Identifying sedimentation patterns in Lake Baikal using whole core and surface scanning magnetic susceptibility*

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Abstract

Forty seven ca. 1 m sediment cores were collected from Lake Baikal during a summer cruise in 1996 and analysed for whole-core susceptibility. Fifteen of these cores were further analysed using a new prototype surface scanning sensor on board the ship R.V. Vereshchagin. The main purpose of this paper is to show that the measurement of Lake Baikal short cores using two susceptibility sensors gives valuable field data and can be used as a tool for identifying undisturbed sediment sequences. Four coring transects were sampled to identify sedimentation patterns reaching from the shelves and sub-basins of the near lake shore and across mainly the northern basin of Lake Baikal (water depth ca. 1500 m). Also in the sub-basins and in the southern basin other groups of cores were taken. One of the main sediment features of interest is that of turbidite sedimentation. Whole core magnetic susceptibility traces are used to identify turbidite 'fingerprints' and correlate them between cores along the transects. The results from the two magnetic susceptibility sensors the whole-core sensor and the new prototype surface scanning sensor, both giving volume Kappa values, are compared and are found to be significantly correlated given the difference in resolution. The whole-core sensor gives a smoothed equivalent to a 'moving average' curve of magnetic susceptibility while the surface scanner can give fine resolution (ca. 2 mm) results picking out fine peaks with Kappa values of between 150 to 650.

The results show that most turbidite sedimentation can be clearly identified; they give a specific magnetic susceptibility 'fingerprint' with larger Kappa values (up to 120) at the base of the turbidite corresponding with the settling of coarser sandy sediments and a steady and gradual decline in values to about 15 at the top of the turbidite where the fines settle incorporating the normal diatomaceous sedimentation. The main control on the magnetic susceptibility of the turbidite sediments is the concentration of ferrimagnetic minerals in different particle size fractions. The turbidites can be correlated between many of the cores collected along the transects but it must be noted that these correlations are partly speculative and will be confirmed with future dating, diatom analysis and geochemistry. Other very fine peaks of less than 5 mm in width identified using the surface scanning sensor may indicate concentrations of ferrimagnetic minerals, namely greigite, formed during the reduction phase.

Introduction

The measurement of mineral magnetic susceptibility (Kappa) has been used in a wide range of environmental research since the 1970's for identifying min-

erals and sediment sources and correlating lake and marine cores (cf. Thompson, 1973; Oldfield et al., 1983; Bloemendal & deMenocal, 1989). In the case of Lake Baikal, susceptibility measurements can be used to 1. infer mineral sources and diagenetic changes (Flower et al., 1995) within the cores, 2. identify turbidites (Lees et al., 1997 in press) and 3. identify climate changes (Peck et al., 1994). Other similar work in marine and lacustrine environments, involving sour-

* This is the final in a series of seven papers published in this issue dedicated to the paleolimnology of Lake Baikal. Dr. Roger Flower collected these papers.

ing of sediments and core correlation include those of Somayajulu et al. (1975), Thompson & Morton (1978), Bloemendal et al. (1979), Oldfield et al. (1983), Appleby et al. (1986), Dearing (1986), Robinson (1990) and Peck et al. (1994). The work of Peck et al. (1994) is the only previous paper presenting core correlations (of ca. 10 m cores) taken from Lake Baikal. Good correlation was found using whole-core susceptibility between 6 cores obtained from the Academician Ridge area which is an area of little sediment disturbance and slow accumulation rates. These cores cover a greater geological time period (Pleistocene and Holocene), however, and are of lower resolution than the mainly 100 to 200 year cores presented here.

In systems with slow sediment accumulation rates, high resolution records are desirable. This paper presents the results from two magnetic susceptibility sensors; a whole-core sensor (MS2C80) and a prototype high resolution surface scanning sensor (MS2E). These were used to analyse 47 short Lake Baikal sediment cores for whole-core susceptibility (Kappa at 1 cm resolution) and a subset of 15 of these were further analysed using the surface scanner (Kappa at 2 mm resolution) collected during a summer cruise in 1996. To date, the surface scanning sensor has not been previously used in the field and this work presents the first field test results of this new equipment. Lake Baikal has three main basins (see Figure 1, Flower, this volume) but this study was mainly located in the Maleo More Sea and North Basin where three major coring transects were situated. A group of cores were also collected in the South Basin. The Central Basin will be the focus of a later expedition (M. Sturm, pers. comm.). The main purpose of the cruise was to identify gaps in our understanding of the role of sediment particles in the formation of recent sediments in Lake Baikal and their ability to store information on environmental change. Special attention was therefore paid to turbidite sedimentation in several transects in the south and north basins (Sturm, 1996a). Results of the sedimentological work will be presented in due course.

The coring transects were designed to track turbidites from the steep shelves and sub-basins of the near shore down into centre of the northern and southern deep basins of Lake Baikal (deepest core at 1450 m). The cores taken in groups aim to identify how correlatable cores from the same area are. The majority of the cores contained turbidites that could be easily identified visually in the field following splitting of the cores (no particle size analyses were employed at this early field stage, these will be included in fur-

ther work). Whole-core magnetic susceptibility traces were used to identify turbidite 'fingerprints' and correlate them between cores along the transects and surface scanning susceptibility was used to identify finer resolution peaks and measure items such as drop stones and iron/manganese layers.

Coring sites and core descriptions

Sediment cores were taken with an EAWAG gravity corer using transparent PVC liners (6.3 cm in diameter) modified for large water depths (after Kelts et al., 1986). Cores of up to 150 cm in length were taken using the corer with attached weights of up to 70 kg. The corer was lowered using winches from the research vessel R. V. Vereshchagin of the Limnological Institute, Irkutsk. Perfect preservation of the sediment/water interface was achieved in over 95% of the cores. Cores which were visibly disturbed were rejected. The cores were collected and sealed using green adsorbent foam, with care not to disturb the sediment/water interface, to soak up excess water and to stabilise the surface sediment. Cores are recorded with the prefix code BAIK and numbered from 42 to 114, but for brevity in this paper the code has not been used extensively. The locations of the cores which were analysed and their corresponding transects/groups are shown in Figure 1 and coordinates are listed in Table 1; the water depths and core lengths are given in Table 2. The numbers of turbidites in the cores are based on visual identification work, ie by their darker grey colour and by their coarser texture than the diatomaceous sedimentation and these features which are marked with a 'T' in the figures. All the cores had an undisturbed surface layer with a distinctive orange oxidised layer which ranged in depth from between 4 and 15 cm from the top of the cores. These layers contain iron (yellow/orange goethite (FeOOH) and manganese crusts (black Mn; cf. Leibovich, 1984) and were observed as a correlatable horizon of the oxidised/anoxic interface in most of the cores. Sometimes the cores contained buried crusts (Sturm, 1996b).

The south basin group of cores (east-west) consists of 5 ca. 75 cm cores (BAIK114, 113, 112, 43 and 45) which were all collected in deep water between 830 and 1445 m and some cores contained up to 4 turbidites. A 35 cm core was collected from the River Angara outflow near Baikal Port (BAIK42) in a water depth of 100 m. This core was mainly sandy but had 5 cm of finer sediments at the top of the core.

Figure 1. Approximate location of coring positions, June/July 1996, for cores which were analysed for whole core susceptibility. The four main coring transects and groups of cores are shown

Table 1. Core codes for each coring transect/group. Cores marked with a * are shown in Figures 2 to 6

Transect	Core codes
South Basin Group (E-W)	BAIK45*, 43*, 112*, 113*, 114*
River Angara outflow near Baikal Port	BAIK42*
Southern Maleo More Sea to North Basin transect (S-N)	BAIK46*, 47*, 54*, 55*, 56*, 57*, BAIK69, 70, 78, 84, 102, 101, 99/100* BAIK92, 87/88
Zavorotney transect (Z) (W-E)	BAIK71*, 77*, 78*, 79*, 80*
Zavorotney sub-basin cores (N-S)	BAIK74, 72, 105, 106, 107
Tcheremsha transect (T) (W-E)	BAIK86, 85, 84*, 83, 82
Sludjanka-Kakhusi group (W-E)	BAIK93*, 92*, 89*
North-Western Shore group (S-N)	BAIK96, 97, 98
Academician Ridge (ACR) (S-N)	BAIK58, 64, 65
Tschiverkui Basin core	BAIK108

The Southern Maleo More Sea to North Basin Transect (south-north) consists of 17 cores (BAIK46, 47, 54, 55, 56, 57, 69, 70, 78, 84, 102, 101, 99/100, 92 and 87/88) of lengths between 35 and 90 cm. They were collected in water depths of 150 m in the shallows of the southern part of the Maleo More Sea (BAIK46) through the deeper North Basin (910 m – BAIK70) to the north of the Northern basin with a water depth of 590 m (BAIK88). In this transect there was one turbidite visually identified in all of the cores except in BAIK100 where three turbidite sequences were observed.

In the Zavorotney Transect (Z) (west-east, BAIK71, 77, 78, 79 and 80) and Zavorotney sub-basin group of cores (BAIK74, 72, 105, 106 and 107) cores lengths ranged from 60 cm to 95 cm taken in water depths of 345 m on the eastern shore to 920 m in the central north basin. In these cores 2–3 turbidites were visually identified. The Tcheremsha Transect (T, west-east) contains five cores (BAIK86, 85, 84, 83 and 82) of lengths between 55 and 90 cm in water depths of 565 m in the west through to water depths of 915 m in the east. These cores contained one main turbidite and a grey sand layer at approximately 15 cm is seen in three of the cores. The Sludjanka-Kakhusi group of cores (BAIK93, 92 and 89) were 67, 80 and 50 cm in

length and were taken in water depths of 300, 770 and 300 m respectively.

The North-western group of cores (BAIK96, 97 and 98) were 85 to 120 cm in length and taken in water depths of 300 m. Two turbidites can be identified in these cores. The Academician Ridge (ACR) transect (south-north) contains three cores BAIK58, 64 and 65 of lengths between 65 and 85 cm in water depths of 250–280 m and finally a core from Tschiverkui Basin (BAIK108) was 35 cm in a water depth of 735 m shows two possible turbidites.

Methodology and measurement

The Bartington Instruments portable MS2 Magnetic Susceptibility System was used with 2 sensors measuring non-mass-specific magnetic susceptibility (Kappa, K), the MS2C whole-core scanning sensor and the prototype MS2E surface scanning sensor (Bartington Instruments Ltd., 1993 and 1995). Kappa is a measure of magnetisation over field both of which have the same units making Kappa is dimensionless. However, the value of K can be successfully calibrated to mass-specific measurements using the MS2B sensor in the laboratory (Lees, 1994).

Table 2. Gravity core information and length of Kappa trace (usually 1 or 2 cm shorter than actual core length) and air measurements for each core. * denotes those cores which were also analysed using the MS2E scanning sensor

Core Code	Water Depth (m)	Latitude	Longitude	No. of 1 cm meas.	Air measurement	
		N	E		Before	After
BAIK 42*	100	Near Port Baikal		34	0	0
BAIK 43*	1450	51°42'18"	105°00'24"	74	0	-2
BAIK 45*	1420	51°42'07"	105°01'55"	61	0	-2
BAIK 46*	150	53°13'53"	107°12'53"	31	0	0
BAIK 47*	130	53°19'53"	107°25'19"	85	0	-2
BAIK 53*	140	53°19'29"	107°25'16"	29	0	0
BAIK 54	140	53°19'56"	107°26'14"	89	0	0
BAIK 55	230	53°24'48"	107°36'42"	35	0	0
BAIK 56*	515	53°30'53"	107°44'45"	52	0	0
BAIK 57	565	53°35'44"	107°52'29"	75	0	0
BAIK 58*	280	53°37'01"	108°17'38"	65	0	-0.5
BAIK 64*	250	53°45'06"	108°27'34"	80	0	0
BAIK 65	250	53°45'13"	108°27'47"	83	0	0
BAIK 69	900	53°46'38"	108°06'53"	31	0	0
BAIK 70*	910	53°46'38"	108°24'01"	39	0	0
BAIK 71*	915	54°12'56"	108°31'40"	59	0	0
BAIK 72	485	54°13'52"	108°28'00"	59	0	0
BAIK 74	535	54°15'36"	108°30'06"	100	0	-1
BAIK 77	920	54°13'29"	108°37'47"	96	0	-1
BAIK 78	910	54°14'22"	108°48'33"	61	0	-1.5
BAIK 79	850	54°15'21"	109°03'49"	82	0	-1
BAIK 80	345	54°16'36"	109°17'59"	82	0	0
BAIK 82*	565	54°32'50"	109°21'33"	54	0	0
BAIK 83	805	54°33'06"	109°12'20"	86	0	-1
BAIK 84*	915	54°33'02"	109°02'15"	76	0	0
BAIK 85*	915	54°33'20"	108°52'37"	81	0	0
BAIK 86	885	54°33'20"	108°42'51"	61	0	0
BAIK 87	590	55°37'03"	109°37'53"	33	0	-0.5
BAIK 88	590	55°36'48"	109°37'60"	81	0	-1
BAIK 89	300	55°23'15"	109°45'24"	49	0	0
BAIK 92	770	55°26'42"	109°30'13"	79	0	-1
BAIK 93	300	55°30'08"	109°13'44"	67	0	0
BAIK 96	300	55°32'39"	109°19'29"	88	0	-1
BAIK 97	310	55°35'06"	109°24'38"	85	0	0
BAIK 98	310	55°35'14"	109°24'49"	119	0	-1.5
BAIK 99	820	55°13'33"	109°26'57"	28	0	0
BAIK 100*	820	55°13'40"	109°26'50"	55	0	0
BAIK 101	830	54°57'37"	109°22'45"	68	0	0
BAIK 102	895	54°46'54"	109°13'51"	84	0	-1
BAIK 105	970	54°13'00"	108°37'25"	89	0	0
BAIK 106	480	54°13'50"	108°28'28"	119	0	0
BAIK 107	780	54°12'16"	108°28'15"	130	0	0
BAIK 108	735	53°53'53"	108°11'21"	108	0	-1
BAIK 111	1370	52°57'60"	106°57'52"	54	0	0
BAIK 112	1445	51°41'32"	104°59'55"	75	0	0
BAIK 113	1120	51°38'51"	104°58'16"	65	0	-1
BAIK 114	830	51°36'28"	104°55'48"	66	-1	-2

The equipment was set up on board ship in a small wood-lined closed laboratory where air movement and temperature changes were kept to a minimum. The equipment was mounted on a wooden desk and the sensors were at least 1 m away from any metal interference. Measurements were made whilst the ship was stationary so as to avoid vibration, movements and electric supply interruptions. The MS2 and sensors were allowed to settle for 15 minutes to stabilise before measurement commenced. Calibration of the sensors was checked before and after all the measurements were made and were consistent with manufacturers specifications (Bartington Instruments Ltd., 1993 and 1995).

The drift in the susceptibility meter MS2 was minimal due to the low number of radio waves and other interfering frequencies in this remote area. This is shown in Table 2 which gives air before and air after values; the greatest drift was 0 to -2 over 61.1 cm measurements and corrections for this drift therefore were deemed unnecessary. Measurements for both sensors were tested for repeatability by measuring the same core on different days and measurements were found to be within ± 1 K unit ($< 0.05\%$). The green absorbent foam used to pack the tops of the cores is diamagnetic (being organic foam) and had a K value of -4 which did not affect sediment measurements below the first two 1 cm slices. This has not been corrected for since the main focus of the work is on the turbidite layers rather than the surface sediments.

1. Whole-core scanning sensor (MS2C80)

The MS2C gives a measure of volume susceptibility of sediments in non-magnetic plastic tubes. The measurements were taken by rolling the cores on four wooden rollers (two either side of the sensor) 1 cm at a time horizontally through the sensor and the meter was set at the *1 scale. As the MS2C has a resolution of 1.5–2 cm a 'moving average' of the susceptibility values have been recorded. This can be seen clearly in the traces in Figures 2 to 5. Small core end effects have not been corrected as the main areas of interest lie well within the ends of the cores. Usually measurement of the first and last 1 cm is reduced by 50% but as a matter of practice only the first measurement was affected and the last 1 cm value was not recorded. The core diameter was approximately 6 cm and the diameter of the sensor was 7.2 cm (coil diameter of 8 cm ie. MS2C80) giving high resolution and sensitivity (Bartington Instruments Ltd., 1993).

2. Surface scanning sensor (MS2E)

The MS2E gives a high resolution measurement (3.8 mm) of magnetic susceptibility horizontally along the surface of opened sediment cores split longitudinally. Response characteristics also show that 50% of the susceptibility value lies within 1 mm vertical depth of the sediment surface and 10% lies within 3.5 mm (Bartington Instruments Ltd., 1995). Measurements were made through food wrapping film onto the flat surface of the opened sediment cores at high resolution (ca. 2 mm to 1 cm and on the *0.1 scale). The sensor was, therefore, protected from any contamination and could identify high resolution changes in the stratigraphies of the 15 cores.

Results

The magnetic susceptibility results are divided into three sections, those of the whole-core sensor, surface scanning sensor and a section comparing the Kappa values from both sensors. In order to reduce the number of Figures required to show results for all cores, representative core results have been selected. Firstly, selected representative magnetic susceptibility results for the whole-core sensor are presented in Figures 2 to 5 and are grouped as listed in Table 2. On these figures turbidites which were visually identified by a change to dark grey and/or coarser sediments on the 15 cores are marked with a T. Other peaks which appear in the Kappa traces are probably turbidites but this will be corroborated by particle size analysis in the future. The graphs of the cores in each transect have been drawn with standard scale for easier core correlation and correlations were made visually by counting the turbidite layers from the surface and matching their individual 'fingerprint' between the cores. The depth of the Fe/Mn crust is marked on most of the cores and some particle size and location annotations are also included. It must be noted that until further sedimentological, diatom and geochemical work is carried out the correlations are semi-speculative. Results presented here are thus preliminary and mainly directed towards field susceptibility values of the two sensors and their value in identifying undisturbed cores and in core correlation. It has been found that magnetic susceptibility does indicate turbidite layers which are also later confirmed by sediment density, particle size, diatom and further mineral magnetic analysis. Cores BAIK40 and 41, collected in March, 1995 and pre-

Figure 2. MS2C Whole-core Kappa traces for cores from the South Basin cores containing, from the southern shelf to the centre of the south basin, cores BAIK42, 45, 43, 112, 113 and 114. Core 42 is from the River Angara outflow near Baikal Port. T = turbidite.

sented in Lees et al., 1998, this volume are an example of this. Interpretation of the sediment composition, sources and pathways of turbidites in Lake Baikal will be examined further in a later publication (M. Sturm, pers. comm.)

Secondly, Figures 6a to 6e show five selected representative cores from the fifteen cores which were analysed using the surface scanning sensor. Causes of the peaks and troughs in the Kappa traces are annotated on these figures. Thirdly, results for both sensors are

Figure 3. MS2C Whole-core Kappa traces for cores from the Southern Maleo More Sea just into the North Basin (near River Angara inflow) transect (S-N) containing cores BAIK46, 47, 54, 55, 56 and 57.

directly compared for BAIK56 in the Maleo More Sea and for BAIK71 in the Zavorotney sub-basin (near the western shore of the Northern basin, Figure 1). These are presented in Figure 7.

1. Whole-core scanning sensor (MS2C80)

South Basin cores and River Angara outflow region
Kappa traces for cores BAIK114, 113, 112, 43, 45 from the southern basin transect and for BAIK42 from the

Figure 4. MS2C Whole-core Kappa traces for cores from the Zavorotney Transect (Z) in the northern basin from West to East, containing cores BAIK71, 77, 78, 79 and 80.

sandy shallow Angara outflow region, are presented in Figure 2. The depth of the Fe/Mn crust between the cores varies from 3–8 cm. Cores BAIK112, 43 and 45, which are approximately 30 km from one another, correlate well with possibly 3/4 correlatable turbidite

layers at depths of 11, 34, 57 and 67 cm (BAIK43). The turbidite layers have a clearly recognisable Kappa fingerprint with larger values (> 25–120) in coarser sediments probably containing ferrimagnetic minerals from the igneous geology of the area. Then there is

Figure 5. MS2C Whole-core Kappa traces for cores from the Sludjanka-Kakhusi area and in the northern basin from West to East, containing cores BAIK93, 92 and 89.

a steady decline to lower values (< 20) as the finer more diatomaceous sediments settle. BAIK42, from the outflow of the Angara River near Baikal Port, has very high Kappa values of between 150 and 300 in the sandy section and even higher values are found in the top 6 cm of the core where the sediment changes to finer clayey minerogenic sediments.

Southern Maleo More Sea to North Basin Transect (S-N)

Kappa traces for BAIK46, 47, 54, 55, 56 and 57 are presented in Figure 3. The distance between the two end cores of this transect is approximately 250 km so sets of cores will be considered separately. First, cores in the Maleo More Sea (BAIK46 to 57) have only one correlatable layer at a depth of 10 cm (BAIK46 and 55) and 20 cm (BAIK47 and 54). BAIK55 has Kappa values of between 0 and 6 units which are the lowest of all the cores measured. The other cores in this area have values of between 10 and 55.

Zavorotney Transect (Z) (W-E) and Zavorotney sub-basin cores

Kappa traces for BAIK71, 77, 78, 79 and 80 in the Zavorotney Transect are presented in Figure 4. BAIK71 has two turbidites (only one visually identified) and an associated grit layer at 46 cm. This

is possibly correlatable with BAIK78 and 79. Core BAIK77 has one peak at 27 cm which correlates with all the cores except BAIK71. Values of the peaks range between 22 (core BAIK80) and 230 (BAIK106). Kappa values are larger on the whole in the Zavorotney sub basin sediments (as in BAIK71), possibly indicating greater minerogenic content and proximity to sediment source (ie. edge of lake shore). BAIK80, from the shallower eastern shore (345 m), has the lowest Kappa values (< 22).

Sludjanka-Kakhusi cores

Kappa traces for BAIK93, 92 and 89 are presented in Figure 5 and there are possible correlatable peaks indicating two turbidite bases at 36 and 65 cm in BAIK92, but the cores appear to have different sedimentation rates. BAIK93 is a delta core on the western shore and is sandy throughout. Kappa values are high and up to 500 in BAIK92. Values are half this in BAIK89 however with a maximum Kappa of 200.

2. Surface scanning sensor (MS2E)

The surface scanning sensor gives much higher resolution of the stratigraphic results of magnetic susceptibility than the whole core sensor which is compared in the following section. Figure 6 shows the results of the

Figure 6. MS2E surface-scanning Kappa results for cores BAIK43 (a), BAIK46 (b), BAIK100 (c), BAIK71 (d) and BAIK84 (e).

representative cores BAIK43, 46, 100, 71 and 84. The discontinuities between the turbidites and normal sedimentation are more accurately marked, for example at 13 and 36 cm in BAIK43. Silt-clay layers typically have values of 5–20 whereas the sand and turbidite

layers are between 20 and 130 in BAIK43. The sensor measured some fine peaks at 6.2 and 16.5 cm in core BAIK46, 35.8 cm in BAIK47 and 12.8 and 16.5 cm in BAIK53 with high Kappa values of 165, 144, 341, 86

Figure 7. Comparisons between the MS2C whole-core Kappa measurements and those of the MS2E scanning sensor for the cores BAIK56 and BAIK71.

Figure 8. Scattergrams of MS2E Kappa versus whole core Kappa for cores BAIK56 (a) and BAIK71 (b), r values are 0.912 and 0.876 respectively.

and 528 respectively. BAIK100 shows three possible turbidites ending at 17.5, 31 and 42.5 cm in depth.

BAIK58 and BAIK64 from the Academician ridge show values up to 45 for silt clay layers and a peak in Fe/Mn crusts at 10–14 cm. BAIK71 (Figure 6d) from the Zavorotney sub-basin shows a turbidite with a coarse grit layer giving rise to Kappa values of 225 whereas the rest of the turbidite layer has constant values of 50. At the base of this core late glacial clays (containing no diatoms) were found at only 52 cm indicating either loss of material from this area down

slope or a low accumulation rate. Kappa values for these clays were low (ca. 1) but are similar to the values of the diatomaceous near-surface sediments. Cores from the Tcheremsha transect show 3 different turbidite fingerprints in BAIK82 to a much deeper layer with relatively high values throughout in core 85. A greenish/black band at 52 cm in BAIK84 (Figure 6e) gave a peak Kappa value of 60 within a layer of grey clay/silt with average Kappa values of 11.

3. Comparison of the MS2C and MS2E sensors

The magnetic susceptibility results from the two sensors, when compared, showed that measured values of Kappa were very close within sedimentary units even given that they measure different volumes of sediment. But for the narrow peak value layers the results were quite different in magnitude. In the lower ranges of values (i.e. under 10) results are within 2 Kappa units, in the higher ranges between 10 and 100 the values are within 5 units. The values for the whole-core sensor are always slightly higher. The surface scanning sensor performs very well in identifying narrow peaks of several mm while the whole core sensor does not reveal such fine resolution, the peak is identified, but the values are averaged over 1.5 cm of measurement. This is shown in Figure 7a for BAIK56 where there is a peak in Kappa of 55 at 24 cm in the scanning sensor trace but this is not seen in the whole-core trace. Scattergrams of whole core Kappa and MS2E Kappa are shown alongside the core traces. The Spearman Rank correlation value (r) for BAIK56 is 0.9122 ($p < 0.001$) and for BAIK71 $r = 0.8764$ ($p < 0.0001$). The peaks in MS2E measurements are labelled and this reduces the correlation values. But the relationships are highly significant.

Comparing the data for BAIK71 (Figure 7b) it is clear that for slightly broader peaks (i.e. more than one point) the results are more comparable. This is clear in the two main peaks in this core, both grit layers at depths of 8–13 cm and 45–52 cm where the whole core sensor indicates larger values 1 cm slice before the surface scanning sensor; highlighting the moving average effect. In the 8–13 cm peak, the surface scanning sensor reaches a Kappa value of 100 while the whole-core sensor reaches only 60. In the second peak (45–52 cm) the values are 230 and 140 respectively. The outline of the peak and the discontinuities in the sediment are clearly and accurately defined using the surface scanning sensor while there is a ± 1 cm smoothing and underestimation of peak values in the whole-core trace.

The MS2E and whole core Kappa results for all 15 cores was correlated and r values range between 0.7135 (BAIK46; $n = 30$) and 0.9751 (BAIK85; $n = 81$). All the cores were highly significantly correlated ($p < 0.001$) but extreme peak values had to be removed pairwise from the correlation as these significantly affected the normality of the data sets and the correlation results.

Discussion

1. Whole-core scanning sensor (MS2C)

The deep water sediment of Lake Baikal is very fine, mainly $< 50 \mu\text{m}$, and $90 \mu\text{m}$ at the start of a turbidite layer (in BAIK41, Lees et al., this volume). This is where peaks in magnetic susceptibility are found indicating that coarser particle sizes contain a greater concentration of ferrimagnetic minerals and that the finer sedimentation, consisting of a larger diatom content, does not. Sandy layers are associated with higher Kappa values in many of the cores, especially at the start of the turbidite sedimentation as has been demonstrated. Particle size effects are also seen in BAIK42 and 93 taken from much shallower water. In BAIK42 very high Kappa values of between 150 and 550 are associated with the core being mainly sandy. In the top 6 cm of the core the sediment has changed from sand to finer sandy/clayey sediments which could be attributed to the 1.5 m rise in water level caused by the building of hydroelectric dams on the Angara at Irkutsk in the late 1950's. These sediments could be derived from local lake bank erosion and are less diluted with diatoms than the sediments of the deeper cores. BAIK 93 in the SK transect which is a delta core (water depth 300 m) also has very high Kappa values of between 125 and 400 associated with its sandy sediments.

Another major control on the Kappa values is regional geology. BAIK55 was collected from one of the few limestone areas of Lake Baikal and has the lowest Kappa values of all the cores. Further north peak values in BAIK78 to 88 are much higher indicating a different geological/pedological sediment source to those of the Maleo More. This generally indicates that sediment sources are from the local lake bank geology and soils; there are no major rivers affecting this area. BAIK80 has the lowest Kappa values in the Zavorotney Transect, indicating a magnetically weaker sediment source in this area. Sediment sources for the other 4 cores in this transect could be controlled from the western shore given the better core correlation. Values for the cores nearest to the shore in the Tcheremsha (BAIK82 and 86) are comparable, indicating that the sediment source may be the same. The turbidite layer in core BAIK85 towards the western shore is very deep, almost 50 cm, and may indicate that the turbidite filled a hollow here or is near a major slump. Material then travelled east to the site of core 84. There is a lowering of values towards the east in the SK transect

which indicates that material may have moved from the western shore out from the delta area.

Some peaks cannot be explained as turbidites, for example the correlatable horizon in the Maleo More Sea cores BAIK46 to 57. This does not appear to be a turbidite and it also is not a Fe/Mn crust since this contains mainly canted-antiferromagnetic minerals, such as goethite which do not have high magnetic susceptibilities. The peak may be a concentration of paramagnetic or ferrimagnetic minerals just above the reducing zone or possible the formation of ferrimagnetic greigite on organic material (Snowball & Thompson, 1988). Also in the NW shore transect is difficult to tell if the peaks relate to turbidite layers from the Kappa traces but this may be a more stable area being a shallower basin. Corroboration with dating, microfossil and geochemical work may clarify this.

2. Surface scanning sensor (MS2E)

Fine peaks with Kappa values of between 144 and 528 were found in BAIK46, BAIK47 and BAIK53. It is possible that these could represent tephra or other dust falls (e.g. the Tunguska event, 1908), but at this early stage it is not proven and confirmation by SEM and X-ray analysis would be needed to confirm this. BAIK100 contains a grey sand layer at the base of the core which has the largest Kappa value of all the sand layers in all the cores and indicates a highly ferrimagnetic sediment source.

3. Environmental implications

We have demonstrated the values of the low and high resolution magnetic susceptibility measurements which can be used to identify disturbed sequences in Lake Baikal sediment cores. The results imply that the cross-core profiles can be used to not only infer sediment source changes but also to correlate cores along lake wide transects. We can tentatively suggest that the peaks in magnetic susceptibility are correlatable between cores. But these need verifying by dating, microfossil and geochemical measurements as has been done with cores collected in 1993 (Flower, 1996, this volume) and with BAIK40 and 41 (Lees et al., 1996, this volume) and will be the subject of a publication on detailed sedimentology and geochemistry of turbidites in recent sediments of Lake Baikal within the BICER-GEOPASS project (M. Sturm, pers. comm.). Probably not all turbidites will be identified using Kappa however as was the case for 1993 core

BAIK22 (Flower, 1996, this volume). Finer resolution measurements made with the surface scanning sensor identify fine peaks at the mm scale which are missed by the whole-core scanner at the 1 cm scale. But the high value peaks mask the presence of turbidites which are better identified in the first place with the whole core sensor.

Conclusions

1. The visually identified turbidites can also be identified easily using Kappa and can be traced long distances by correlation of the cores collected from the southern basin, the Maleo More Sea and the northern basin of Lake Baikal. This would enable turbidites to be identified quickly (within 10 min of a core being collected) and would save waiting for the core to be sliced in half to find out if it is turbidite free or not. Above all there appears to be a good correlation between many of the cores collected along the major transects indicating a lack of local variability throughout the basins probably due to the great water depths.

2. The whole-core sensor gives rapid, reliable and repeatable results which are useful for initial correlation of cores and identification of cores with turbidite layers and other layers of sediment with different particle sizes.

3. The surface scanning sensor gives fine resolution results which are useful for identifying fine peaks and layers and for identifying crusts and discontinuities in sediment cores.

4. Fine layers with high peak Kappa values have been identified using the surface scanning sensor, with further analysis it may be found that these are ferrimagnetic greigite layers or possibly tephra layers.

5. Both sensors have proved useful and comparison between the values of the two sensors within sediment units is very good and significantly correlatable indicating a reliable calibration given that they measure different resolutions.

6. The major controls on the values of Kappa are primarily associated with particle size, but also sediment source effects are important as seen in the limestone area of the Maleo More.

7. Correlations between the cores need further confirmation from microfossil and geochemical analysis and dating chronologies.

8. Regions of undisturbed sediment can be identified which would allow longer cores to be taken for reconstructions of past climatic changes. It appears that

turbidites are fairly widespread and affect much of the sedimentation area of the Maleo More Sea, Northern Basin and central Southern basin.

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