Use of mineral magnetic concentration data as a particle size proxy: A case study using marine, estuarine and fluvial sediments in the Carmarthen Bay area, South Wales, U.K.

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Abstract

Compositional (non-magnetic) data can correlate strongly with particle size, which deems it appropriate as a particle size proxy and, therefore, a reliable means of normalising analytical data for particle size effects. Previous studies suggest magnetic concentration parameters represent an alternative means of normalising for these effects and, given the speed, low-cost and sensitivity of the measurements may, therefore, offer some advantages over other compositional signals. In this work, contemporary sediments from a range of depositional environments have been analysed with regard to their mineral magnetic concentration and textural characteristics, to observe if the strength and nature of the relationship identified in previous studies is universal. Our data shows magnetic parameters (χ_{LF} , χ_{ARM} and SIRM) possess contrasting relationships with standard textural parameters for sediment samples collected from marine (Carmarthen Bay), estuarine (Gwendraeth Estuary) and fluvial (Rivers Gwendraeth Fach and Gwendraeth Fawr) settings. Magnetic concentrations of sediments from both the marine and estuarine environments are highly influenced by the magnetic contribution of finer particle sizes; Gwendraeth Fawr River sediments are influenced by the magnetic contribution of coarser particle sizes, while sediments from the Gwendraeth Fach River are not influenced significantly by any variations in textural properties. These results indicate mineral magnetic measurements have considerable potential as a particle size proxy for particular sedimentary environments, which in certain instances could be useful for geochemical, sediment transport, and sediment provenance studies. However, the data also highlight the importance of fully determining the nature of the relationship between sediment particle size and magnetic properties before applying mineral magnetic data as a particle size proxy.

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1. Introduction

Mineral magnetic measurements are now considered a routine form of analysis when investigating the compositional properties of rocks, sediments and soils (Thompson and Oldfield, 1986; Walden et al., 1999; Maher and Thompson, 1999). The technique has been applied to various depositional environments (e.g. Arkell et al., 1983; Oldfield et al., 1985, 1999; White et al., 1997; Walden et al., 1995, 1997; Schmidt et al., 1999; Wheeler et al., 1999). Many of the studies have explored the relationship between mineral magnetic measurements and chemical/physical properties of sediments and soils (Oldfield et al., 1985; Oldfield and Yu, 1994; Clifton et al., 1997, 1999; Chan et al., 1998; Petrovsky et al., 1998; Xie et al., 1999, 2000; Booth, 2002). Based on these investigations, mineral magnetic measurements have been identified as a suitable tool for determining sediment provenance (Oldfield and Yu, 1994; Booth, 2002), sediment transport pathways (Lepland and Stevens, 1996), and also to serve as a proxy for geochemical, radioactivity, organic matter content and particle size data (Bonnett et al., 1988; Oldfield et al., 1993; Hutchinson and Prandle, 1994; Clifton et al., 1997, 1999; Xie et al., 1999, 2000; Zhang et al., 2001).

It is widely established that sediment-related analytical data can be strongly affected by particle size effects. For instance, generally, the finer a sediment the greater its concentration of both natural and anthropogenic pollutants (e.g. its trace metal concentration (Forstner and Salomons, 1980; Salomons and Forstner, 1980; Thorne and Nickless, 1981; Loring, 1990), radionuclide content (Aston et al., 1985; Bonnett et al., 1988; Oldfield et al., 1993; Clifton et al., 1997, 1999; McCubbin et al., 2000) or polychlorinated biphenyls (PCBs) quantity (Klamer et al., 1990; Camacho-Ibar and McEvoy, 1996). Typically, this is due to finer grained sediments possessing larger specific surface areas, surface charges and cation exchange capacities, which enhance the extent of their preferential chemical adsorption. This non-uniform distribution of pollutants over the range of particle size classes causes variations in the chemical composition of sediment samples. To directly compare samples of

different particle sizes, it is thus necessary to correct for particle size effects.

Normalisation is a common process to compensate for particle size and mineralogical differences in sediments and soils. A range of correction procedures has been developed to minimise these effects. Popular approaches tend to normalise data either relative to the abundance of a specific particle size interval class or to carry out their analyses on a specifically separated particle size fraction (e.g. <16 μm (Klamer et al., 1990), <20 μm (Ackermann, 1980; Ackermann et al., 1983; Christiansen et al., 2002), <63 μm (Salomons and Forstner, 1980; Araujo et al., 1988; Klamer et al., 1990), <100 μm (Langston, 1986), <150 μm (Jones and Turki, 1997), <250 μm (Hornung et al., 1989)). Although these methods can be considered reliable and advantageous, they require additional and, in the latter case, time-consuming laboratory work.

Other techniques have also been adopted involving a correction factor for an inert or organic material (Thomas, 1972; Williams et al., 1978; Cauwet, 1987; Ergin et al., 1996; Camacho-Ibar and McEvoy, 1996; Fernandez Caliani et al., 1997; Russell et al., 2001) or by comparison with 'conservative' elements (i.e. elements with strong correlations to particle size, but themselves are not pollutants), such as aluminium (de Groot et al., 1982; Ergin et al., 1996), iron (Lapp and Balzer, 1993), caesium (Ackermann, 1980), or rubidium (Middleton and Grant, 1990). In general, these approaches also employ extrapolation from regression curves or sometimes entail a mathematical formulation of correcting particle size effects after analysis of bulk samples (de Groot et al., 1982; Covelli and Fontolan, 1997; Szava-Kovats, 2002).

Where a particle size proxy can be measured in an efficient fashion (that is, shorter analysis time or lower cost than determination of the particle size distribution or preparation of specific size fractions for analysis), it can offer potential advantages. However, to assess the appropriateness of an analytical technique as an efficient particle size proxy and as an accurate means of normalising data, it is necessary that the nature of the relationship between the proposed parameters and particle size follow a universal pattern (like those of trace metals, radionuclides and PCBs with particle size).

Fig. 1. Location maps (a) U.K.; (b) Carmarthen Bay; (c) Gwendraeth Estuary; and (d) the rivers Gwendraeth Fach and Gwendraeth Fawr.

Given the combination of low-cost and sensitivity of the method, it can be argued that mineral magnetic measurements might have some considerable potential to act as a particle size proxy. The method is also rapid; bulk samples require little in the way of preparation and individual measurements of magnetic susceptibility (χ_{LF}) can be made in approximately 1 min, in either a laboratory or field setting. Previous workers have investigated this potential of the method. For example, Oldfield et al. (1993) has identified (a) that anhysteretic remanent magnetisation (ARM) measurements can be used to reflect the concentration of fine-grained magnetite ($<0.1 \mu\text{m}$) in the clay fraction and (b) χ_{LF} measurements can be used to infer the presence of coarser multi-domain magnetite ($>1.0 \mu\text{m}$) in sands and coarse silts. In a more detailed investigation it was found that (a) χ_{LF} was strongly associated with sands and medium silts, (b) susceptibility of ARM (χ_{ARM}) was strongly associated with clay and fine silts, and (c) saturated isothermal remanent magnetisation (SIRM) was strongly associated with very fine to medium silts (Clifton et al., 1999). More recently, Zhang et al. (2001) suggested that both percentage frequency-dependent magnetic susceptibility ($\chi_{FD\%}$) and χ_{ARM} can be used as a proxy for clay content.

In general, this evidence supports the inference that high magnetic concentration measurements can be associated with large amounts of fine-grained sediments and an inverse relationship with coarse-grained sediments. However, few studies have examined the relationships between mineral magnetic measurements and textural properties from a series of different, but related, sedimentary environments within a single field setting, to observe if the strength and nature of the relationship is universal.

This paper will explore two methodological issues. First, as in the earlier studies cited above, it will examine the extent to which particular mineral magnetic parameters are reliable indicators of differences in particle size. Second, the ‘universality’ principle that all sedimentary environments show the same relationship between mineral magnetic and particle size properties is considered by examining the relationships between mineral magnetic concentration measurements and textural properties in

marine, estuarine, and fluvial sediments within a single field setting (Fig. 1).

2. Methodology

Ongoing research by the current authors within the Carmarthen Bay area, South Wales, U.K. provided a suitable database of field samples with which to examine these methodological issues (Booth, 2002). This previous work provided a suitable field context, with existing knowledge of the sediment transport environment, tidal patterns, bathymetry and sediment sources (Jones, 1977; Evans and Thompson, 1979; Jago, 1980; Barrie, 1981; Al-Ghadban, 1986; Collins, 1987; Mercer, 1990; Jago and Hardisty, 1984; McLaren, 1999; Velegrakis et al., 1999; Booth, 2002). The field setting includes large areas dominated by marine (Carmarthen Bay), estuarine (Gwendraeth Estuary) and fluvial (Gwendraeth Fach and Gwendraeth Fawr Rivers) sediments within the overall sedimentary system (Fig. 1), allowing the second methodological issue outlined above to be examined.

A total of 308 samples were collected and analysed. Marine samples were collected from Carmarthen Bay ($n=113$) using a Shipek grab sampler, which retrieves the uppermost centimetres of seabed sediment. Representative samples from each successful grab were stored in labelled, self-seal plastic sample bags (McLaren, 1999). Estuarine samples from the Gwendraeth Estuary ($n=95$) and fluvial samples from the Gwendraeth Fach ($n=50$) and Gwendraeth Fawr ($n=50$) rivers were collected using a technique previously employed by French (1993). This involved using the edge of a clean plastic trowel that was scraped across an exposed sediment surface to remove only the top few millimetres of sediment. The sediment was then transferred into clean, pre-labelled, self-seal, plastic bags, until samples yielding ~100–150 g dry weight was obtained. Samples of this size allowed for replicate analyses to be conducted and for other types of analysis to be performed as required.

Textural properties of the sediments were measured by laser diffraction using a Malvern Mastersizer Long-bed X. The technique allows rapid and accurate measurement of particle sizes within the

0.1–2000 μm range (Syvitski, 1991). All macroscopic organic matter and shell fragments were removed from representative sub-samples before being dampened by the dropwise addition of a standard chemical solution (40 g of sodium hexametaphosphate $((\text{NaPO}_3)_6)$ per litre of distilled water (Zhao et al., 1999) to help disperse aggregate particles. To ensure complete disaggregation, each sediment slurry was then subjected to ultrasonic

dispersion in a Malvern MSX17 sample presentation unit. For greater precision, the mean of five replicate analyses was measured with a mixed refractive indices presentation setting. A standard range of textural parameters was calculated (Tucker, 1991). As in the studies of Clifton et al. (1997, 1999), these included the quantity of sand, silt and clay class sizes (expressed as percentages). Throughout this work, the Malvern instrumentation was regularly validated using latex beads of known size, to confirm it was performing to traceable standards.

For mineral magnetic analysis, all samples were subjected to the same preparation and analysis procedure, following Walden (1999), in which ~20 g of each bulk sample was allowed to dry at room temperature ($<40^\circ\text{C}$) and were then weighed, packed in 10 ml plastic pots and immobilised with clean sponge foam and tape prior to analysis. A standard range of magnetic parameters was measured on all samples. Initial, low-field, low-frequency, mass specific, magnetic susceptibility (χ_{LF}) was measured using a Bartington MS2 susceptibility meter. Anhysteretic remanence magnetisation (ARM) was imparted by a Molspin A.F. demagnetiser with an ARM attachment. ARM created within the sample was measured using a Molspin 1A magnetometer and then demagnetised using the A.F. demagnetiser. Values were then converted to give the mass specific susceptibility of ARM (χ_{ARM}). Samples were then exposed to a series of successively larger field sizes up to a maximum of 800 mT, followed by a series of successively larger fields in the opposite direction (backfields). After each ‘forward’ and ‘reverse’ field, the isothermal remanent magnetisation (IRM) of the sample was measured using the magnetometer. Table 1 provides a basic description and interpretation of each of the main parameters derived from these measurements.

3. Results

Summary mineral magnetic and texture data for the samples are presented in Tables 2 and 3. The χ_{LF} values show considerable variation, with Carmarthen Bay ($0.17\text{--}2.72 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$), the Gwendraeth Estuary ($0.32\text{--}4.94 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$) and the Gwen-

Table 1

Mineral magnetic parameters discussed in the text and their basic interpretation (after Dearing, 1999; Thompson and Oldfield, 1986; Maher, 1988; Walden et al., 1999)

Parameters	Interpretation
$\chi_{\text{LF}} (\times 10^{-7} \text{ m}^3 \text{ kg}^{-1})$	<i>Initial low field mass specific magnetic susceptibility</i> (χ_{LF}) is measured within a small magnetic field and is reversible (no remanence is induced). Its value is roughly proportional to the concentration of ferrimagnetic minerals within the sample, although in materials with little or no ferrimagnetic component and a relatively large antiferromagnetic component, the latter may dominate the signal.
$\chi_{\text{ARM}} (\times 10^{-7} \text{ m}^3 \text{ kg}^{-1})$	<i>Susceptibility of Anhysteretic Remanent Magnetisation</i> (χ_{ARM}) is roughly proportional to the concentration of ferrimagnetic grains in the 0.02–0.5 μm (stable single domain) size range. For this work, ARM was induced in the samples by combining a peak AF field of 100 mT with a DC biasing field of 0.04 mT and the final result expressed as mass specific ARM (Maher, 1988).
SIRM ($10^{-5} \text{ Am}^2 \text{ kg}^{-1}$)	<i>Saturation Isothermal Remanent Magnetisation</i> (SIRM) is the highest amount of magnetic remanence that can be produced in a sample by applying a large magnetic field. It is measured on a mass specific basis. In this study a ‘saturating’ field of 800 mT has been used and this will produce saturation in most mineral types (except some antiferromagnetic minerals). The value of SIRM is related to concentrations of all remanence-carrying minerals in the sample, but is also dependent upon the assemblage of mineral types and their magnetic grain size.

Table 2

Mineral magnetic concentration data for Carmarthen Bay ($n=113$), Gwendraeth Estuary ($n=95$), Gwendraeth Fach River ($n=50$) and Gwendraeth Fawr River ($n=50$)

Sedimentary environments	Parameters	χ_{LF}	χ_{ARM}	SIRM
Carmarthen Bay	Mean	0.86	0.09	114.55
	S.D.	0.51	0.10	67.11
Gwendraeth Estuary	Mean	2.10	0.66	309.51
	S.D.	1.22	0.54	192.44
Gwendraeth Fach River	Mean	11.01	0.51	2013.99
	S.D.	6.10	0.25	1033.65
Gwendraeth Fawr River	Mean	3.01	0.25	492.48
	S.D.	0.50	0.02	112.46

draeth Fawr River ($2.32\text{--}4.39 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$) exhibiting low to moderate concentrations of magnetic minerals, while the Gwendraeth Fach River ($4.29\text{--}27.17 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$) shows a moderate to high concentration of magnetic minerals.

The χ_{ARM} values indicate that the Carmarthen Bay ($0.02\text{--}0.65 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$) samples contain low to moderate concentrations of stable single domain magnetite. The Gwendraeth Fach and Gwendraeth Fawr Rivers ($0.24\text{--}1.19 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$ and $0.21\text{--}1.19 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$, respectively) contain moderate to high χ_{ARM} concentrations. The Gwendraeth Estuary ($0.04\text{--}1.80 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$) exhibits a very variable concentration of stable single domain magnetic minerals with low to very-high χ_{ARM} values.

SIRM values show variations similar to χ_{LF} ; Carmarthen Bay ($25.8\text{--}404.4 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$), the Gwendraeth Estuary ($39.3\text{--}770.2 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$) and Gwendraeth Fawr River ($341.0\text{--}765.6 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$) contain low to moderate concentrations

Table 3

Textural data for Carmarthen Bay ($n=113$), Gwendraeth Estuary ($n=95$), Gwendraeth Fach River ($n=50$) and Gwendraeth Fawr River ($n=50$)

Sedimentary environments	Parameters	Sand	Silt	Clay
Carmarthen Bay	Mean	93.20	5.98	0.83
	S.D.	11.25	10.00	1.27
Gwendraeth Estuary	Mean	49.80	45.73	4.47
	S.D.	35.13	32.17	3.31
Gwendraeth Fach River	Mean	77.91	20.47	1.62
	S.D.	14.35	13.45	1.06
Gwendraeth Fawr River	Mean	51.07	44.58	4.35
	S.D.	17.22	16.09	1.40

of all remanence-carrying magnetic minerals. By contrast, the Gwendraeth Fach River ($826.0\text{--}4779.0 \times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$) shows a moderate to high concentration of all remanence-carrying magnetic minerals.

Table 4 shows the Pearson's correlation coefficient values (r) between the mineral magnetic concentration parameters and standard textural parameters, grouped according to their sedimentary environment. Significant negative correlations exist between each of the mineral magnetic concentration parameters and the percentage sand for both Carmarthen Bay and the Gwendraeth Estuary. If χ_{ARM} is excluded, the same is also true for the Gwendraeth Fawr River. However, the nature of the Gwendraeth Fawr River correlations (positive with respect to percentage sand) is the reverse of those for Carmarthen Bay and the Gwendraeth Estuary. Irrespective of this, each of these relationships are in contrast to those observed for the Gwendraeth Fach River, which shows no significant relationship between any of the mineral magnetic concentration and textural parameters. With respect to the Gwendraeth Fach River, it is also apparent that each textural parameter shows differing strengths of correlation with each of the magnetic concentration parameters.

Fig. 2a–d show bivariate scatter plots of sand content (%) versus χ_{LF} ($\times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$) for each

Table 4

Mineral magnetic concentration and texture correlation coefficient values (r) for Carmarthen Bay ($n=113$), Gwendraeth Estuary ($n=95$), Gwendraeth Fach River ($n=50$) and Gwendraeth Fawr River ($n=50$)

Sedimentary environments	Parameters	χ_{LF}	χ_{ARM}	SIRM
Carmarthen Bay	Sand	−0.495*	−0.957*	−0.603*
	Silt	0.498*	0.958*	0.605*
	Clay	0.470*	0.943*	0.578*
Gwendraeth Estuary	Sand	−0.923*	−0.900*	−0.911*
	Silt	0.924*	0.901*	0.913*
	Clay	0.818*	0.794*	0.799*
Gwendraeth Fach River	Sand	−0.125 ^{NS}	−0.161 ^{NS}	−0.128 ^{NS}
	Silt	0.121 ^{NS}	0.158 ^{NS}	0.123 ^{NS}
	Clay	0.165 ^{NS}	0.180 ^{NS}	0.164 ^{NS}
Gwendraeth Fawr River	Sand	0.700*	−0.058 ^{NS}	0.829*
	Silt	−0.707*	0.057 ^{NS}	−0.837*
	Clay	−0.479*	0.061 ^{NS}	−0.572*

* Significant at $p < 0.01$ level.

^{NS} Not significant at $p < 0.05$ level.

Fig. 2. Sand content as a function of χ_{LF} in bulk sediment samples (a) Carmarthen Bay ($n=113$); (b) Gwendraeth Estuary ($n=95$); (c) Gwendraeth Fach River ($n=50$); and (d) Gwendraeth Fawr River ($n=50$).

of the sedimentary environments. Both the Gwendraeth Estuary and Gwendraeth Fawr River samples have relatively modest degrees of scatter around the line of best fit (Fig. 2b and d). This suggests differences in the concentration of ferrimagnetic minerals and/or antiferromagnetic component in these samples could be used as a proxy for the proportion of sand, although care would be needed with the Gwendraeth Estuary samples as the data are clearly not normally distributed. In contrast, both Carmarthen Bay and the Gwendraeth Fach River samples, as suggested by lower correlations coefficients (Table 4), show greater scatter (Fig. 2a and c) and, while the relationship between sand content and χ_{LF} is significant for the Carmarthen Bay sample set, the data distributions in Fig. 2a

and c would not give high levels of confidence in susceptibility as a sand content proxy in either case. Fig. 3a–d show similar plots for sand content (%) versus SIRM ($\times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$). The relationships for each sample set are identical to those for χ_{LF} and this suggests that for these sample sets at least, χ_{LF} and SIRM are responding to the same magnetic component. In any further analyses of these sediments, only one of these two variables would need to be measured.

Fig. 4a–d provide similar bivariate scatter plots of sand content (%) versus χ_{ARM} ($\times 10^{-5} \text{ Am}^2 \text{ kg}^{-1}$). In this case, the plots for the Carmarthen Bay and Gwendraeth Estuary samples (Fig. 4a and b) both appear to support a strong, negative relationship between the proportion of sand present and χ_{ARM} ,

Fig. 3. Sand content as a function of SIRM in bulk sediment samples (a) Carmarthen Bay ($n=113$); (b) Gwendraeth Estuary ($n=95$); (c) Gwendraeth Fach River ($n=50$); and (d) Gwendraeth Fawr River ($n=50$).

although the relationship for Gwendraeth Estuary is possibly non-linear. In contrast, variations in the concentration of ultrafine ferrimagnetic minerals of the samples in either the Gwendraeth Fach River or the Gwendraeth Fawr River do not appear to be influenced by differences in the proportion of sand (Fig. 4c and d).

4. Discussion

Previous magnetic studies of coastal and estuarine sediments (Bonnett et al., 1988; Clifton et al., 1999) have noted significant correlations between χ_{LF} , χ_{ARM} , SIRM and particle size. These studies have shown sand to correlate negatively with χ_{LF} ($r=-0.94$), χ_{ARM} ($r=-0.81$), but SIRM to be insignificant; silt to cor-

relate positively with χ_{LF} ($r=0.96$), χ_{ARM} ($r=0.93$) and SIRM ($r=0.96$); and clay to correlate positively with χ_{LF} ($r=0.77$), χ_{ARM} ($r=0.92$) and SIRM ($r=0.81$). When data presented here are compared to these earlier investigations, it is apparent that some of the correlations and trends observed are similar to previous studies (e.g. sand and χ_{ARM} ($r=-0.96$), silt and χ_{LF} ($r=0.92$), clay and SIRM ($r=0.80$)). However, some differences also occur (e.g. sand and χ_{ARM} ($r=-0.06$), silt and χ_{LF} ($r=-0.71$), clay and SIRM ($r=-0.57$)) in terms of both significance and nature (positive or negative) of the trends.

The hypothesis that the formal correlation identified between analytical data and textural variation (e.g. heavy metal concentration, radionuclide activity or PCBs content increasing as particle size decreases) means that the correction of particle size effects relies

Fig. 4. Sand content as a function of χ_{ARM} in bulk sediment samples (a) Carmarthen Bay ($n=113$); (b) Gwendraeth Estuary ($n=95$); (c) Gwendraeth Fach River ($n=50$); and (d) Gwendraeth Fawr River ($n=50$).

on the universal applicability of the relationship. However, based on data presented here, such a simple relationship does not exist for mineral magnetic concentration parameters. It would appear that it is only in certain sedimentary environments and specific settings that mineral magnetic measurements are appropriate for granulometric normalisation. Our data suggest χ_{LF} and SIRM measurements are appropriate particle size proxies in the Gwendraeth Estuary and the Gwendraeth Fawr River, and that χ_{ARM} measurements form an appropriate particle size proxy in Carmarthen Bay and the Gwendraeth Estuary. In contrast, no mineral magnetic measurements are appropriate for normalising particle size effects in the Gwendraeth Fach River. Some of these trends agree with previous investigations (Bonnert et al., 1988; Clifton et al., 1999), which have emphasised

the potential of mineral magnetic measurements as a simple, reliable, rapid, sensitive, inexpensive and non-destructive method of normalising for particle size. However, a cautionary note is required here as our relationships between mineral magnetic concentration and texture also indicate the association may not be as simple as previous work proposes.

It has been identified that Carmarthen Bay and the Gwendraeth Estuary have some similarities, in terms of strength and nature of the relationship between mineral magnetic concentration and textural properties. Based on the results of a mathematical sediment-unmixing model (Booth, 2002), this is most likely due to the fact that Carmarthen Bay sediments acts as the primary source ($\sim 77\%$) of sediments in the Gwendraeth Estuary. Differences between the Carmarthen Bay and the Gwendraeth Estuary may be due to the

Gwendraeth Estuary being influenced by other sediment sources (Gwendraeth Fach River (~13%) and Gwendraeth Fawr River (~10%)). However, in addition to this, since the magnitude of the χ_{ARM} values of the estuary samples are greater than those of the sources and since the measure of this parameter is approximately proportional to the concentration of ferrimagnetic grains in the stable single domain size range (Maher, 1988), it is interpreted that authigenic greigite (Oldfield, 1999a,b) and/or bacterial magnetite (Petermann and Bleil, 1993; Hesse and Stolz, 1999) also contributes to the direction and significance of the relationship between magnetic concentration and texture in the estuary (Booth, 2002).

The Gwendraeth Fach and Gwendraeth Fawr rivers drain contrasting geologies (Gwendraeth Fach River—Devonian Sandstones; Gwendraeth Fawr River—Carboniferous Coal Measures) and their sediment load has a primarily detritus origin (Booth, 2002). Hence, in the main, the magnetic mineral assemblage is deemed to be predominately detrital in nature. However, although relatively low-key, both rivers have been subject to different anthropogenic uses in the historical past. For instance, the Gwendraeth Fawr River was employed for transporting anthracite coal by wooden barges (~1760 s) from the South Wales coalfield (Morris, 1970) and the banks of the Gwendraeth Fach River was the site of a tinplate rolling mill near Kidwelly (Ludlow, 1991). The location of the latter industry and the nature of the manufacturing could offer an explanation as to why none of the magnetic concentration parameters for the Gwendraeth Fach River are related to the textural parameters. Electron microscope analysis has shown the presence of metal-rich, clay to fine sand size, spherical particles to be present in significant proportions in the Gwendraeth Fach River, but not the Gwendraeth Fawr River (Booth, 2002). Their appearance is similar in size, shape and chemistry to combustion-generated particles (Swaine, 1994; Hanesch and Peterson, 1999). It is widely known that coal combustion produces fly-ash particles displaying a remarkable degree of sphericity (Singh and Rawat, 1995), ranging from 1 to 2000 μm (Krajickova and Mejstrik, 1984), and coated with various metal-oxides, which form magnetite, haematite and maghemite minerals (Del Monte and Sabbioni, 1987; Singh and Rawat, 1995). Therefore, it is possible that past

industrial emissions have imparted a non-particle size specific overprint on the magnetic concentration signature of contemporary sediments in the river, with anthropogenically derived pollutants occupying a wide size range. However, this said, it must be remembered that the study area represents a mainly typical detrital system. Therefore, the diverse mineral magnetic versus particle size relationships displayed here could occur in similar systems.

5. Conclusion

In addressing the two methodological questions posed earlier, the results presented here do indicate that mineral magnetic data can be used as a particle size proxy. However, this should only be attempted with caution as the relationship between magnetic concentration parameters (e.g. χ_{LF} , χ_{ARM} and SIRM) and particle size properties are not necessarily 'universal'. These data demonstrate the relationship between mineral magnetic concentration measurements and textural properties can be different for particular sedimentary environments even within the same overall sedimentary system and, in some circumstances, the mineral magnetic approach can be unsuitable as a particle size proxy.

As a consequence, it is recommended that the nature of the relationship between magnetic and textural properties should be explored fully for the particular sedimentary environment and individual field setting, before using magnetic measurements as a proxy for particle size. Where such a preliminary study demonstrates that a strong correlation exists, mineral magnetic measurements can then offer considerable potential as a particle size proxy of use in geochemical, sediment transport and sediment provenance studies. However, it is recommended that future work demonstrates whether fractionated samples and geochemical evidence can support these findings.

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