THE LASER DIFFRACTION GRAIN SIZE ANALYSIS OF LATE MIOCENE FLOOD-PLAIN SEDIMENTS FROM LANTIAN, IN SHAANXI PROVINCE, NORTHERN CHINA

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TABLE OF CONTENTS

ABSTRACT ................................................................................................................ 4

1. INTRODUCTION ............................................................................................. 5

2. MATERIAL AND METHODS ......................................................................... 6
   2.1. SAMPLES .................................................................................................. 6
   2.2. PILOT STUDY ....................................................................................... 6
   2.3. SUBDIVIDING ....................................................................................... 8
   2.4. SAMPLE PREPARATION ........................................................................ 9
   2.5. LASER DIFFRACTION GRAIN SIZE ANALYSIS ................................ 10

3. RESULTS ........................................................................................................... 12
   3.1. GRAIN SIZE DISTRIBUTION .................................................................. 12
   3.2. GRAIN SIZE PARAMETER PROFILES ............................................... 14
       3.2.1. MEAN GRAIN SIZE ................................................................. 14
       3.2.2. MEDIAN AND QUARTILES ....................................................... 15
       3.2.3. MODE ......................................................................................... 16
       3.2.4. MEAN TO MEDIAN RATIO ....................................................... 17
       3.2.5. MEAN TO MODE RATIO ........................................................ 17
       3.2.6. MEDIAN TO MODE RATIO ..................................................... 18
       3.2.7. STANDARD DEVIATION .......................................................... 18
       3.2.8. SKEWNESS ............................................................................... 19
       3.2.9. KURTOSIS ................................................................................. 20
       3.2.10. COEFFICIENT OF VARIATION ............................................ 20

4. DISCUSSION ..................................................................................................... 21
   4.1. CORRELATIONS ..................................................................................... 21
   4.2. VISUAL OVERVIEW ............................................................................. 23
   4.3. GRANULOMETRY .................................................................................. 24
       4.3.1. LOWEST PART ........................................................................ 24
       4.3.2. TOP PART .................................................................................. 24
4.4. GENERAL CHARACTERISTICS OF
CONSTRUCTED TIME SERIES .............................. 26
4.5. COMPOSING TIME SERIES............................... 26
  4.5.1. TRENDS ................................................ 28
    4.5.1.1. REGRESSION .............................. 28
    4.5.1.2. TRENDS SUMMARY .......................... 33
  4.5.2. CYCLICITY .......................................... 34
  4.5.3. HIGH AND LOW MODES,
        HIGH FREQUENCY FLUCTUATION ........... 36
4.6. PROCESSES .................................................. 37
  4.6.1. FLUVIAL SYSTEM .................................. 38
  4.6.2. EOLIAN COMPONENT ............................... 38
4.7. DISCUSSION OF METHODOLOGY ........................ 39

5. CONCLUSIONS .................................................. 40

6. ACKNOWLEDGEMENTS ....................................... 41

7. REFERENCES .................................................. 41
Abstract

The purpose of this study is to determine grain size parameters of the sediment samples, to analyze the trends and patterns distinguished from the parameters and to discuss the processes involved in the sedimentation of the studied part of the Late Miocene Bahe Formation (Shaanxi province, Central China).

A pilot study was performed to determine the need for ultrasonic dispersion prior to analysis, and it was deemed unnecessary. The sampled thickness was 1650 cm with 165 samples at 10 cm intervals. These samples were divided to obtain ca. 0.5 g for the grain size determination. The subsamples were pretreated using hydrogen peroxide and hydrochloric acid and dispersed with sodium pyrophosphate and sodium dithionite using distilled water as liquid medium. The analyzes were done using a Coulter Ls 200 laser diffraction grain size analyzer, which has a detection range from 0.375 µm to 2000 µm, using the Fraunhofer's theory in the calculation of the grain sizes.

The studied series can be divided into three portions: (1) The lowest 200 cm is a coarse grained sediment. (2) The middle 210-1200 cm have coarse sediment material only intermittently. (3) The top 1210-1640 cm has greater number of it's sample modes in the coarse range, and it's fines get finer. The sampled sedimentary series indicate a definite fining trend towards the top, which is likely the result of the increasing distance from the stream or possibly the filling of the floodbasin. The cyclicity of the time series was determined by spectral analysis of the detrended time series data with enhanced autocorrelation using the Hanning window. The sediment is mainly of fluvial origin, but with a major part of eolian particles of loess-like silt size. The fines are deposited by the winds and flood-waters, the coarser sandy material is deposited by flood waters or as splays. The fluctuations of grain size in the series can arise from within or without the fluvial system as a result of avulsion of the river inside the basin or the effects of climatic cycles on the eolian material input or precipitation.

These results can be used to gain a proxy for the environment and its changes in the studied location and time period. Applying timing to the data gives substance to the cyclicities observed, as they can be compared to known climatic cycles. This comparison can be used to determine whether they are of local or regional origin, whether they arise from the patterns of the stream or from climatic patterns. The climatic information of the grain size data can be supported by performing magnetic susceptibility studies on the sediment column.

Keywords: Laser diffraction, Granulometry, Late Miocene, Eolian and hydraulic sediments, Lantian, China.
1. Introduction

The area studied lies along Bahe river in Lantian near the city of Xi'an in the province of Shaanxi, Central China. The samples derive from the Bahe Formation, which is on the northern slopes of the Bailuyuan Plateau adjacent to Qinling mountains (Fig. 1). The sediments of the formation were laid down in the Weihe Graben. The Bahe Formation is of Late Miocene in age (Kaakinen & Lunkka 2003). It is overlain by the Lantian Formation, which is composed of eolian ”Red Clay” sediments.

The total thickness of the formation is ca. 300 m. It includes sets of mudstones, sandstones and conglomerates of mainly fluvial origin. A substantial number of fossil vertebrates has been recovered thorough the sequence (Lu et al. 1960, Zhang et al. 2002, Qiu et al. 2003, Zhang 2003, Qiu et al. 2004a, Qiu et al. 2004b). The outcrop of Bahe Formation along the Bahe River is of special importance because it is one of the few localities where the early Late Miocene is recorded in China (Kaakinen & Lunkka 2003).

The sediment column analyzed here derives from a sequence of fine-grained material in the Main Section of the Bahe Formation (Kaakinen & Lunkka 2003). The deposit is mainly composed of mudstones and sandstones. The mudstones display a sheet-like geometry, and are up to 20 m in thickness extending laterally for several kilometers. The analyzed column ranges from 121,1 to 137,6 m at the top of the section (Fig. 2). The sampled fine-grained facies is a representative for the type of deposits that form the bulk of the formation. The color of the mudstone is reddish brown with some greenish portions. The sampling interval used was 10 cm. The sampled thickness was 1650 cm and the total number of samples thus 165. The sediment is mainly sandy silt from fluvial environments (Kaakinen & Lunkka 2003).
The purpose of this study is to determine grain size parameters of the samples, to analyze the trends and patterns distinguished from the parameters and to discuss the processes involved in the sedimentation of the studied part of the Bahe formation. To achieve this, the properties of the grain size distribution are analyzed statistically. The observed patterns were then used to interpret the climate and other environmental variables during the studied period.

2. Material and Methods

2.1. Samples

From the 10-cm-long subsamples only a small quantity was required for analyzes, therefore, the samples were divided to a smaller size of ca. 0.5 g to obtain a suitable subsample for the grain size determination. The splitting of samples was performed using a rotary sample divider in order to get representative subsamples.

The grain size analysis was run using a Coulter LS-200 laser diffraction grain size analyzer which has been found to be accurate and precise (Vriend & Prins 2004). The study also aimed to get familiarized with the instrument and to determine the capabilities and limitations of the method.

2.2. Pilot study

The need for ultrasonic dispersion in the laser diffraction grain analysis of the floodplain sediments was examined to find out the optimal amount of ultrasonic action to disperse the studied sample material. The samples were prepared for the pilot study in a similar way to the main study. Using 20 cm$^3$ of 30% hydrogen peroxide, 10 cm$^3$ of 10% hydrochloric
acid, 0.5 g sodium pyrophosphate and 0.5 g of sodium dithionite the samples were de-calcified and dispersed. The effects of four liquid medium pump speeds of the analyzer were also determined. The effects of ultrasonic action at six power levels were studied by dividing a sample into 22 similarly treated fractions and sonicating these at six amplitudes for six times (Table 1).

Table 1. Test series to examine optimal treatment of samples. The amplitudes and times of ultrasonic dispersion were varied to determine their effects. The impact of the liquid medium pump speed were also investigated. The conditions of sample run 11 are repeated at runs 18, 20 and 21 to ascertain the repeatability of the method. Sample run 15 was performed at a lower amplitude than runs 13 or 14 to avoid the boiling of the sample.

<table>
<thead>
<tr>
<th>Sample run</th>
<th>1</th>
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</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>1</td>
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<td>1</td>
<td>2</td>
<td>2</td>
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<td>5</td>
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</tr>
<tr>
<td>Time</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>2</td>
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</tr>
<tr>
<td>Pump speed</td>
<td>59</td>
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<td>20</td>
<td>40</td>
<td>59</td>
<td>81</td>
<td>59</td>
<td>59</td>
<td></td>
</tr>
</tbody>
</table>

The analyzes did show differences within the fractions (Fig. 3). In high obscuration runs, differing treatment causes scatter in the large grain size end of the grain size diagram and affects the amplitude of the 12-48 µm peak. Some of the runs were of low obscuration, and their grain size diagrams show an artificial peak at the high grain size end of the grain size diagram. Run 7 is one of the low obscuration runs.

![Fig. 3. Grain size distributions of selected sample runs of the pilot study.](image)

The observed deviation does not correlate with the power levels or the duration of the sonication (Table 2.). These deviations were not due to varying duration of sonication, but the result of the sensitivity of the laser grain size analysis to errors in the preparation of the subsamples. This is corroborated by the fact that the analysis of five of these samples shows low obscuration, leading to inconclusive analysis by the laser grain size analyzer. The lack of correlation between grain size parameters and total sonication attests that there is no significant relation with the length of sonication duration and the size distribution of the grains in the sediment sample measured (Fig. 3.).
In other words, the pilot study indicates that ultrasonication is unnecessary for this type of sediment.

The slight negative effect of pump speed on grain size parameters was expected. It is presumably caused by the prolonged suspension time of larger grains in fast moving medium. The pump speed of 59 appears to be adequate for this type of sediment, although higher speeds may lead to a slight improvement in the detection of larger grains.

*Table 2.* Correlation matrix (n=22) of the pilot study grain size parameters, liquid medium pump speeds and total ultrasonic dispersion energy. The correlations between sonication energy and central tendency parameters are low. The effect of pump speed is more significant. The detected average grain size decreases as pump speed increases.

<table>
<thead>
<tr>
<th>Mean</th>
<th>Median</th>
<th>Mode</th>
<th>Pump speed</th>
<th>Sonication energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>0,787</td>
<td>0,927</td>
<td>-0,501</td>
<td>-0,094</td>
</tr>
<tr>
<td>0,787</td>
<td>1,000</td>
<td>0,797</td>
<td>-0,346</td>
<td>0,104</td>
</tr>
<tr>
<td>0,927</td>
<td>0,797</td>
<td>1,000</td>
<td>-0,631</td>
<td>-0,040</td>
</tr>
<tr>
<td>-0,501</td>
<td>-0,346</td>
<td>-0,631</td>
<td>1,000</td>
<td>-0,083</td>
</tr>
<tr>
<td>-0,094</td>
<td>0,104</td>
<td>-0,040</td>
<td></td>
<td>1,000</td>
</tr>
</tbody>
</table>

2.3. Subdividing

The original dry samples weighting 80 g to 250 g were divided two to three times using an eight vessel electric rotary sample divider to obtain an approximately 0,5 g representative subsample for each sampled level (Konert & Vandenberghe 1997). The rotary sample divider splits a sample into eight subsamples using a vibratory feeding to achieve a constant flow of the sample material. The constant flow is necessary for a representative and unbiased subsampling.
2.4. Sample preparation

The subsample preparation method was a combination of methods that have been used in preparing samples for laser diffraction grain size analysis (Loizeau et al. 1994, Konert & Vandenberghe 1997, Chappel 1998). As the sample was silty to sandy, the fraction size was set at 0.5 g. Distilled water was used as the liquid medium instead of tap water (cf. Chappel 1998). Chemical dispersion was used in the pretreatment of the samples. This prevented unwanted flocculation of mud-scale particles. As seen in pilot study, the use of ultrasonic dispersion was regarded unnecessary.

The subsample (0.5 g) was put into a 1000 cm$^3$ decanter. 10 cm$^3$ of 30% hydrogen peroxide was added to the decanter along with less than 50 cm$^3$ of distilled water. The hydrogen peroxide was used to remove organic materials (humus) from the sediment (Bauselink et al. 2002). This mixture was heated on a stove for approximately 5 minutes. After this, more distilled water was added to avoid drying of the mixture. The mixture was then left to cool for a few minutes and was then decanted to a mortar. The largest clusters were broken gently by pressing them against the mortar with a pestle. This was not done to samples devoid of visible clustering. The pressure used was modest to avoid breaking the grains. The mixture was placed back to the decanter. Another 10 cm$^3$ of 30% hydrogen peroxide was added to the decanter and the mixture was heated until gas producing reaction could no longer be detected. Water in excess of 50 cm$^3$ was left to evaporate and the decanter was removed from the heat. The decanter was then left to cool to room temperature.

The edges of the decanter were rinsed with distilled water and filled up to 100 cm$^3$ with distilled water. 10 cm$^3$ of 10% hydrochloric acid was added and the mixture was boiled for one minute. The hydrochloric acid was used to remove calcium carbonate that have been possibly cementing grains together or being present as calcitic nodules. After this the edges of the decanter were washed with distilled water again and more distilled water was added to a total of 1000 cm$^3$. The decanter was then left still overnight to allow the sample to settle.

Extraneous water was drained with a pipette. 0.5 g of sodium pyrophosphate, which acts as a dispersing agent (Sun et al. 2002), and 0.5 g of sodium dithionite, which removes any iron binding the particles, were added to the sample. Distilled water was added to a total to 50 cm$^3$. The mixture was then quickly heated to its boiling point.
After cooling, the samples were washed with distilled water and centrifuged for 30 min at 3000 rpm until the size of the sample was at most 10 cm³. This was usually achieved with two to three wash-separation cycles. Subsamples were stirred and transferred to the rotary auto-preparation station of the laser diffraction grain size analyzer.

2.5. Laser diffraction grain size analysis

The analyzes of the study were done using a Coulter Ls 200 laser diffraction grain size analyzer with an optional automatic rotating sample auto-preparation station.

The laser diffraction grain size analysis is based on the principle of light beam scattering by small particles. The scatter beam is divided into two which are focused with a reverse Fourier lens optics into the 126 detectors. The diffraction pattern formed by the laser beam scattering from the sample suspended in a liquid medium is caught by the detector rings of the analyzer. The analyzer interprets the diffraction pattern using either Fraunhofer's or Mie's theory. The analyzer has 92 size channels which provide a detection range from 0.375 µm to 2000 µm. Particles below the minimum measuring range are ignored by the Coulter laser diffraction grain size analyzer. The channel center is calculated from the logarithmic mean of the edges of the channels.

The basic statistics of the grain size distributions were calculated by a program provided with the instrument. The calculations were all done using the same standard formulae.

The mean grain sizes were calculated with the following formula:

$$X_a = \frac{\sum X_c \times n_c}{\sum n_c}$$

Where $X_c$ equals the weighted center of the c'th channel, in µm, µm2 or µm3 and $n_c$ equals the percentage of particles in the c'th channel.

The standard deviation, $SD_a$, was calculated with the following formula:

$$SD_a = \sqrt{\frac{\sum [n_c (X_c - X_a)^2]}{\sum n_c}}$$

The coefficient of variation, CV, was calculated with this formula:
The skewness was calculated with the following formula:

\[ g_1 = \frac{\sum [n_c (X_c - X_a)^3]}{SD_a^3 \sum n_c} \]  

(4)

The kurtosis was calculated with this formula:

\[ K_a = \frac{\sum (X_c - X_a)^4}{SD_a^4} \]  

(5)

The laser diffraction particle size analysis method was chosen for this study because it is considerably faster than the other alternative, the sieve-pipette method. Likewise, the reproducibility of the Coulter laser diffraction grain size analyzer was better than that of the sieve-pipette method (Bauselink et al. 2002). Also, compared to other methods, the laser particle size analyzer results have good agreement with sieving and electroresistance particle counter (Loizeau et al. 1994). Still, it has to be noted, that there are differences in the grain size distribution results obtained by different methods.

The results of the laser diffraction grain size analyzer method differ from the results of the traditional pipette regarding particles less than 8 µm in size. This can be explained by is in the difference in the nature of the attribute of the particles that is measured by various methods. The platy shape of clay particles give them more area to be measured than comparable spherical particles. The non-spherical area is always larger because the smallest possible surface area of an object is with a spherical object (Konert & Vandenberghe 1997). In the sieve-pipette method the result of the analysis is the smallest dimension of large particles and the spherical approximation of the volume of small particles. In the laser diffraction particle size analysis the measurement indicates a spherical approximation of the volume of the particles calculated from their surface area.

According to Lu et al. (2001) the clay fraction boundary is 5.5 µm with laser compared to 2 µm with pipette. For comparison with the sieve-pipette method it is necessary to establish calibration relationships for the specific sediments studied (Bauselink et al. 2002). The exact relationship between the grain sizes of the fine size category measured with laser diffraction and the sieve-pipette
method in these sediments was not determined. As the definition of the clay-silt boundary is dependent on method, the boundary was categorically set at 3.86 µm. The chosen boundary is defined by correlations, compared to other possibilities and discussed later (Fig. 24).

The laser diffraction grain size analysis was performed as follows. The subsamples were placed in the rotary auto-preparation station attached to the Coulter Ls 200 equipment. No proprietary dispersants were used, no extra fluid was added to the samples prior to the analysis. The samples were sonicated for 3.0 seconds at power level 4 (out of 8) immediately before the analysis, using the built-in ultrasonicator of unknown power, to disperse any clusters formed while the sample was in line. The sample tubes were emptied automatically for 2 seconds with an additional flushing by 3-second pulsed water stream. During the first 72 analyzes the liquid medium pump of the Coulter analyzer was set to speed 62, in later analyzes it was set to speed 70. Most of the subsamples were analyzed twice to check the reproducibility of the analyzes.

In the automatic calculation of the grain sizes the Frauenhofer's theory was used (Loizeau et al. 1994). This was made as the sample was not mainly composed of clay-size particles near the 10 wavelenght limit of detection. The Frauenhofer's theory is inappropriate at particle sizes lower than 10 wavelenghts. Mie's theory has to be used in such cases. Usually variations in refractive indices are small and can be ignored. The Frauenhofer's theory will allow detection of a larger percentage of the clay-size particles. Using the laser diffraction grain size analyzer variability is low (0.3%), although for skewness the variability is as high as 9.2%. Sediment preparation procedure is responsible for greater variation. Usually it is best to use Frauenhofer's theory, as the Coulter LS 100 detects 38-67% of the clay of pipette method with Frauenhofer's theory, and only 2-17% of clay with Mie theory (Loizeau et al. 1994).

3. Results

3.1. Grain size distributions

The grain size distribution curves for most of the samples are bimodal (Fig 5). On a closer examination, however, it is apparent that these two modes are composed of several submodes.
Using a sample average curve (Fig. 7), the locations and relative amplitudes of these modes can be distinguished.

The main mode is at ca. 4 to 32 µm and the secondary mode is at 192–384 µm (Fig. 7). The larger main mode is composed of at least 6 submodes at ca. 1 µm; 4 µm; 6 µm; 12 µm; 28 µm; 34 µm. The smaller secondary mode is composed of 2 modes at ca. 320 µm and 768 µm.

The curves of two neighboring samples are not necessarily close to each other, their modes can appear at widely different places, as the relative dominance of the fine 4-64 µm mode and the coarse 256-1024 µm mode varies (Fig. 6).

**Fig. 5.** The grain size distributions of samples from different levels indicate a similar composition being composed of two main modes. The proportions and exact location of these modes vary. These modes can be seen to be composed of multiple submodes.

**Fig. 6.** Grain size distributions of two neighboring samples showing differing main modes. Both are bimodal, and their modes are in the same general range. Despite this when the samples are examined from a purely modal viewpoint, they seem far apart.
This is visible on all basic statistic graphs of the sample series as a high frequency fluctuation.

The overall mean size of the samples varies from fine sand at the bottom to fine to coarse silt at the top (Fig. 7). The overall median size of the samples varies from fine silt to medium silt. It varies througout the series. All samples are positively skewed (Fig. 7). The sample at 60 cm was anomalous and of low obscuration and was discarded.

![Fig. 7. The grand average grain size distribution for all the studied 165 samples. The vertical axis holds the percentage of grain size at each point.](image)

3.2. Grain size parameter profiles

3.2.1. Mean grain size

The mean grain size in the first 2 meters varies from 67,50 µm to 125,00 µm with one fine sample of 37,20 µm at 0 cm (Fig. 8). From 210 cm to 1200 cm the mean grain size varies from 19,10 µm to 71,80 µm with two high points at 220 cm (113,00 µm) and 510 cm (112,00 µm) and one low point at 850 cm (0,15 µm). The top part from 1210 cm to 1640 cm has the mean grain size varying from 16,40 µm to 55,60 µm with two high points at 1470 cm (113,00 µm) and 1600-1610 cm (69,40 µm), and numerous low points from 6,67 µm to 13,70 µm. The mean grain size in the first 200 cm is in the fine sand range, coarse to medium silt in the mid 210-1200 cm, and coarse to medium silt in the top 1210-1640 cm. The coarsest samples are find sand at 220cm, 510 cm, 1470 cm and 1600-1610 cm. The finest samples are fine silt at 850 cm and fine to fine silt at 1220 cm, 1250 cm, 1300-1320 cm, 1410 cm, 1500 cm, 1590 cm and 1590 cm and 1640 cm.
3.2.2. Median and quartiles

The first quartile of the grain size of the samples in the first 200 cm varies from 3,33 µm to 5,72 µm. In the mid 210-1200 cm the first quartile size varies from 1,78 µm to 12,70 µm (Fig. 9). In the top 1210-1640 cm the first quartile size varies from 1,35 µm to 6,62 µm. The first quartile grain size in the first 200 cm is fine silt to coarse clay, in the mid 210-1200 cm the first quartile grain size is fine silt to medium clay, and in the top 1210-1640 cm the first quartile grain size is fine silt to medium clay.

The median grain sizes in the first 200 cm vary from 13,50 µm to 24,70 µm with one low point of 10,24 µm at 0 cm (Fig. 9). The median values for the 210-1200 cm vary considerably from 4,39 µm to 35,4 µm with numerous low and high points within these limits. The median values of the top 1210-1640 cm vary from 4,55 µm to 17,34 µm with three low points at 1220 cm (3,24 µm), 1470 cm (3,64 µm) and 1510 cm (3,91 µm). The median grain size of the first 200 cm is in the medium to fine silt range, the median grain size of the 210-1200 cm mid part is in the coarse to fine silt range, and the median grain size of the top 1210-1640 cm is in the medium to fine silt range. The finest samples are in the fine silt range in the first 200 cm, in the fine silt range in the mid 210-1200 cm, and in the coarse clay range in the top 1210-1640 cm.

The third quartile of the grain size of the samples measured in µm in the first 200 cm varies from 32,60 µm to 196,15 µm (Fig. 9). In the mid 210-1200 cm the third quartile size varies from 13,00 µm to 74,80 µm. In the top 1210-1640 cm the third quartile size varies from 10,50 µm to 47,40,
with a high point of 51.55 µm at 1230 cm. The third quartile grain size of the bottom 200 cm is fine sand to coarse silt, with one sample at 60 cm in coarse sand. In the mid 210-1200 cm the third quartile grain size is fine sand to fine silt. The third quartile grain size of the top 1210-1640 cm is coarse silt to fine silt, with one sample at 1230 cm in fine silt.

3.2.3. Mode

The grain size mode of the first 200 cm varies from 23.9 µm to 390 µm with high points at 100 cm (470 µm), and low points at 0 cm (6.43 µm), 40-50 cm (13.60 µm) and 110 cm (8.55 µm) (Fig. 10). The grain size modes of the mid 210-1200 cm vary from 3.70 µm to 66.50 µm. The grain size modes of the top 1210-1640 cm vary from 2.78 µm to 28.80 µm. The grain size modes of the first 200 cm fall into the medium sand to medium silt range, the mid 210-1200 cm is in the fine sand to coarse silt range, and the top 1210-1640 cm is in the fine silt range.
clay range, being mostly in the silts, the top 1210-1640 cm is in the medium silt to coarse clay range.

3.2.4. Mean to median ratio

The mean to median ratio in the lowest 200 cm varies from 3.57 to 6.43. The mean/median ratio of the mid 210-1200 cm varies from 1.30 to 15.37 (Fig. 11). In the upper 1210-1640 cm the mean/median ratio varies from 1.47 to 11.83 with one high point of 30.95 at 1470 cm. Overall the ratio stays higher than unity, therefore, the mean grain size of the samples is always higher than the median grain size.

![Fig. 11. Mean to median ratio of the sample series calculated from values in µm.](image)

3.2.5. Mean to mode ratio

The mean to mode ratio in the first 200 cm varies from 0.27 to 6.74 with one high point of 8.40 at 110 cm (Fig. 12). The mean/mode ratio of the 210-1200 cm varies from 0.63 to 14.65, with three high points at 220 cm (23.19), 250 cm (17.80) and 510 cm (27.72). In the top 1210-1640 cm the mean/mode ratio varies from 0.92 to 15.12 with one low point of 0.48 at 1590 cm and one high point of 40.37 at 1470 cm. In general the mean/mode ratio is above unity and, therefore, the mean grain size of the samples is generally higher than the modal grain size.
3.2.6. Median to mode ratio

The median to mode ratio in the first 200 cm varies from 0.51 to 0.99 with several low points at 10-30 cm (0.06-0.07), 100 cm (0.05), 130 cm (0.05), 160-170 cm (0.05-0.06) and three high points at 0 cm (1.59), 40 cm (1.05) and 110 cm (1.72) (Fig. 13). The median/mode ratio of the 210-1200 cm varies from 0.30 to 1.70 with two high points at 210 cm (1.89) and 510 cm (2.72). In the top 1210-1640 cm the median/mode ratio varies from 0.36 to 1.42, with a low point of 0.23 at 1590 cm and a high point at 1600-1610 cm (1.68-1.97).

3.2.7. Standard deviation

The standard deviation of the samples in the lowermost 200 cm calculated in μm varies from 124.30...
to 216.40, with one low point of 64.00 at 0 cm (Fig. 14). The standard deviation of the mid 210-1200 cm varies from 30.5 to 157.4, with low points at 830-850 cm (14.27-22.61) and high points at 220 cm (246.4) and 510 cm (216.0). In the top 1210-1640 cm the standard deviation varies from 9.62 to 130.50, with a high point of 288.10 at 1470 cm.

![Fig. 14. Standard Deviation of the sample series calculated from values in µm.](image)

### 3.2.8. Skewness

The skewness of the first 200 cm calculated in µm varies from 1.65 to 3.49 (Fig. 15). In the mid 210-1200 cm the skewness varies from 2.13 to 6.26, with low points at 830-840 cm (1.40-1.54) and high points at 330 cm (7.12) and 1050 cm (6.68). The skewness in the topmost 1210-1640 cm varies from 1.85 to 6.52, with a high point of 10.15 at 1290 cm. The samples are all skewed towards the coarse side.

![Fig. 15. Skewness of the sample series calculated from values in µm.](image)
3.2.9. Kurtosis

The kurtosis of the first 200 cm calculated in µm varies from 3,71 to 13,61, with low points at 100 cm (1,46) (Fig. 16). The kurtosis for the mid 210-1200 cm varies from 3,42 to 57,58 with a low point of 1,89 at 840 cm. The kurtosis of the top 1210-1640 cm varies 4,17 to 50,18, with a low point of 3,68 at 1590 cm and a high point of 134,30 at 1290 cm. The lowest part is leptokurtic to leptokurtic, with one platykurtic sample. The mid part is mesokurtic to extremely leptokurtic, with one mesokurtic sample. The top part is leptokurtic to extremely leptokurtic, with one mesokurtic sample. Overall most of the samples are leptokurtic in some degree.

3.2.10. Coefficient of variation

The coefficient of variation in the first 200 cm varies from 152,9% to 222,2% (Fig. 17). In the mid

![Fig. 16. Kurtosis of the sample series calculated from values in µm.](image1)

![Fig. 17. Coefficient of Variation of the sample series calculated from values in µm.](image2)
210-1200 cm the coefficient of variation varies from 91.42% to 292.1%. The coefficient of variation in the top 1210-1640 cm varies from 98.68% to 283.30%.

4. Discussion

4.1. Correlations

The sample from level 60 cm is considered as an outlier and it has been omitted from the correlation data set. The various statistics of the data were cross-correlated. From these correlations, the significant ones were given a closer look (Table 3.). Significance level was determined by P-value of 0.005 or less.

Correlation between A and B series is 0.776 with a P-value less than 0.001. This means that the data series are well reproducible on repeated runs. The reproducibility seems lower than in previous studies, but this is most likely because of the sinkage of the large grains as the pump speed was still inadequate (Loizeau et al. 1994, Bauselink et al. 2002).

The correlation between mean and median is 0.303 with a P-value of 0.0025, and the correlation between mean and mode is 0.285 with a P-value of 0.0047. This is because they are influenced by different parts of the grain size distribution.

Correlation between mean and standard deviation is -0.922 with a P-value less than 0.001. This means that where the samples are finer in grain size, the grain size distribution approaches normal. This is easily understood, as the coarse mode is visibly offset from the normal main mode. The less

| Table 3. Table of correlations, correlations with P-values less than 0.005 in red. |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Mean             | Median           | Mode             | D(3,2):          | Mean/Median      | Mean/Mode        | Median/Mode      | S.D.:            | Skewness:        | Kurtosis:         | 90%              | 75%              | 50%              | 25%              | 10%              |
| 1.000            | 0.303            | -0.285           | -0.127           | 0.749            | -0.199           | -0.439           | -0.922           | 0.409            | 0.383            | 0.953            | 0.673            | 0.350            | 0.143            | 0.036            |
| 0.303            | 1.000            | -0.777           | -0.850           | -0.394           | -0.488           | -0.349           | 0.000            | 0.214            | 0.103            | 0.192            | 0.823            | 1.000            | 0.944            | 0.815            |
| -0.285           | -0.777           | 1.000            | -0.561           | -0.224           | -0.884           | -0.766           | -0.069           | 0.263            | 0.151            | 0.194            | 0.762            | 0.777            | 0.865            | 0.953            |
| -0.127           | -0.880           | -0.561           | 1.000            | 0.525            | 0.290            | 0.116            | -0.187           | -0.107           | -0.019           | 0.027            | -0.589           | -0.850           | -0.983           | -0.981           |
| 0.749            | -0.394           | -0.224           | 0.525            | 1.000            | 0.102            | -0.224           | -0.835           | 0.247            | 0.294            | 0.782            | 0.105            | -0.394           | -0.530           | -0.585           |
| -0.199           | -0.486           | -0.864           | 0.290            | 0.102            | 1.000            | 0.845            | 0.058            | -0.290           | -0.189           | 0.151            | -0.067           | -0.488           | -0.346           | -0.256           |
| -0.438           | -0.345           | -0.766           | 0.116            | -0.224           | 0.045            | 1.000            | 0.345            | -0.365           | -0.277           | -0.398           | -0.624           | -0.348           | -0.170           | -0.064           |
| -0.022           | 0.000            | -0.069           | -0.187           | -0.893           | 0.059            | 0.345            | 1.000            | -0.259           | -0.253           | -0.835           | 0.435            | 0.000            | 0.168            | 0.274            |
| 0.303            | 0.214            | -0.363           | -0.107           | 0.247            | -0.290           | -0.366           | -0.256           | 1.000            | 0.975            | 0.577            | 0.435            | 0.214            | 0.112            | 0.048            |
| -0.385           | 0.103            | -0.121           | -0.109           | 0.494            | -0.169           | -0.277           | -0.233           | 0.973            | 1.000            | 0.549            | 0.320            | 0.103            | 0.027            | -0.035           |
| 0.156            | 0.216            | 0.194            | 0.027            | 0.786            | -0.151           | -0.308           | -0.062           | 0.876            | 1.000            | 0.549            | 0.192            | 0.035            | 0.093            | -0.063           |
| 0.073            | -0.836           | -0.766           | -0.564           | 0.105            | -0.001           | -0.624           | -0.435           | 0.433            | 0.320            | 0.591            | 1.000            | 0.828            | 0.851            | 0.517            |
| 0.030            | 0.100            | -0.777           | -0.850           | -0.394           | -0.468           | -0.346           | 0.000            | 0.214            | 0.103            | 0.185            | 0.825            | 1.000            | 0.944            | 0.865            |
| 0.143            | -0.944           | -0.630           | -0.903           | -0.530           | -0.348           | -0.170           | 0.166            | 0.112            | 0.017            | 0.035            | 0.651            | 0.944            | 1.000            | 0.949            |
| 0.030            | -0.653           | -0.523           | -0.864           | -0.586           | -0.256           | -0.064           | 0.214            | 0.068            | -0.060           | 0.517            | 0.855            | 0.969            | 1.000            | 1.000            |
coarse material in the sample, the more normally it is distributed.

Correlation between mean and skewness is 0.409 with a P-value less than 0.001. This indicates that, the distribution is positively skewed where the samples are coarse. This is caused by the fact that the samples are mainly skewed toward the fine side, and the appearance of coarse sediments draws the skewness towards the coarse side.

Correlation between median and mode is 0.777 with a P-value less than 0.001. They are possibly influenced by same parts of the grain size distribution.
Correlation between median and D(3,2) (the mid-quartiles) is -0.893 with a P-value less than 0.001. According to this negative correlation is because of the multimodality of the samples' grain size distributions.

Correlation between skewness and kurtosis is 0.976 with a P-value less than 0.001. The samples are most symmetric where they are highly peaked, ie. where most of the material is normally distributed.
4.2. Visual overview

Taking a look at the data in a visual representation gives us an overview of the proportions of the modes of the grain size distributions. As observed previously, the sample series can be divided into three elements. The lowest 200 cm are characterized by their high coarse grained sediment content. The middle 200-1200 cm have greater quantities of coarse sediment material only intermittently. The modes of the samples in the mid-element lie in the fine-medium range. The top 1210-1640 cm has...
greater number of its samples modes in the coarse range, and at the same time samples in fine modes get finer. Especially in the mid-element, but to a lesser degree in others too, one can observe high frequency fluctuation of the grain size modes. Some samples have their grain size modes in coarser or finer parts of the spectrum than their neighbours.

4.3. Granulometry

4.3.1. Lowest part

The lowest approximately two meters are visibly different from the rest of the sequence. The samples in this range (0-200 cm) are coarser; this holds true for both the fine and the coarse layers. The modes of the layers fluctuate with greater variability than in the rest of the sediment. The grain size distribution curves of these layers are flatter, i.e. with lower kurtosis, than the rest, as they do not have the well-defined main mode at 4-32 μm as the other sediments. The lower layers are also less skewed and less sorted, higher S.D., owing to their greater coarse modes.

4.3.2. Top part

The top part of the series is similarly, although less definitely distinguishable from the main part of the series. Especially from 1400 cm up the sediment is characterized by increasing proportions of coarse grained sediments. The mean of the samples is high as the median and mode stay low.

In general it is possible to separate the sediment into sections that are coarser and into sections that are finer grained. The finer grained sections get more prevalent and thicker towards the top of the series. The finer sections are approximately at the following depths (D_{50} < 15 μm): 210-600, 630-710, 740-870, 930-940, 1020-1640 (inclusive), with interrupting coarse layers with the maximum thickness of the sampling resolution (ie. 10 cm).

According to the grain size medians, modes and means, the sediment is stratified, with sizes fluctuating at 1-3 (10-30 cm) sample intervals. The fine and coarse layers that alternate can be visually and numerically distinguished by their great difference to adjacent layers (Fig. 18).
The values of the grain size modes and their location vary with apparent cyclicity through this whole range along the series. Visually there can be seen distinct cyclic pattern in the variation of grain size (Figs. 18 & 22). The number of visual cycles is ca. 50. The period of the visual cycles is therefore approximately 1/50. The nature of the cyclicity is discussed later.

The modal groups of the samples are distributed in the following way: 7 in the medium sand subcategory, 2 in the very fine sand subcategory, 29 in the coarse silt subcategory, 49 in the medium silt subcategory, 17 in the fine silt subcategory, 55 in the medium silt subcategory, 17 in the fine silt subcategory, 5 in the coarse clay subcategory. Of all 164 samples 150 have their modes in the silt category, and therefore silt is the defining grain size category of the samples.

The modes of the sediments are settle into three groups, roughly at 4 µm, 32 µm and 256 µm (Fig. 10 and Table 4.). Of these groups 256 µm is dominant at the bottom, 32 µm in the middle and 4 µm at the top of the sediment.

To gain more information, using the mean or modal grain size only is difficult, as most of the sediments studied are polymodal.

4.4. General characteristics of constructed time series

The quartile and decile summary of the time series shows that although the mean grain size through the series is ca. 40 µm, the median is closer to 10 µm and the mode is ca. 20 µm (Fig. 19). Almost all of the studied material is below grain size 128 µm, with generally a higher portion (20-70%, median 45%) in the "silt
fraction” (10.78-76.42 µm) or the “clay fraction” (0.375-3.863 µm) (20-45%, median 28 %) (Fig. 20).

4.4.0. Composing the time series

Owing to the multimodality of the grain size distribution curves, there is no definite way of analysing the grain size distribution of samples in time dimension. The grain size data was categorized using differing methods to gain maximal insight into their nature. The time series created from the raw data can be divided into the following categories: 1. Central tendency statistics (mean, median, mode) (Fig. 19); 2. Averaged modal groups (0-8 um, 8-128 um, 128-1822 um) (Figs. 10, 20, 22); 3. Approximated grain size categories derived through correlation (clay, fine silt, silt, fine sand, sand) (Fig.21).

The central tendency statistics based time series are derived from the summarized average grain size of each sample. The average grain sizes used are: mean, median and mode. owing to the bi- or multimodality of the grain size distribution curves, these time series will contain a lot of high frequency fluctuation. Analyzing these series reduces the effects of the modes to an average, smoothing the curves. Visual examination of the series graphs gives some indication on the relation of the high and low modes to this averaged time series curve (Fig. 22).

The averaged modal groupings based time series are determined by visually comparing the 20 sample average grain size distribution curves and finding the low points on the curves separating the averaged modes (Fig. 23). The separation at 128 µm is universal among the 20 sample averages, and the 12 µm divide discerns 5 of the fine grain size modes of the 20 sample average from each other. The time series are examined in triadic division (0-12, 12-128, 128+) and a binary fine (0-128) vs.
The approximate grain size categories based time series are derived from the raw data grouped into grain size categories. Owing to the unknown relation of the grain size determinations of the laser diffraction grain size analyzer in comparison to the traditional sieve and pipette method the categories were determined from a correlation matrix of the whole raw data set. The areas of coarse (128+) division.

Fig. 22. Spectral view of the grain size distribution of the sample series. Sampling level increases from left to right. Grain size increases upwards. Lighter colors represent higher relative proportion of grains at a particular grain size.

Fig. 23. Averaged grain size distribution curves of the samples. 20-sample averages from 0-1400, 24-sample average from 1410-1640, and an the grand average for all samples.
positive and negative correlations were mapped out, and the categories were determined accordingly (Fig. 24). Each of these categories has stronger absolute correlation within itself than with the other categories, therefore, these categories can be considered natural. The category limits are defined at the 0-correlation lines. The categories are: clay (0.375-3.863 µm); fine silt (4.24-9.818 µm), silt (10.78-76.42 µm); fine sand (83.89-256.9 µm); sand (282.1-1822 µm). These categories do not compare one on one with the formal grain size categories. This is in part because of the analysis method and in part due to the relationships of the neighboring grain size classes determined by the analyzer. The gaps among the categories are not real, they appear because the data output of the analyzer is expressed nominally, not continuously.

4.4.1. Trends

4.4.1.1. Regression

The trends of the various time series were determined by simple linear regression. In the central tendency statistics based time series the general trend was towards finer grain sizes (Figs. 25, 26, 27). The coefficient of the trend of the mean grain size is -0.031. The coefficient in the median grain size is -0.005 and in the modal grain size it is -0.055. The most visible and well defined outliers of the mean grain size time series lie at 0-200 cm and 1400-1640 cm, being a lot coarser (Fig. 25). In the median grain size time series the outliers seem more random (Fig. 26). In the modal grain size time series the outliers cluster at the first 200 cm, and are definitely coarser level than the trend line (300-500 µm compared to 80 µm) (Fig. 27). The box plots of the detrended time series show that the median trend is the best fit and the modal trend is the poorest fit (Fig. 28).

The averaged modal groups based time series trends indicate that most of the rise in finer grain sizes
Fig. 25. Mean grain size trend.

$Y = 70.219 - 0.031 \times X; R^2 = 0.319$

Fig. 26. Median grain size trend.

$Y = 16.449 - 0.005 \times X; R^2 = 0.139$

Fig. 27. Mode grain size trend.

$Y = 79.025 - 0.055 \times X; R^2 = 0.128$
are present in the sub 8 µm part of the grain size continuum (Fig. 29). The mid part of the time series are possibly dominated by medium sized (8-128 µm) particles, but the rise of the clay-size particles is most distinct (Fig. 30). The coefficients of the trends are: clay (0-8 µm) +0.1 (Fig. 29); silt (8-128 µm) -0.003 (Fig. 30); sand (128-1822 µm) -0.007 (Fig. 31); all fines (0-128 µm) +0.007 (Fig. 32).

The well-defined outliers are clustered in the 0-200 cm and 1400-1640 cm regions, in the sand plot these are most visible, and they are mirrored in the total fines plot (Figs. 31, 32). The sand/coarse trend is the best fit and the silt trend is the poorest (Fig. 33).
The approximate grain size categories based time series trends indicate an increasing trend in the sub-silt region and a corresponding negative trend in the coarser fractions (Figs. 34-38). The coefficients for the trends are: "clay" +0.007; "fine silt" +0.004; "silt" -0.003; "fine sand" -0.003; "sand" -0.004. The highest trend is in the "clay" fraction.

The most well-defined outliers lay in the lowest and highest regions of the "sand" group (Fig. 38). These are at considerably higher level than the trend line and are at 0-200 cm and 1400-1640 areas. They are visible in the "fine sand" plot too (Fig. 37).

Fig. 31. Sand (128-1822 μm) trend of the averaged “triadic” modal group.

Fig. 32. Fine (0-128 μm) trend of the averaged “binary” modal group.

Fig. 33. Comparison of box plots of the components of the “triadic” and “binary” grain size modal groups of the grain size series. The box plots indicate how closely the series' follow their trends.
Fig. 34. Trend of the "clay" fraction of the approximate grain size categories based time series.

![Clay fraction trend](image1)

\[ Y = 23.725 + 0.007 \times X; R^2 = 0.121 \]

Fig. 35. Trend of the "fine silt" fraction of the approximate grain size categories based time series.

![Fine silt fraction trend](image2)

\[ Y = 18.187 + 0.004 \times X; R^2 = 0.163 \]

Fig. 36. Trend of the "silt" fraction of the approximate grain size categories based time series.

![Silt fraction trend](image3)

\[ Y = 39.701 - 0.003 \times X; R^2 = 0.01 \]

Fig. 37. Trend of the "fine sand" fraction of the approximate grain size categories based time series.

![Fine sand fraction trend](image4)

\[ Y = 9.068 - 0.003 \times X; R^2 = 0.21 \]
The best fit for the trend line was found in the "fine silt" group, and the poorest fit in the "sand" group (Fig. 39).

4.4.1.2. Trends summary

The general trend of the grain size in the time series is from coarser grained to more fine grained fraction. The components responsible for this are increasing proportion of fines in the clay to fine silt range, and correspondingly decreasing proportion of coarse grained sediments in the fine sand to sand range (Fig. 40). The increase in fines is constant through the series, contrary to the sands which are high in the bottom and also the top parts of the series. Because of this the coarser silts have a stable neutral to slightly negative trend, even though the amount of silt is highest in the middle and lower in the bottom and top parts (Fig. 40).

At the top of the time series clay fraction trend has reached the silt fraction trend. The amount of clay is equal to the amount of silt.
4.4.2. Cyclicity

The cyclicity of the various time series was determined by spectral analysis of the detrended time series data. The spectral analysis was carried out with enhanced autocorrelation using the Hanning window. The detrended time series were then fitted to a sinusoidal curve using the most significant periods.

The three strongest periods in the central tendency statistics based time series in the order of amplitude are: 1/5, 1/15 and 1/6. 1/15 is a possible harmonic of 1/5. The most meaningful periods are, therefore, 1/5 and 1/6 (Fig. 41).
The two strongest periods in the averaged modal groups based time series in the order of amplitude are also 1/5 and 1/6 (Fig. 42).

![Fig. 42. The periodicities of the modal grain size groups. Y-axis shows the relative strengths of the periodicities. All numbers are based on trendless values.](image)

The two strongest periods in the approximated grain size categories based time series in the order of amplitude are 1/3 and 1/10. 1/6 is possibly a harmonic of 1/3, and 1/10 is a harmonic of 1/5 (Fig. 43).

Overall the strongest periodicities are at 1/3 and 1/5, with harmonics at at least 1/6, 1/10 and 1/15. The 1/3 period is approximately 550 cm and the 1/5 period is 330 cm. There is also a non-harmonic periodicity at 1/16, which is ca. 100 cm. (Fig. 44).

![Fig. 43. The periodicities of the approximate grain size groups. Y-axis shows the relative strengths of the periodicities. All numbers are based on trendless values.](image)
4.4.3. High and low modes, high frequency fluctuation

Looking at the averaged grain size distribution graph and mode grain size scattergram, two main modes can be discerned (Figs. 7, 45). The coarse mode is between 256 and 512 µm, and the fine mode is between 4 and 32 µm. The fine mode is divided into two lesser modes, one from 3 to 10 µm, and the other from 12 to 70 µm. Which one of these modes is dominant, seems to vary from sample to sample, belonging to the fine modes most of the time, but in the bottom part the coarse mode may also be dominant.

Fig. 44. Periodicities of the studied time series. The y-axis holds the proportional strengths of the periodicities. The “trendless” variables are approximate grain size categories, the “detrended” variables are the binary and triadic modal size groups and central tendency groups. The “central average” is the average of the central tendency groups, the “averaged modal sum” is the average of the modal groups, and the “alt grain size average” is the average of the approximate grain size groups. All are detrended, i.e. trendless.

Fig. 45 The placement of the modes of the grain size distributions. (Grain size in µm.)
The period of this high frequency fluctuation which is reflected in the modal grain size is less than 50 cm (1/33). It appears to be most coherent at 1/35-1/40 cycles (Fig. 46, 47). This fluctuation is caused by the interplay among the “triadic” silt and sand fractions. Some of the stronger higher frequencies seem to be tied to the “fine sand” fraction, although the “fine silt” and “silt” fractions also have their own.

4.5. Processes

The sediment in the Bahe Formation has been deposited in a low energy fluvial environment. The sampled sequence has been deposited as bed-load and floodplain suspension fall-out. (Kaakinen & Lunkka 2003). This is indicated by the grain size distribution of the sampled sediment, especially the
variation in the occurrence of the coarse sediments, indicates this. The possible processes in the Bahe and Lantian Formations also include eolian activity, gravity flows and deposition in active channels (Kaakinen & Lunkka 2003). The observed cyclicities in the grain size distributions are assumed to be dependent on the eolian and fluvial processes.

4.5.1. Fluvial system

The sediments in the Bahe Formation are from a fluvial basin. The sediments in the sampled sequence are composed of floodplain sediments. The average grain size is diminishing throughout the series indicating either increasing distance from the stream proper or a progressive filling of the floodplain basin. The higher coarse sediment content in the beginning and at the end of the series are possible indications of proximity to the stream itself.

The fluctuations of grain size in the series can arise from within or without the fluvial system. The changing position of the river itself effects the sedimentation in the basin. As the channel migrates in the floodplain, its relative position to the studied sediments changes. Flooding and other overbank events deposit coarser sediments outside the riverbed. Some of the observed cyclicity can be explained through the avulsion of the river inside the basin. The avulsion cycles can be affected by changes in the conditions of the drainage area, and the underlying reason for the high frequency fluctuation in the sand grain size sediments is plausibly in the variability of rainfall in the drainage area. The amount of precipitation in the drainage area affects the amount of discharge and through it the amount and composition of sedimentary material carried by the river. These will be affected by large-scale climatic cycles, and can with the help of proxy data explain the cyclicity apparent in the sediments, both in the average modal groups based series and in the coarse sediment time series.

4.5.2. Eolian component

About one half of the sediment material studied relates to the loess grain size range. Most of this material is in the silt range, although of finer size. The modes of unimodal loess (16-32 µm) and Chinese bimodal loess (0.5-8 µm and 20-50 µm) coincide with the modes of the series. Still there is no strong relation among the modes of the bimodal loess. The submodes of the finer grain sizes fit well into the submodal grain sizes detected in loess and 'red clay' sediments at 16-32 µm and 3-8 µm (Fig. 7). These can be equated to the modern eolian dust background suspension and event plume modes (Donghuai 2004).
A significant part of the main mode lies in the 8-16 µm range, which is not directly related to any eolian transportation method, and is between the bimodal loess modes.

Recent study dates the beginning of eolian deposition back to 22 My (Guo et al. 2002). The deposition of loess and loess-like “red clay” has continued to present times. (Miao et al. 2004). It is possible that the sedimentary material is of loessic origin, but reworked and mixed in the fluvial environment. The mixed and reworked loess is a mixture of eolian and hydraulic sediment (Sun et al. 2002). The presence of calcitic nodules indicates some dry spells or seasonality, enabling deposition in dry conditions.

The grain-size of the coarse component can act as a proxy index of the near surface monsoon circulation. The cyclicities in the silt-size sedimentary material is possibly caused by climatic changes affecting the monsoon system. The >30 µm fraction is strongly related to the winter monsoon strenght and is less modified (Lu et al. 2002, Sun et al. 2002). The winter monsoons affect the amount of wind-carried silt and indirectly the amount of water in the stream. This is independent of the floodbasin activity. This can in part explain the lack of correlation among the bimodal loess modes. The source of the loessic material is the High Asia region, as the region is a major generator of silt particles. The high frequency oscillation, or the part of it in the fine grain size range can be related to the climatic forces. The changes in aridity and strenght of winds at the silt source area can affect the fine sediments. Accordingly the climatic cycles affecting these can possibly cause the high frequency fluctuation in the fines.

4.6. Discussion of methodology

The exact relation of the grain sizes gained from laser diffraction grain size analyzer and traditional sieve and pipette method in these sediments remains unclear and they have not been be calibrated accurately. The reproducibility of the analyzess was deficient in the coarse grain sizes. The amount of coarse grained sediment in second analyzes of the same material was usually less. This is possibly caused by the higher sinking rate of the coarser grains, especially considering that the number of grains necessary for an observed area is less in coarser grains. This can be remedied by using higher speed on the liquid medium pump of the analyzer. As the results of the pilot study regarding this are inconclusive, this remains to be seen. Having too small sample size could cause a low obscuration situation, where the coarse grains get overrepresented. This occured only once in the studied series,
but several times in the pilot study. This overrepresentation will effect statistic study of the samples, and, therefore, the low obscuration samples have to be disregarded.

To gain insight into the behavior of the samples through the series, a few statistic analyzes were performed. The overall trends of the sediment grain size distribution were studied with linear regression. To obtain another look at the observed high frequency fluctuation and possible other cyclicity, and to enable a closer examination of the processes involved in the sedimentation of the sampled material, the detrended time series were subjected to spectral analysis. The correlations among different statistics of the time series were considered.

5. Conclusions

The laser diffraction grain analysis gives access to higher resolution in the analysis of the sediment grain size series. This allows one to observe short time-scale changes in the grain size distributions. The main difficulties in the analysis were the multimodality of the grain size distributions of the sample and the elusiveness of the high-frequency cyclicity in the series. This can be bypassed by analysing the sediment sample data via statistic methods. The three dimensional visualization of the data is also useful in distinguishing patterns in the grain size series.

The sediment is mainly of fluvial origin, but with a major part of eolian particles of loessic silt size. The flood-plain nature of the sediment seems to be supported by its grain size distributions. The fines are deposited by the winds and flood-waters, the coarser sandy material is deposited by flood waters or as splays. The intermitten distribution of the coarse layers in the main part of the series indicates this.

The series has at least five sections. The bottom of the series is dominated by coarse sediments, and is visibly different from the rest. The following sections are less distinct. The second section has modes in the fine, medium and coarse sediments, although the coarse layers are an exception. The third section is mainly composed of sediments with their modes in the medium grain sizes and some layers with fine or coarse modes. The fourth section is composed of sediments with their modes in the medium grain sizes and an abundance of fine-moded layers. The top section is composed of sediments with both fine and coarse modes.

The sampled sedimentary series indicate a definite fining trend towards the top. The sediments finer
than the “silt” group increase in proportion as the sediments coarser than this divide decrease. This is most likely the result of the increasing distance from the stream or possibly the filling of the floodbasin. The “sand” trend fit worst into this overall view mainly because of the bottom and top parts of the series, which have a different composition and more coarse sediment than the main part of the series.

These results can be used to gain a proxy for the environment and its changes in the studied location and time period. The grain size acts as a sensitive indicator of the sedimentary environment. The cyclicity of the sediment grain size can be caused by processes inside the river basin or outside. The outside causes are related to major climatologic cycles effecting the monsoons and through them the loessic sediment material, and the total amount of water in the river system and the magnitude of seasonal flooding. Climate, especially winter monsoon, affects grain size and sedimentation rate. The grain size distribution of loessic deposits is a function of climate, particularly the strength of the monsoon winds.

Applying timing to the data gives substance to the cyclicities observed, as they can be compared to known climatic cycles. This comparison can be used to determine whether they are of local or regional origin, whether they arise from the patterns of the stream or from climatic patterns. The climatic information of the grain size data can be supported by performing magnetic susceptibility studies on the sediment column.

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