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Clastic sediment source characterisation using discrete and included magnetic particles—their relationship to conventional petrographic methods in early Pleistocene fluvial–glacial sediments, Upper Don River Basin (Russia)

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Abstract

Data from mineral magnetics, heavy mineral and quartz grain micromorphology analysis are compared, from early Pleistocene glacial sediments in the River Don palaeo-valley (central part of the Russian Plain). The aim was to evaluate the relative sensitivity of discrete and included magnetic particle populations to depositional processes, sediment provenance and particle size fractionation. Two size fractions from each sample were used for the magnetic measurements, 0.5–1 and 0.25–0.5 mm, on both the original fractions and after acid dissolution to isolate the magnetic inclusions. Quartz micromorphology was assessed on the 0.25–0.5 mm fraction, and is an indicator of the depositional environment and transport process. This shows three morphological groups, whose abundance in each section appears unrelated to their geographic position in the palaeo-valley. The heavy mineral data on the 0.1–0.25 mm fraction, shows a difference in the relative content of sediment derived from a Scandinavian source, mainly reflected in the epidote and amphibole content. The content of Fe-oxides reflects this Scandinavian source by its larger magnetic abundance parameters and lesser haematite content. The discriminating power of magnetic data for separating sediment provenance is not the same across the two studied grain size fractions. The discrete magnetic particles seem to be more powerful in the finer fraction and the included magnetic particles in the coarser fraction. These data show that combined discrete and included mineral magnetic approach offers potentially complementary and powerful means of characterizing glacial sediments for purposes of provenance indication.

Keywords: Sediment provenance; Magnetic inclusions; Environmental magnetism; Quartz micromorphology; Heavy minerals

1. Introduction

There are broadly two subpopulations of ferrimagnetic particles within clastic sediments, "discrete" and "included" magnetic grains (Hounslow and Maher, 1996; Caitcheon, 1998; Hounslow and Morton, in press). Discrete magnetic particles are those that are not significantly intergrown with non-remanence carrying phases, whereas included magnetic particles occur dispersed within a much larger volume of non-magnetic host (Vali et al., 1989; Heider et al., 1993; Hounslow and Maher, 1996). The properties of discrete sediment magnetic particles have been used as a tool for more than three decades for the identification of particular pathways for the formation of magnetic particles such as those produced in soils or by biogenic processes (Thompson and Oldfield, 1986; Oldfield, 1991; Yu and Oldfield, 1993; Maher et al., 1999; Hesse and Stoltz,

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1999). These have allowed identification of distinctive sets of magnetic signatures, which can be used to characterize these source signatures, in both in situ occurrences and in their derived products (Oldfield, 1994; Dearing, 1999, 2000).

However, signatures of magnetic clastic grains derived from erosion of the multiplicity of rock types present at the earths surface appears to present no single distinctive magnetic signature. The few detailed studies, which have tried to discriminate signatures from different clastic sources (e.g. Walden et al., 1996; Lees, 1999; Dearing, 2000), have been studied on a case-specific basis because there is little or no commonality in the clastic magnetic signal between them. This is undoubtedly due to the rich variety of earth processes that dictate the concentration, mineralogy and magnetic grain size of the discrete magnetic particles.

Sediment transport can sometimes profoundly modify the mineralogy and magnetic properties of the discrete magnetic mineral fraction (Oldfield et al., 1985; Dearing, 2000; Martinez-Monasterio et al., 2000). Perhaps of fundamental importance in this transport, is the influence of fluid hydrodynamics in density and grain size sorting, during the source to sink transport (Björck et al., 1982; Dearing, 2000). The impact of this transport process is relatively well understood from heavy mineral studies (Morton and Hallsworth, 1994, 1999), but has yet to be wholeheartedly embraced by the environmental magnetic community. The strong influence of diagenesis in modifying the magnetic mineralogy of the discrete magnetic mineral component is also clearly apparent (Morad and Aldahan, 1986; Karlin, 1990; Hounslow and Maher, 1999).

Magnetic particles, included within host clastic silicate particles, make up a varying proportion of the total magnetic population that may vary from 100% (Heider et al., 1993; Hounslow and Maher, 1996) to less than 20% (Caitcheon, 1998; Hounslow, unpublished data). These included grains are largely isolated from the transport and diagenetic processes, which strongly distort the ability of the discrete magnetic clastic fraction to identity differences in clastic provenance, and hence hold better promise as a tracer for identifying clastic sediment sources (Hounslow and Morton, in press).

As a result of the rich variety of sediment transport processes, and size of Fe-oxides in rocks, abundance of discrete magnetic particles varies with clastic particle-size. Thompson and Morton (1979), Thompson and Edwards (1982) and Walden et al. (1996) identified peak magnetic abundance in the silt fraction, with in some cases a second in the coarse sand fraction. Björck et al. (1982) in a gneiss and granite terrain found peak abundance in the fine sand to coarse silt, with in some cases a secondary abundance peak in the >0.5 mm grain sizes. In contrast Bradshaw and Thompson (1985) and Dearing et al. (1981) found maximum mass susceptibilities in the sand fraction. Björck et al. (1982) explained their magnetic abundance to grain-size variation as controlled largely by the nature of the source rock, and its potential for fragmentation during weathering and transport, liberating different sized discrete magnetite particles. One implication of this is that specific grain size fractions may be more 'provenance sensitive' to certain rock sources in sediment dispersal systems and insensitive to other sources. Hence, in trying to understand source to sink relationships in clastic environmental systems, there is a need to be selective in choosing 'the most sensitive' grain size fractions to investigate. Clearly, more than magnetic mineral abundance is often required to characterize particular sediment sources, but variation of other magnetic indices as a function of clastic grain size has been barely investigated to date.

The aim of this study was to evaluate the relative sensitivity of discrete and included magnetic particle populations to provenance differences and grain size fractionation. A medium to coarse sand fraction was chosen for the mineral magnetic measurements because this fraction in part overlaps with the grain-size fraction required by the ancillary techniques applied. The magnetic data were compared to a base line provided from conventional heavy mineral analysis, petrographic analysis and quartz grain surface micromorphology. The quartz grain micromorphology was used to try and evaluate major differences in the transport processes of the clastic grains.

2. Sampling

Early Pleistocene glacial, fluvial–glacial and glacial-lacustrine sediments from a buried palaeo-valley in the Upper Don River Basin were studied (Fig. 1). This region of the Russian Plain has been extensively investigated for many years and is well understood in terms of its Quaternary geomorphology and sedimentology (Krasnenkov and Iosifova, 1980, 1987; Sudakova and Faustov, 2004). The sections studied are at Novokhopersk, which is stratigraphically near the base of an ancient buried river valley, and Volnaya Vershina, which is in the upper part and border of the Pleistocene river valley. These sections have a height separation of about 30 m, and form part of the complicated infill of the buried palaeo-Don River valley (Krasnenkov and Iosifova, 1980), which is largely incised into Mesozoic and Cenozoic sandstones, limestones and shales. Subsets of samples from the sections were previously evaluated for bone and fresh water shell content, which has provided the data for sediment dating (Krasnenkov and Iosifova, 1980, 1987). The sediment age was determined as the Russian Don Stage (Q_1dns: 470–510 ka) of the Early Pleistocene. The sediments from these sections were deposited by glacial and fluvial–glacial processes, which

Fig. 1. Location map of the two studied sections at Novokhopersk and Volnaya Vershina and the approximate track of the River Don palaeovalley in the vicinity of the studied sections. Rivers in pale grey, country boundaries dotted.

were assessed according to their sedimentology, petrography and mineralogical composition (Sudakova and Faustov, 2004). Ten samples were studied in detail from these fluvial–glacial deposits.

The studied fluvial–glacial sediments from the Volnaya Vershina section are from a 2 m thick interval, and consist of grey-brown clayey sands with occasional gravel layers consisting of sandstone, limestone and igneous rock pebbles. These glacial deposits lie under alluvial sediments assigned to the Russian Muchkap Stage (Q_1mčh: 440–470 ka). Only the lower two metres of the 30 m of glacial sediment in the Novokhopersk section have been studied here. These sediments are predominantly grey silty and sandy-clay with small amounts of shell detritus and gravels of various sedimentary rocks. They lie above the alluvium deposits of the Russian Ilin Stage (Q_1il: 510–560 ka). Two clastic size fractions from each sample were studied (0.5–1 and 0.25–0.5 mm), obtained by washing and conventional mechanical sieving. These were separated from larger mother samples consisting of approximately 500 g of samples from each sampling position.

3. Methods

3.1. Quartz grain micromorphology

Scanning electron microscopy (SEM) has been used to study the surface microtextures of quartz sand grains, as a tool for differentiating ancient sedimentary environments and potential transport mechanisms (Krinsley and Doornkamp, 1973; Higgs, 1979). This methodology assumes that grain shape and surface features reflect the environmental history of the particles. Abrasion of quartz produces mechanical surface textures, which are characteristic of specific environments. Features due to chemical action can also be distinguished by SEM and a number of criteria are available to separate these mechanical and chemical textures (Krinsley and Doornkamp, 1973).

As recommended by Krinsley and Doornkamp (1973) grains were picked randomly from each sample using a binocular microscope. We used selected grains from the 0.25–0.5 mm sand fraction to reduce the effect of grain size on surface-feature variability (Whalley and Krinsley, 1974; Whalley and Langway, 1980). These quartz grains were glued to aluminium specimen stubs with double-sided adhesive tape and sputter coated with gold. Twenty-five grains from each sample were examined, which is sufficient to represent the variability present in a single sample (Baker, 1976; Higgs, 1979; Krinsley and Doornkamp, 1973). The grains were viewed with a Cambridge 90 SEM. For viewing whole grains, magnifications of 250 and 300 were found most useful. Larger surface features such as conchoidal fractures, straight and arc-shaped steps were examined with magnifications of 750–1000. Satisfactory observation of smaller features, such as V-shaped impact indentations and upturned plates required magnification of 2000–3000 and more. We observed a complex of 16 quartz surface microtextures of mechanical and chemical origin, which have been described previously in many studies (Krinsley and Funnel, 1965; Krinsley and Doornkamp, 1973; Higgs, 1979). They are, angular and rounded outlines, conchoidal fracture, straight and arc-shaped steps, fracture faces, parallel striations, straight and curved scratches, grooves, V-shaped indentations, upturned plates, oriented etch pits, adhering particles, solution pits and crevasses, silica globules and flowers. The special combination of these microtextures allowed conclusions to be made about the likely transport histories of the clastic grains.

3.2. Heavy mineral analysis

The 0.1–0.25 mm fraction was placed in bromoform with a specific gravity of 2.8 (Morton and Berge, 1995; Ananyeva, 1998). Heavy minerals were allowed to settle under gravity, with frequent stirring to ensure complete separation. The resulting heavy fraction was separated, washed with methanol and dried. For each sample, 200 grains were identified on the basis of their optical properties using reflected and transmitted light (Mange and Maurer, 1992). In addition to determining the relative abundance of non-opaque detrital phases, specific mineral ratios were determined, including garnet:zircon (%garnet/[%garnet + zircon]) and rutile:zircon (%rutile/[%rutile + zircon]), denoted as index values of GZi and RuZi. These indices are relatively insensitive to changes in hydraulic conditions or diagenesis and therefore may reflect source characteristics (Morton and Hallsworth, 1994).

3.3. Magnetic analysis

Two clastic size fractions from each sample were studied 0.25–0.5 and 0.5–1 mm. Each of these size fractions were subjected to two rounds of magnetic measurements, the first, on the non-acid treated fractions to produce the 'untreated data', and the second after acid treatment of the same sample to produce the 'acid-treated' data.

The acid treatment consists of boiling the sample with about 100 ml of 36% HCL for 20 min, which removes discrete magnetic oxides. This methodology was based on dissolution trials on ground coarse-grained magnetite, specular haematite kidney-ore and commercial ilmenite (with a little magnetite and haematite as an exsolution product). The magnetic oxide ores for this trial were ground in an agate pestle and mortar to pass a 0.25 mm sieve and thoroughly mixed (using pestle and mortar) at a 5% mass concentration, with a pre-ground quartz power to provide a 'stock' of oxide/quartz mix for each mineral. Blanks (only quartz power) were also run to correct for the small change in the acid-treated quartz power. Four subsamples from each stock of oxide were treated for 5, 10, 15 and 20 min to boiling, after which the reaction was quenched with cold distilled water. This removed 99–99.9% of the discrete magnetic oxides (Fig. 2). The residuals shown in Fig. 2 at longer treatment times are mostly due to Fe-oxide inclusions within residual silicates, hosted in the original ore minerals. The content of these residual silicates varies slightly between each subsample.

Samples from the two clastic size fractions were subjected to the same measurement sequence for both the untreated fractions, and after acid treatment to measure the magnetic inclusions. The untreated samples are clearly a combination of the discrete and included magnetic particles. A Bartington MS2 susceptibility meter was used to measure the low frequency mass specific susceptibility (χ_{lf}). Anhysteretic remanent magnetisation (ARM) was imparted by subjecting the specimens to an alternating magnetic field of 90 mT in a 0.08 mT direct field. ARM was applied using the Molspin AF demagnetiser and ARM attachment. A saturation isothermal remanent magnetisation (SIRM) was applied with a 1 T magnetic field in a Highmoor electromagnet ($\mathrm{SIRM} = \mathrm{IRM}_{1\,\mathrm{T}}$). Four successively larger demagnetising fields (backfields) were used (20, 50, 100 and 300 mT) to provide the percentage of coercivity acquired in these backfield increments (e.g. $\%\mathrm{IRM}_{0\text{–}20\,\mathrm{mT}}$, $\%\mathrm{IRM}_{20\text{–}50\,\mathrm{mT}}$ etc.). The backfield IRM's were produced using a Molspin pulse magnetizer. The remanent measurements of samples were made after each application, using a Molspin spinner magnetometer. A conventional set of environmental magnetic parameters for both untreated and acid treated fractions was calculated (Walden et al., 1999).

Cluster analysis was applied to the magnetic data to objectively identify samples that have similar magnetic properties using proxies for magnetic abundance, magnetic grain size and composition. Hierarchical cluster analysis (HCA) was used for determining the membership of groupings of sample with similar sets of magnetic properties (Manly, 1994). In the HCA, Ward's cluster formation method was used, because it is recommended by Lees (1999) and shown by Milligan (1980) to be fairly typical in its response to data noise. Multidimensional scaling (MDS) was also used, using the same set of variables as the hierarchical cluster analysis, as a visual means of examining the between-cluster relationships and the robustness of the clusters based on the HCA

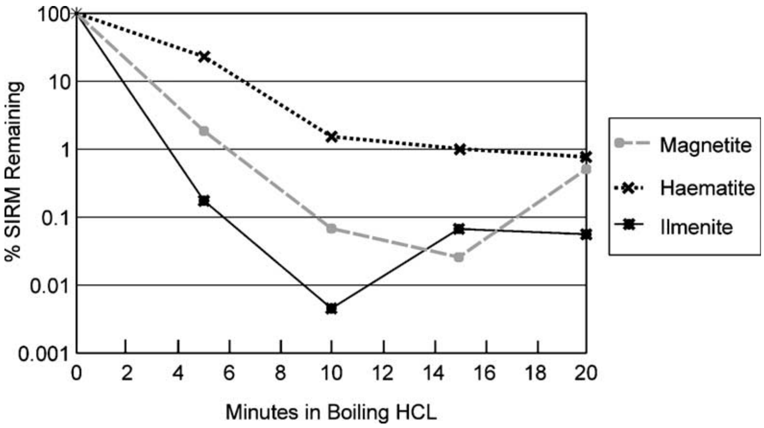

Fig. 2. The loss of normalized SIRM in mineral standards used in determination of the method for removal of discrete Fe-oxides in 36% boiling HCl. Each point represents a single run, starting from the untreated state. Magnetite and ilmenite standards show almost complete loss after 5 min, whereas the kidney-ore haematite shows a more gradual loss up to 20 min. Residual SIRM of less than 1% is mostly due to Fe-oxide inclusions in contaminating silicates, which remain, in variable proportions in the residue. All samples dispersed in ground quartz silt.

(Minchin, 1987; Rock, 1988; Pentecost, 1999). A 2-dimensional MDS analysis was used, with Euclidean distances for the similarity matrix. Prior to both the HCA and MDS analyses on the sample sets, the data were converted to Z-scores (i.e. mean of 0 and SD of 1). The cluster analysis was performed using SPSS version 10.

4. Results

4.1. Heavy mineral analysis

The common regional peculiarity of the heavy mineral data from Quaternary successions in the region of the upper Don River basin is the prevalence of stable minerals such as staurolite, kyanite, tourmaline, ilmenite, garnet and zircon (Fig. 3(a)). Staurolite (abundance of 12–14%) and kyanite (abundance of 9–12%) are the dominant heavy minerals. Sediments from the Volnaya Vershina section have a much higher content of glauconite (~11%) due to Pleistocene fluvial–glacial re-working of nearby Mesozoic glauconite-rich sandstones. A specific characteristic of these sediments is the relatively small content of unstable heavy minerals (cf. Morton, 1984) from metamorphic sources, such as hornblende (~9%) and epidote. Overall the stable heavy mineral composition shows no systematic difference between the two sections, evident by the garnet–zircon and rutile–zircon indexes (Fig. 3(c)). However, the relatively unstable heavy minerals hornblende and epidote do show a difference. The maximum content of 21% of non-stable heavy minerals is in the sediments of the Novokhopersk section within a glacial till unit and is lesser in the sediments of the Volnaya Vershina section.

4.2. Quartz grain micromorphology

The same suite of surface micromorphology features was determined for the grains from both sections. Those features produced by mechanical processes can be divided into three groups.

(A) Angular and subangular grains dominate in the first micromorphological group (Fig. 4(a)). Conchoidal fractures and arc-shaped steps are common.

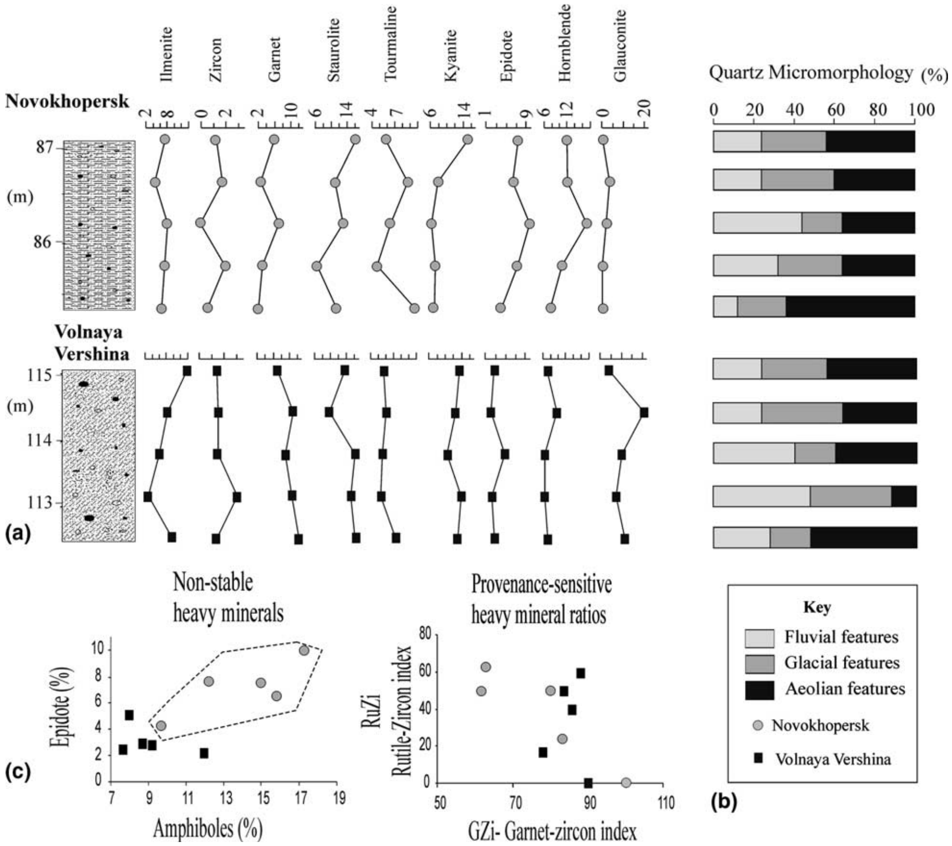

Fig. 3. (a) The heavy mineral composition of the studied sections, with percentage of grains of each heavy mineral component indicated. (b) Quartz micromorphology of each sample. Grains with fluvial features: Novokhopersk: 12–44%, Volnaya Vershina: 24–48%. Grains with glacial features: Novokhopersk: 20–36%, Volnaya Vershina: 20–40%. Grains with aeolian features: Novokhopersk: 36–64%, Volnaya Vershina: 12–52%. (c) Selected heavy mineral data, showing the distinction between the two sections on the basis of the percentage epidote and amphibole content, but not on the basis of the rutile–zircon (RuZi) and garnet–zircon (GZi) indexes.

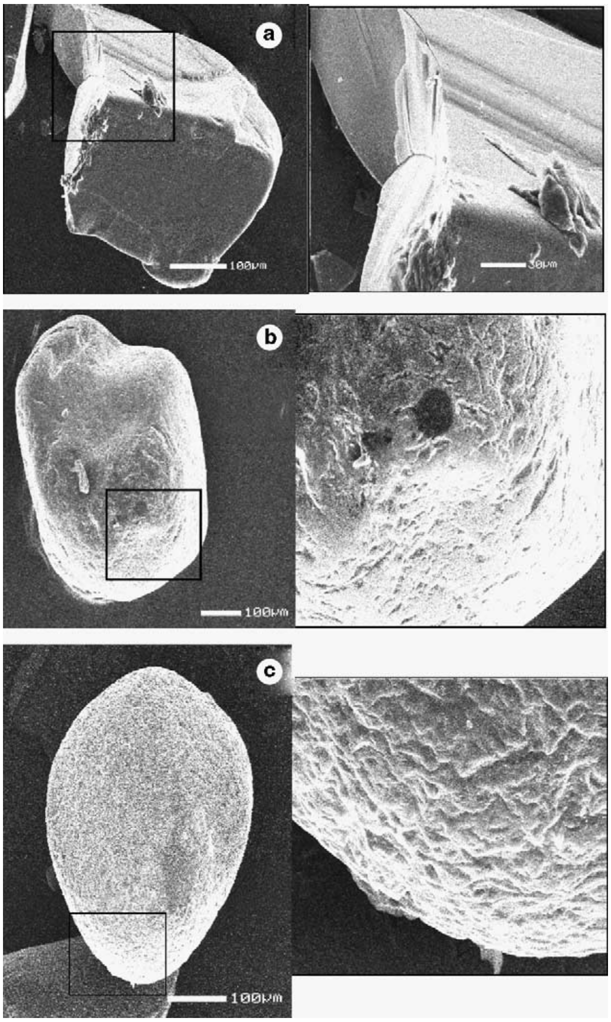

Fig. 4. (a) Glacially fractured subangular quartz grain showing fracture planes with adhering particles. (b) Subrounded quartz grain of fluvial origin showing the V-shaped indentations, straight and curved grooves and scratches. (c) Rounded aeolian quartz grain with upturned plates and meandering ridges.

Fracture faces, subparallel scratches and straight grooves occur with great regularity. A considerable number of grains with such a suite of surface textures have more rounded outlines with V-shaped indentations and slightly curved grooves overprinted on their surfaces. The content of grains with these surface microtextures is between 28% and 30%.

(B) The grains from the second micromorphological group are subangular to subrounded (Fig. 4(b)). These grains show the dominant presence of V-shaped indentations, straight and curved grooves and scratches, and arc-shaped steps. The content of grains with these features is 28–32% for both sections.

(C) The third group includes grains, which are subrounded to rounded (Fig. 4(c)). Upturned plates, arc-shaped steps and dish-shaped concavities are common on the surfaces of these grains. In addition, some grains from this group show V-shaped indentations, straight and slightly curved grooves and scratches. This group contains 36–44% of the total grains studied.

Solution pits and crevasses of different size and forms appear on 72–92% of the grain surfaces. Also commonly present on the majority of studied grains, are adhering clays particles forming accumulations of different thickness both on the exposed grain surfaces and within the fracture planes and depressions.

4.3. Environmental magnetism

The sections under study show very different discrete magnetic mineral content, both in terms of magnetite abundance and hard IRM (%$\mathrm{IRM}_{0.3\text{–}1\,\mathrm{T}}$) content. SIRM values from the Novokhopersk section are some three times larger than those in the Volnaya Vershina section and χ_{lf} values are more than five times larger (Table 1), whereas the mean %$\mathrm{IRM}_{0.3\text{–}1\,\mathrm{T}}$ is approximately half that of the Volnaya Vershina section. The SIRM and χ_{lf} values of the coarser fraction (0.5–1 mm) are generally double that of the 0.25–0.5 mm fraction (Table 1). These data are inferred to indicate a magnetite-like contribution, which dominates, but with a significant haematite (or goethite) content, particularly in the Volnaya Vershina section.

Acid treatment removes ~87% of the SIRM and ~85–87% of the χ_{lf} in both grain size fractions in the Novokhopersk section and some 79–84% of the SIRM and ~83–93% of the χ_{lf} in the fractions from the Volnaya Vershina section (Table 1). In contrast, the χ_{ARM} is not reduced to the same extent as the SIRM by the acid treatment, its loss being generally less consistent. The χ_{ARM}/SIRM values range from 0.06 to 0.51×10^{-3} mA^{-1}, for the untreated samples, and $0.46\text{–}0.81 \times 10^{-3}$ mA^{-1} for the acid treated fraction, implying a consistent decrease in the magnetite grain size caused by the acid treatment, using an analogy to synthetic magnetic (Maher, 1988). This is also shown by the IRM's up to 100 mT, which consistently show an increase in the proportion of coercivity between 50 and 100 mT (Table 1). This general increase in magnetic hardness and squareness implies the loss of a greater proportion of the magnetically coarser particles during the acid treatment. The IRM in excess of 300 mT in the Volnaya Vershina dataset is removed by some 50% with the acid treatment, producing post-treatment values a little higher than those in the Novokhopersk section (Table 1).

4.4. Cluster analysis

Classification methods, such as cluster analysis can fail when non-informative variables are included in the

Table 1
Average magnetic parameters for the samples from the Novokhopersk and Volnaya Vershina sections, for the untreated and acid-treated specimens from each grain size fraction

Sand fraction	χ_{lf} ($\times10^{-7}$ m^3/kg)	SIRM ($\times10^{-5}$ A m^2/kg)	χ_{ARM} ($\times10^{-8}$ m^3/kg)	%IRM$_{20–50\,mT}$	%IRM$_{50–100\,mT}$	%IRM$_{0.3–1\,T}$
Novokhopersk						
Untreated						
0.50–1.0 mm	0.71	43.76	2.64	24.8	18.4	14.3
0.25–0.5 mm	0.34	22.65	7.92	19.3	21.4	13.0
Post-acid treatment (inclusions)						
0.50–1.0 mm	0.09	6.23	2.85	28.4	25.3	12.4
0.25–0.5 mm	0.05	3.15	2.56	27.5	34.2	9.9
Volnaya Vershina						
Untreated						
0.50–1.0 mm	0.14	12.55	6.43	16.0	9.8	31.7
0.25–0.5 mm	0.06	6.55	2.45	17.1	11.6	28.4
Post-acid treatment (inclusions)						
0.50–1.0 mm	0.01	2.04	1.42	25.4	18.4	17.9
0.25–0.5 mm	0.01	1.38	0.87	20.3	23.6	12.3

analysis (Milligan, 1980; Fowlkes et al., 1988). Hence, it is necessary to select a subset of variables that are most powerful for discrimination, whilst having the lowest inherent noise (Lees, 1999; Rowan and Goodwill, 2000). This noise might include measurement, sampling or natural property variability. On the basis of visual examination of bi-plots SIRM, χ_{ARM}, %IRM$_{20–50\,mT}$, %IRM$_{50–100\,mT}$ and %IRM$_{0.3–1\,T}$ were selected as being most suitable for use in the cluster analysis. These five parameters were used in the four separate cluster analyses (HCA and MDS) performed on the two grain-size fractions (both untreated and acid treated samples; Fig. 5(a)). In each of these four cases, values were converted to Z-scores to remove the affect of magnitude scaling on the clustering process (Manly, 1994; Lees, 1999).

In all four cases either for individual grain fractions, acid-treated or non-acid treated there was a separation using the hierarchical cluster analysis into two major clusters related to the section from which the samples were derived (Fig. 5). The one exception to this is a sample at 87.1 m from the Volnaya Vershina section (0.25–0.5 mm inclusion fraction) that is sufficiently distinct from all other samples (Dimension 1 > 0.5) to be classified as an outlier in the clustering process (Fig. 5(a)).

The degree of distinctiveness of the Volnaya Vershina and Novokhopersk clusters can be gauged visually by the tightness of grouping of the samples and the separation of the clusters on the MDS plots (Fig. 5(a)). A measure of the cluster separation can be gauged by the HCA scaled distance between the agglomeration of the two section-groups, and the final agglomeration of samples from both sections. This is provided by the scaled distance separation (SDS) on the *x*-axis of the dendrogram from the hierarchical cluster analysis (Fig. 5(b)). This scaled distance measure (SDS) is directly proportional to the squared Euclidean distance between the two clusters. Hence, using this index the discrete 0.25–0.5 mm fraction produces the most distinctive difference between clusters (SDS = 0.88) followed by the 0.5–1 mm inclusion fraction (SDS = 0.76; Fig. 5). The weakest distinction is for the 0.5–1 mm untreated samples (SDS = 0.4), with the two-cluster model showing some divergence for the smaller (inclusion) grain size fraction. These data demonstrate the grain-size related nature of provenance sensitivity for both the discrete and included fractions. The magnetic parameters which are most powerful in this discrimination are χ_{ARM} and %IRM$_{50–100\,mT}$ with a smaller role provided by SIRM and %IRM$_{0.3–1\,T}$ with %IRM$_{20–50\,mT}$ the least powerful. The strong role played by χ_{ARM} and %IRM$_{50–100\,mT}$ suggests that the finest-grained ferrimagnetic particles play an important part in the discrimination process.

5. Discussion

The heavy mineral data suggests two primary sources (Sudakova and Faustov, 2004):

(a) A source derived from erosion of adjacent Mesozoic and Cenozoic sediments, which produced a relatively high content of stable heavy minerals, which is prevalent in the Volnaya Vershina section. This mineralogical association is typical for the south-eastern part of the Russian Plain, and has been previously identified as sediment samples with a ‘‘high content of metamorphic minerals with some hornblende’’ (Kaplin, 1981). The low content of unstable heavy minerals may be due to diagenetic removal in the Mesozoic and Cenozoic sediments during burial (cf. Morton, 1984).

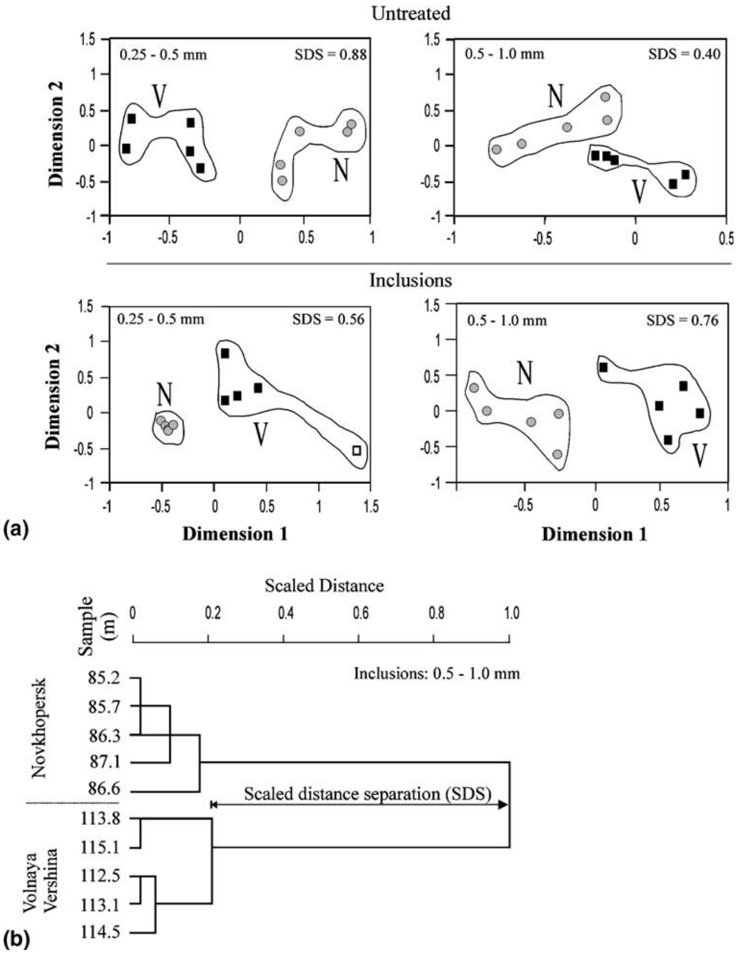

Fig. 5. (a) Multidimensional scaling plots, showing the separation of the samples from the two sections, for both the untreated and the acid-treated specimens from both grain size fractions. Each plot represents a separate MDS analysis, and in each case the two dimensions represent different combinations of magnetic parameters. SDS in each plot is the scaled distance separation (illustrated in (b)) between the amalgamation of the data into two clusters corresponding to each site. The exception to this is the multidimensional scaling plot for the 0.25–0.5 mm inclusion fraction, where the SDS is the distance at formation of the two major clusters; but in this case an additional sample (marked with unfilled symbol) in the Volnaya Vershina section joins the clustering after this, and so is considered an outlier point. Novokhopersk section = N; Volnaya Vershina = V. (b) Illustrative example of the dendrogram from the hierarchical cluster analysis (0.5–1.0 mm fraction, inclusions). A scaled distance of 1.0 corresponds to a point in the agglomeration schedule when all the samples form a single cluster, and 0 when no samples are agglomerated. The vertical lines in the dendrogram show at which scaled distance the samples were agglomerated, so that at scaled distances less than 0.25 progressively more clusters are developed. The example shows a scaled distance separation of 0.76, indicating a high degree of distinctiveness of the two section clusters. The three other dendrograms in (a) are not illustrated.

(b) A source with consistent but small amounts of exotic non-stable heavy minerals, hornblende and epidote, which is prevalent in the Novokhopersk section. Pebbles, mostly concentrated in the centre of the palaeo-valley fill have been shown to have a source from the South Karelia region of the Scandinavian Shield (Kaplin, 1981). Hence the unstable heavy minerals hornblende and epidote are thought to be derived mostly from this same source.

The quartz grain surface micromorphology shows the presence of 3 distinct grain groups. The subrounded grains from the first group with the presence of V-shaped indentations, straight and curved grooves and scratches are considered to be the product of high-energy transport in riverine or littoral environments (Krinsley and Doornkamp, 1973). The mostly subangular grains from the second micromorphological group with the prevalence of conchoidal fractures, arc-shaped steps and subparallel scratches are of glacial and fluvial–glacial origin (Krinsley and Doornkamp, 1973; Mahaney et al., 1996). The grains from the third group with rounded outlines, upturned plates and dish-shaped concavities are considered to be the product of aeolian transport (Krinsley and Funnel, 1965). Solution pits and crevasses are probably the result of in situ chemical weathering or diagenesis in the source sediments (Krinsley and Doornkamp, 1973). Adhering clay particles, forming accumulations of different thickness, are perhaps the result of glacial grinding during the transportation (Smalley, 1966).

The micromorphology suggests the quartz grains have an unexpectedly heterogeneous origin from aeolian-fluvial processes, as well as the anticipated glacial origin. The presence of only 28–30% of grains with glacial micromorphological features may be because of reduced ice pressures at this southern limit of the ice sheets. Alternatively, this may be due to little or no glacial reworking of the sedimentary source rocks adjacent to the palaeovalley (cf. Krinsley and Funnel, 1965). The fact that the content of quartz grains with glacial-type micromorphological features is relatively similar in both sections, suggests that grains in both sections have been subjected to a similar set of transport and abrasion processes. The largest content of aeolian grains occurs in the oldest part of the sections, and is probably due to extensive wind reworking during periglacial conditions prior to the initiation of glacial sedimentation.

The data obtained by magnetic measurements show the good definition between the sediments from the two locations (Fig. 5). There appears to be no relationship between the clustering of specimen magnetic data and the transport process as measured by quartz micromorphology.

One of the important controls on the distinctiveness of the clusters appears to be magnetic mineral abundance, both in the discrete and included magnetic mineral components. The greater than twofold increase in SIRM in the Novokhopersk section, is probably a reflection of the greater Fe-oxide content from the Scandinavian source, both as inclusions and discrete grains. Of the two size fractions, the finer-grained component (0.25–0.5 mm) of the discrete magnetic mineral fraction appears to be the most useful for discriminating the sediments within the palaeovalley. Some of this distinctiveness is lost in the inclusion data from the 0.25–0.5 mm size fraction. However, the inclusion data from the coarser grained fraction (0.5–1 mm) shows improvement over the discrete magnetic data for this size fraction. The implications of this are that the finer-grained fractions of these sediments are most likely to be useful for discriminating provenance differences, when using the conventional discrete magnetic components. Whereas the included Fe-oxide component, appears to be most powerful for discriminating provenance when using the coarser part of the sediment fraction. Walden et al. (1996) is one of the few studies that have tried to identify which grain size fraction of discrete magnetic particles, is most sensitive for provenance discrimination. In their glacial and fluvial–glacial sediments they found medium silt (16–32 μm) out-performed both the finer and coarser fractions. In contrast Hounslow and Morton (in press) found that the 0.25–0.5 mm fraction out-performed finer-sand and coarsest silt fractions in Triassic fluvial sediments, using the Fe-oxide inclusions for provenance discrimination. These two studies seem to re-iterate the results here, even though our data is based on a limited grain-size range.

The reasons that the inclusions provide a more distinctive signature in the coarser fraction may be due to the greater abundance of rock and composite silicate/Fe-oxide fragments in the coarser fraction. These composite fragments are likely to provide a distinctive source rock signature. Conversely, fracturing and fragmentation of such composite grains into small grains may liberate the small Fe-oxides as discrete magnetic particles, which may be lost from the system and in the process, loose some of the distinctive inclusion magnetic properties from the sand fraction. The loss of distinctiveness in the discrete magnetically coarse fraction may be due to transport and diagenesis, oxidation and alteration of the large discrete magnetic oxides. The alteration and oxidation process generally proceeds by a grain internal subdivision process into smaller subparticles (Dimanche and Bartholome, 1976; Morad and Aldahan, 1986), which may impose an alteration signal on the discrete magnetic data. The inclusions are isolated from this alteration, provided the hosts survive.

6. Conclusions

The heavy mineral data from the Novokhopersk and Volnaya Vershina sections shows a difference in the content of sediment derived from a Scandinavian source, which is mainly reflected in the epidote and amphibole content. The quartz grains from these sediments, which are within a glacial and fluvial–glacial succession, show the imprint of a heterogeneous origin, with the micromorphology indicating approximately equally division between aeolian, fluvial and glacial transport processes. The content of Fe-oxides reflects the Scandinavian source by its larger magnetic abundance parameters and perhaps lesser haematite (or goethite) content, than particles which were locally derived from the Russian Plain.

The sensitivity at discriminating different sediment provenances, both in the discrete and included particles, does not seem to be related to the transport process. The discriminating power of magnetic data for separating sediment provenance is not the same across the two grain-size fractions. The discrete magnetic Fe-oxide particles seem to be most powerful at provenance discrimination in the finer fraction, whereas the included magnetic particles are most powerful in the coarser fraction. Hence, a combination of techniques based on included and discrete magnetic particles may be most robust at clastic source evaluation in the sand fraction. We speculate that part of the reason for this grain-size dependency is related to the composite nature of the host particles, which are probably more prevalent in the coarser grains, whereas the poorer discrimination ability of the discrete magnetic particles in coarser fractions may be due to Fe-oxide alteration and oxidation, during sediment transport or in situ processes.

This study emphasise, perhaps more than anything else, the great importance of selecting the 'most sensitive' grain-size fraction when undertaking clastic-provenance evaluation using magnetic techniques. This study goes a small way to help this selection process, but much more work is needed to better understand the criteria that should be used in selecting the most provenance sensitive grain size fraction in any particular source to sink system.

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