siltstones.

Oogonia of Charophyta were found in samples of claystones and described by KARCZEWSKA & ZIEMBIŃSKA-TWORZYDŁO (1970). Some of these samples contained also ostracods (see SZCZECHURA & BŁASZYK, 1970).

In the opinion of the present author, the lithological character and the sedimentary features of the sediments indicate that the remains of tortoises, crocodiles, fishes and pelecypods were buried by river channel or substratum deposits, while the Charophyta were preserved in floodbasin or channel-fill deposits. It is stressed that the pelecypods were found exclusively in intraformational gravels which rest upon scoured surfaces and have the character of channel-lag deposits. This fact contradicts the opinion expressed by MARTINSON (1966) that the pelecypods found in Upper Cretaceous sediments of Mongolia (and therefore also in the Nemegt Basin) are preserved in sediments deposited on the bottoms of large lakes.

TRACE FOSSILS

Trace fossils are common in the Upper Nemegt Beds, and occur less frequently in the Lower Nemegt Beds. They occur chiefly in sandy sediments and claystones and are more rare in siltstones. The structures are clearly visible on weathered exposure faces. Collection of specimens is difficult because of poor cementation of the sediments.

The most common type of trace fossils occur as sediment-filled tubes, ranging in diameter from a few mm to 15 mm. The tubes extend in various directions and in some cases bifurcate (Pl. XLII, Fig. 1). In sand beds, such structures are usually randomly dispersed throughout the entire bed, but sometimes they are concentrated immediately below the top surface. In fine-grained sediments the tubes do not usually reach deeper than 10—15 cm below the top surface. The material filling the tubes often differs slightly in grain size from the enclosing sediment. The surface of the tubes has a granular ornamentation, resembling that of *Ophiomorpha* sp. or *Granularia* sp. (see HÄNTZSCHEL, 1962).

Short tubes 2—3 mm in diameter and 10—20 mm long, with smooth walls are much frequent. They occur on the basal surfaces of sandstones producing a positive hyporelief (see SEILACHER, 1964, p. 299, Fig. 1). The structures are either oriented in parallelism (Pl. XLII, Fig. 2) or show no preferred orientation.

CONCLUSIONS

1. The Nemegt Beds consist of exclusively clastic, continental sediments of red-beds type. The Upper Nemegt Beds concordantly overlie the Lower Nemegt Beds. A gradual passage exists between the two formations.

2. The gross petrographies of the Upper and Lower Nemegt Beds are essentially similar. In both formations sand-grade sediments are dominant as arkoses. The main clay minerals are montmorillonite, kaolinite and illite occurring together, with montmorillonite predominating. Exotic pebbles are rare. All clastic material was derived from one source area, comprising acid, effusive and related pyroclastic rocks, as well as arkosic sediments and plutonic and metamorphic rocks. The source area did not lie in the immediate neighbourhood of the sedimentary basin, but was situated at a distance of a hundred or more kilometres away, probably to the NE of the Nemegt Basin.

3. The sedimentary features of the Upper Nemegt Beds: commonly occurring scoured surfaces and erosional channels with associated intraformational conglomerate, composite inclined stratification, large-scale trough cross-stratification, climbing-ripple structures and fining-upwards cycles indicate a fluvial environment of deposition. The Upper Nemegt Beds are alluvial-plain sediments. Point-bar and channel-bar sediments predominate, while channel-floor and overbank sediments occur in smaller proportions.

4. The absence of scoured surfaces of wide extent, scarcity of erosional channels, relatively large, lateral persistence of some beds and the massive character of sediments suggest that the Lower Nemegt Beds were probably deposited in a lacustrine environment, though a fluvial origin cannot be excluded.

5. The fact that the flora consists exclusively of Charophyta and calcified tree trunks is due to oxidizing conditions in the area of deposition.

6. The dinosaur remains, occurring abundantly in the Upper Nemegt Beds, are associated with point-bar and channel-bar sediments. The rapid accumulation of sediments created favourable conditions for the preservation of bone material The absence of bone breccias suggests that transportation of bone material did not play an important role. The complete nature of many dinosaur skeletons and the arrangement of bones belonging to a given skeleton indicate burial at or near the site of death.

7. Both the petrographic composition of the sediments as well as the sedimentary features and fauna of the Upper Nemegt Beds suggest a warm and rather humid climate during the deposition of this formation. The considerable lithological variability of the channel sediments evidences large variation of river stages, which, in turn, indicates an alternation of dry and rainy seasons.

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PLATES

R. GRADZIŃSKI: SEDIMENTATION OF UPPER CRETACEOUS DEPOSITS

PLATE XXXV

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Fig. 1. Lower Nemegt Beds (lower and middle part of canyon wall) and Upper Nemegt Beds (upper part of canyon wall). Gorge in northern part of Nemegt locality 180

Fig. 2. Upper Nemegt Beds: Passage Series in lower part of exposure. Note large-scale inclined stratification. Height of exposure about 40 m. Nemegt locality, Northern Sayr 181

Photo: R. Gradziński

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PLATE XXXVI

Page

Fig. 1. Upper Nemegt Beds. Note wedging out of sands (lower part of photograph). Bed of intraformational conglomerate, on which is developed denudation terrace, visible in upper part. Height of exposure about 5 m. Locality Altan Ula IV 181

Fig. 2. Margin of erosional channel. Upper Nemegt Beds, locality Altan Ula IV. Open Sayr. Height of exposure about 3 m. 182

Photo: R. Gradziński

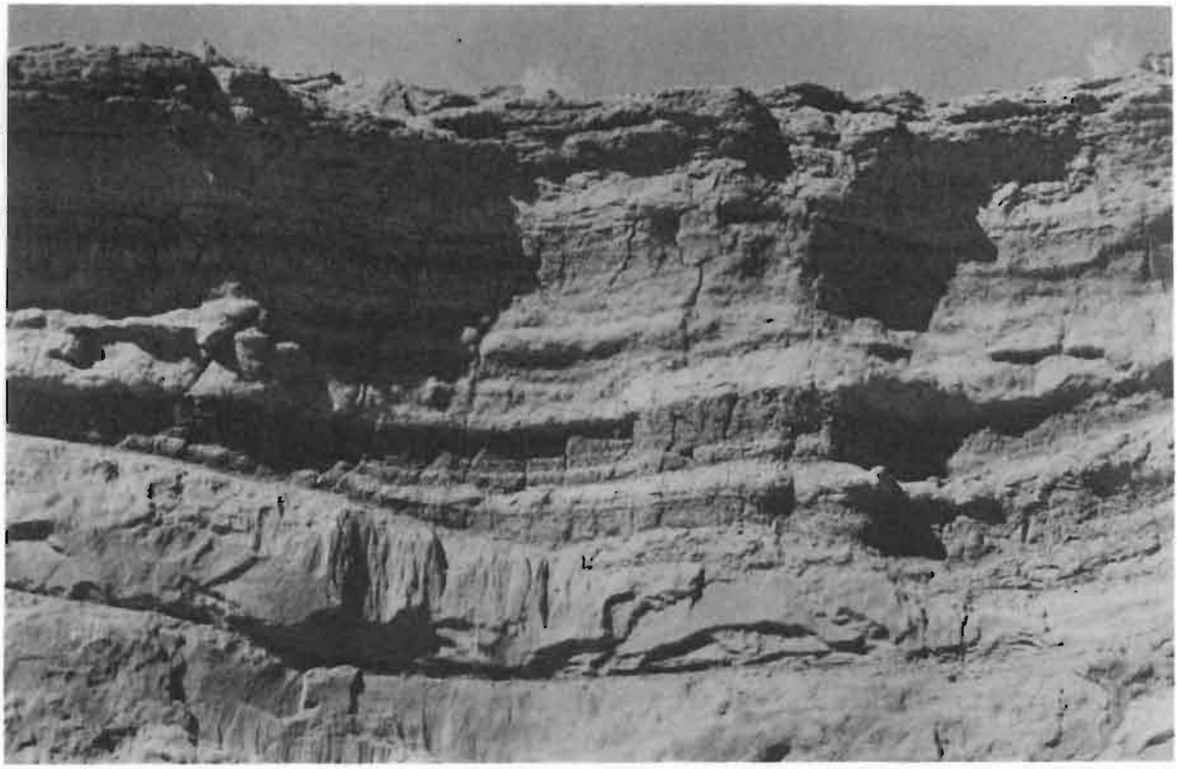

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PLATE XXXVII

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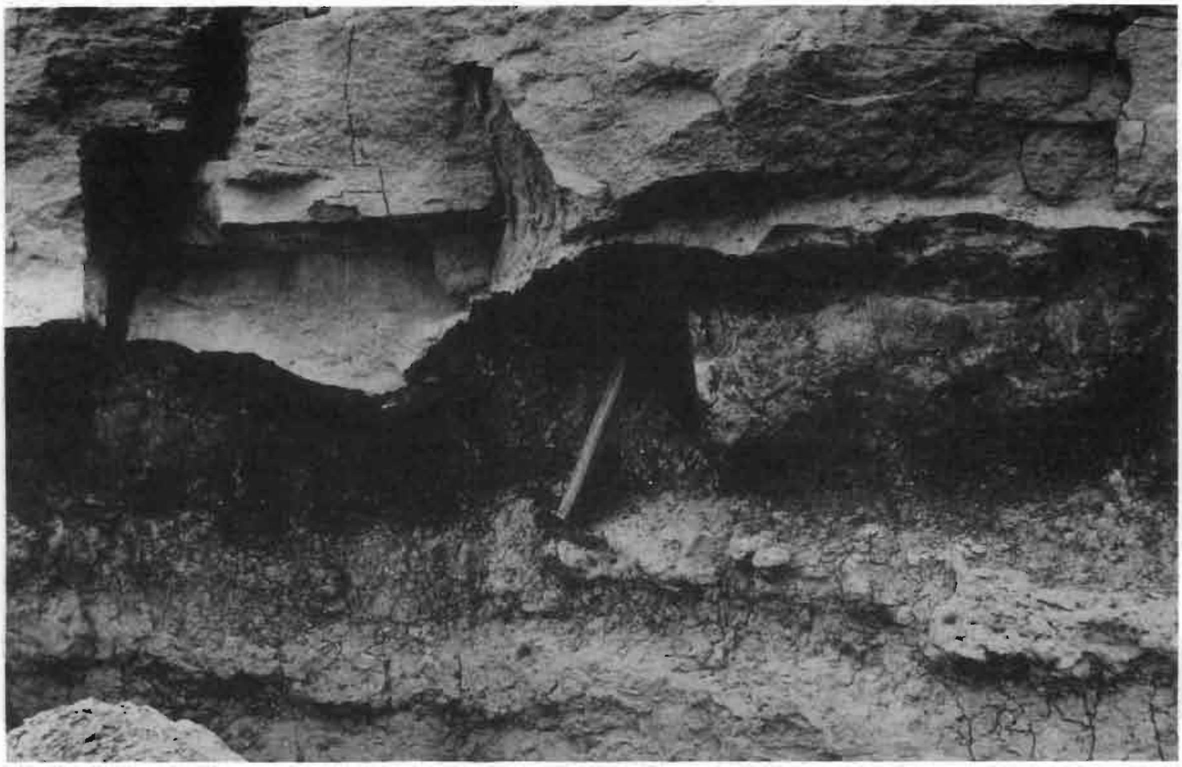
Fig. 1. Fragment of scoured surface, with secondary erosional structures. Large-scale cross-stratification visible within the structure on the left-hand side. Red claystone lies below the scoured surface. About it is a drab sandstone containing small, intraformational clasts. Upper Nemegt Beds, Nemegt locality, Western Sayr 183

Fig. 2. Irregularly shaped load casts. Red claystone at base, overlain by drab, poorly consolidated sandstone. Upper Nemegt Beds, Nemegt locality, Central Sayr. 199

Photo: R. Gradziński



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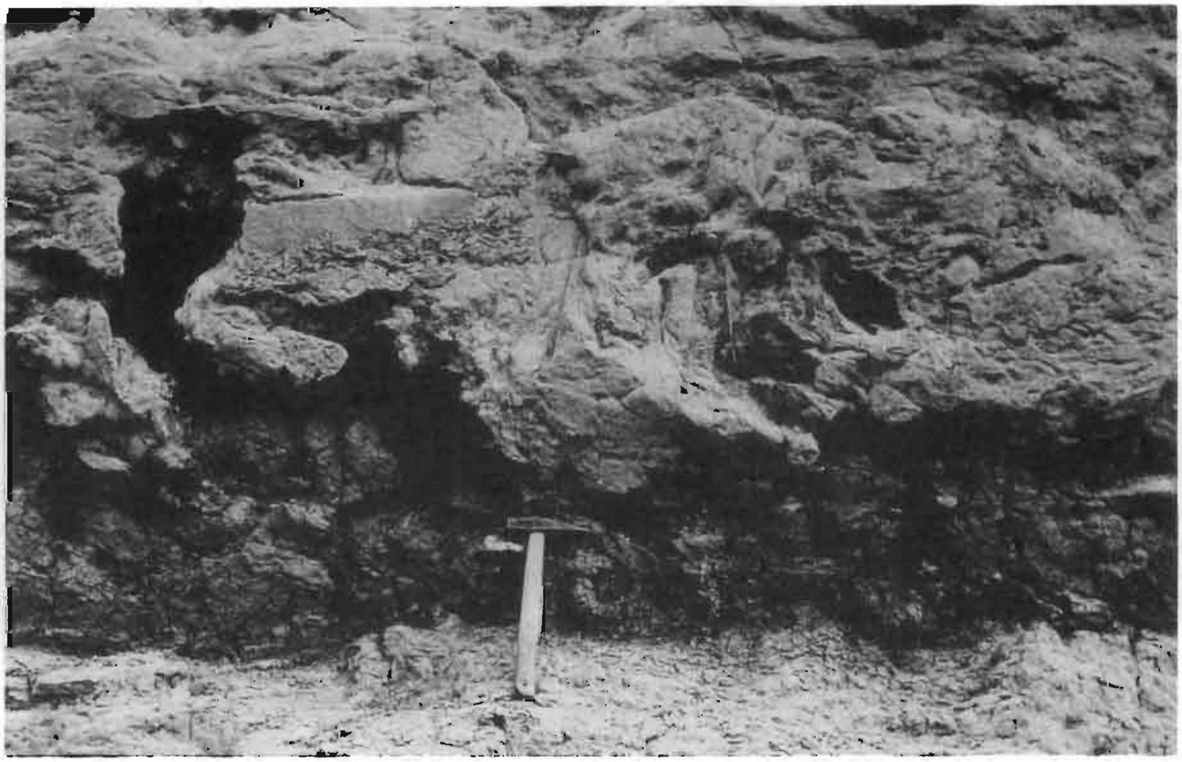

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R. GRADZIŃSKI: SEDIMENTATION OF UPPER CRETACEOUS DEPOSITS

PLATE XXXVIII

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Fig. 1. Large-scale trough cross-stratification in sandy sediments with siltstone and claystone pebbles. Thickness of set 35 cm. Upper Nemegt Beds, locality Tsagan Khushu 190

Fig. 2. Climbing-ripple structure. Current direction from right to left; 1/4 natural size. Upper Nemegt Beds, locality Tsagan Khushu 188

Photo: R. Gradziński

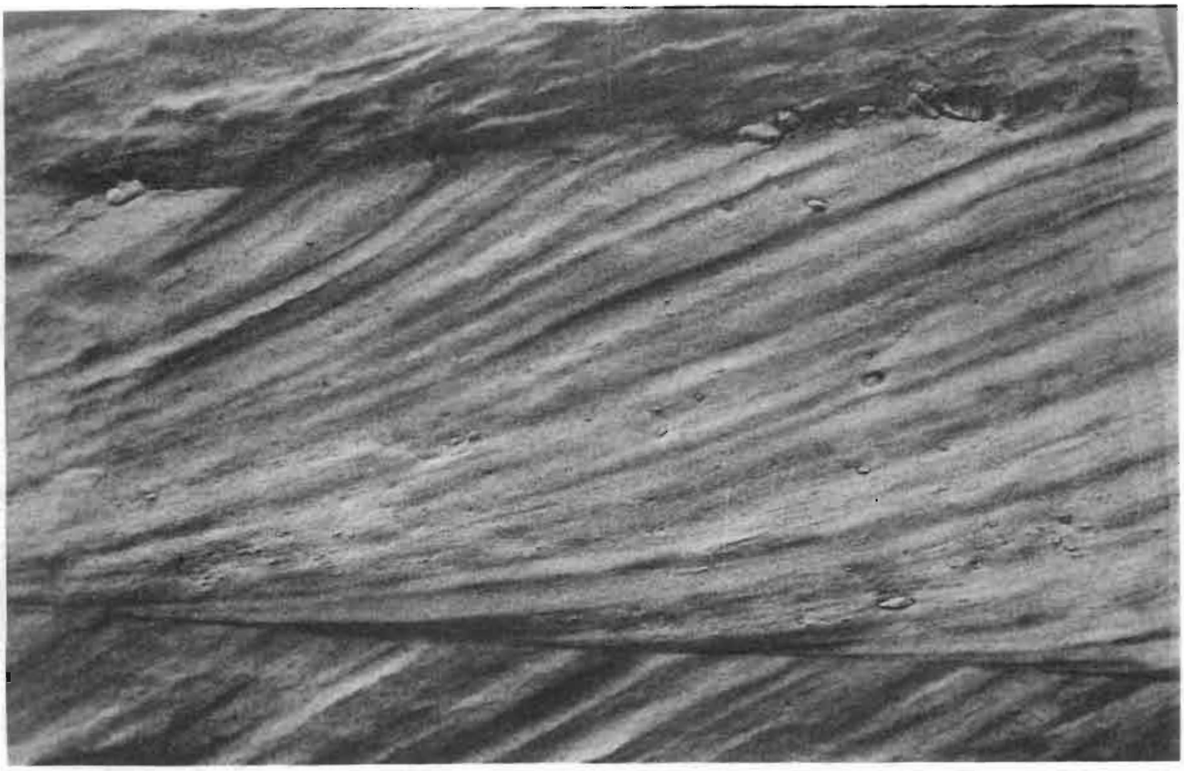

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PLATE XXXIX

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Fig. 1. Horizontal lamination in sands (central part of photograph), overlying pebbles and boulders of siltstone, and covered by sands with small-scale cross-stratification. Upper Nemegt Beds, locality Altan Ula IV, Eagle Sayr 184

Fig. 2. Upper part of very thick claystone layer (with light-coloured, calcareous concretions). truncated by scoured surface. Alternating, inclined beds of silts rest on scoured surface 161

Fig. 3. Intraformational gravel: siltstone or claystone balls and irregular fragments embedded in sandy matrix. At top, sand with horizontal lamination and another gravel bed; 1/5 natural size. Upper Nemegt Beds, locality Altan Ula IV, Eagle Sayr. 164

Fig. 4. Large-scale trough cross-stratification in lower level of a composite layer. Upper Nemegt Beds, locality Altan Ula IV, Eagle Sayr 189

Photo: R. Gradziński

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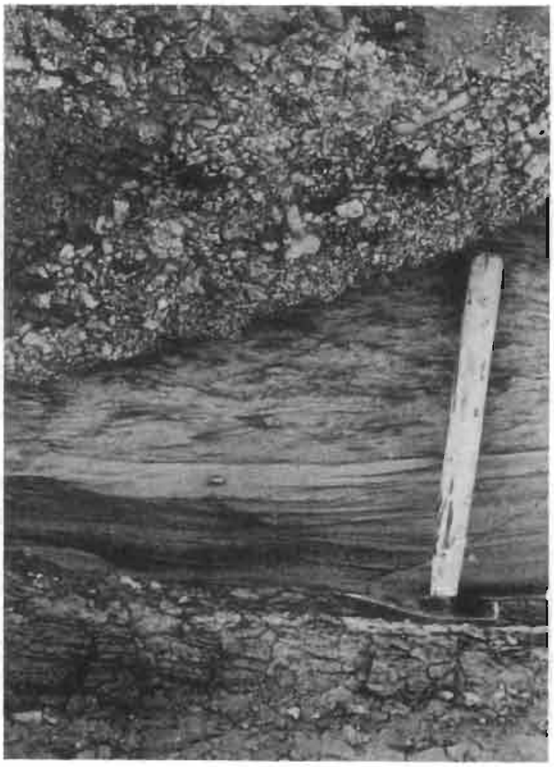

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PLATE XL

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Fig. 1. Large scale inclined stratification of "delta-type". A layer of intraformational conglomerate and sands, with composite inclined stratification, rests on the scoured surface. Upper Nemegt Beds, Passage Series, Nemegt locality, Central Sayr 197

Fig. 2. Alternating, inclined beds of sands and siltstones within a composite layer. Upper Nemegt Beds. Nemegt locality, northern part of Central Sayr 193

Photo: R. Gradziński

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PLATE XLI

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Fig. 1. Fill of erosional channel. Sediments with large-scale cross-stratification on nearly horizontal scoured surface. Height of exposure in central part of photograph is 4.5 m. Upper Nemegt Beds, Nemegt locality, Western Sayr 183

Fig. 2. Inclined strata of a composite layer visible in lower part of exposure are overlain by a thick, horizontal claystone bed. Latter truncated by a scoured surface and overlain by an intraformational conglomerate bed, seen at the marked change in slope. Height of vertical face is 4.5 m. Upper Nemegt Beds, locality Altan Ula IV, Eagle Sayr 193

Fig. 3. Deformational structures in cross-stratified sand. Upper Nemegt Beds, Nemegt locality, near Central Sayr 199

Photo: R. Gradziński

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PLATE XLII

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Fig. 1. Trace fossils in cross-stratified sands. Vertical exposure face; 1/5 natural size. Upper Nemegt Beds, locality Tsagan Khushu 222

Fig. 2. Basal surface of sandstone bed with two types of trace fossils; 3/5 natural size. Upper Nemegt Beds, Nemegt locality, Reconnaissance Hill 222

Fig. 3. Exposures of Upper Nemegt Beds, Nemegt locality, northern part of Central Sayr. Margin of extensive denudation terrace in foreground. Observers standing around excavated skeleton of *Tarbosaurus* sp. (Nemegt, No. 1). Flat top of hill in background is fragment of older pediment. View towards SE. 210

Photo: *R. Gradziński*

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