Sediment Budgets 1 (Proceedings of symposium S1 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 291, 2005.

Fluvial contribution to the sediment budget of the Tay Estuary, Scotland, assessed using mineral magnetic fingerprinting

PIERRE A. JENKINS, ROBERT W. DUCK & JOHN S. ROWAN
Environmental Systems Research Group, Department of Geography, University of Dundee, Dundee DD1 4HN, UK
r.w.duck@dundee.ac.uk

Abstract The sediment budget of the Tay Estuary, Scotland, UK, was evaluated using mineral magnetic fingerprinting. A multivariate unmixing model, based on constrained linear programming, permitted quantification of source contributions to the estuarine bottom sediments. Factor and multivariate discriminant analysis demonstrated that the two fluvial sources could be separated on the basis of five, linearly additive magnetic properties. However, lack of data dimensionality necessitated amalgamation of the two marine sources originally recognized. The model demonstrates the present-day dominance of marine bottom sediment derivation (78 ± 10%), whereas fluvial source contributions are 4 ± 10% from the River Earn and 18 ± 10% from the River Tay. The fluvial contribution should be considered in the context of the Tay being Britain's foremost river in terms of discharge (long-term average ~167 $m^3 s^{-1}$). Source contributions to intertidal flat sediments collected over a spring–neap tidal cycle imply a temporal constancy to bed sediment provenance.
Key words bed sediment; fluvial contribution; magnetic fingerprinting; Scotland; sediment budget; Tay Estuary

INTRODUCTION

Sediment fingerprinting using tracer properties, such as mineral magnetics, geochemistry and radionuclides, has become an accepted approach to sediment provenance studies in a wide variety of environments (Foster & Lees, 2000). Most attention has, however, focused on rivers, lakes, reservoirs and flood plains with few previous studies of estuarine environments (Yu & Oldfield, 1989; Duck *et al*., 2001; Jenkins *et al*., 2002). In this investigation, the provenance of the bottom sediments of the Tay Estuary of eastern Scotland, UK, was explored using mineral magnetic tracers. The Tay Estuary is an important water body, because it receives the inflow from the foremost British river in terms of discharge (see below), and although extensively studied in the past, quantification of the estuary's sediment budget remains elusive. The key contribution here is to quantify the fluvial contribution to the overall sediment budget and refine preliminary analyses (based on fewer samples) previously reported (Duck *et al*., 2001; Jenkins *et al*., 2002).

THE STUDY AREA

Discharging eastwards into the North Sea, the Tay Estuary is one of the major Scottish estuaries and is held to be one of the cleanest major water bodies in Europe. It receives the freshwater input of two rivers, the Tay and the Earn, which deliver a long-term mean flow of 198 $m^3 s^{-1}$ from a combined catchment area of approx. 6500 km^2. The River Tay contributes ~84% of the inflow (long-term average discharge 167 $m^3 s^{-1}$), the highest freshwater discharge of any British river, whereas the River Earn provides the remaining 31 $m^3 s^{-1}$ (McManus, 1986). The upper catchments of both rivers are located to the north of the Highland Boundary Fault, overlying mixed assemblages of Precambrian metamorphic rocks. To the south of the fault, suites of sandstones, conglomerates, lavas and tuffs of the Lower Devonian underlie the lower catchments. Pleistocene drift deposits, comprising tills and fluvioglacial sands and gravels, are widespread in the region.

The Tay Estuary is macrotidal (tidal range 4–6 m), partially mixed, has a maximum depth of approx. 30 m and a tidal reach of 50 km. Buller *et al.* (1971) subdivided the latter into four reaches (Fig. 1), of which the "uppermost", incorporating the confluence of the Rivers Tay and Earn, was channelized to improve navigation in the mid-19th century. Here, the artificially enlarged southern channel cuts into Pleistocene clays, while the largely natural northern channel has partially silted. The northern side of the "upper" reach of the estuary is characterized by extensive, largely stable intertidal mudflats backed by reed beds. The main channel (Navigation Channel) in this reach closely follows the southern shoreline and is characterized by mobile coarse sands and gravels. The "middle" reach displays a highly dynamic configuration of migrating channels separated by large intertidal sandbanks. The channels are floored by mobile sands that are dominated by dune bedforms due to strong tidal currents, >1 $m s^{-1}$

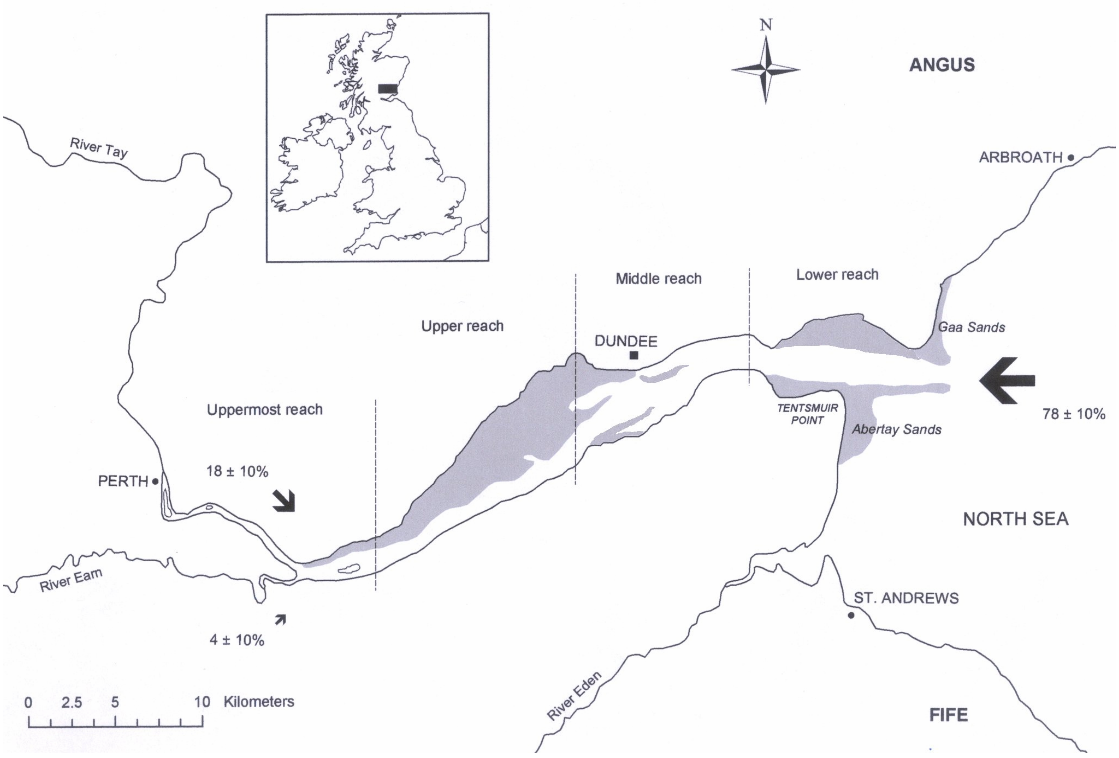

Fig. 1 The Tay Estuary showing locations referred to in the text. Reaches are defined according to Buller *et al.* (1971), shaded areas are intertidal. Arrows with percentages indicate bottom sediment derivation to the estuary.

(Duck & Wewetzer, 2000). In the "lower" reach, intertidal sand flats backed by beach and dune ridges are present along both the northern and southern shores. The main channel, lined with gravel, links the estuary with the North Sea between two major sand spit complexes, the Abertay Sands (north) and the Gaa Sands (south). At the estuary mouth beaches are developed along both the northern (Angus) and southern (Fife) shores. Those to the north have a long history of erosion, which has led to the installation of protection works at several localities. By contrast, Tentsmuir Point to the south has accreted northeasterly at a rate of approx. 15 m $year^{-1}$ since 1941 (McManus & Wal, 1996). Net longshore sand transport, induced by wave activity and implemented by the tidal circulation pattern, operates as two cellular systems moving in opposite directions that converge at the mouth of the estuary and deliver sediment upstream on the flood tide. No estimates of the amounts of marine derived sediment introduced into the estuary have been made but Al-Dabbas & McManus (1987) have drawn attention to the presence of shell fragments of *Mytilus edulis* in bottom deposits up to 6 km landwards of the westernmost known colonies, indicative of up-estuary net residual motion. Four end-member sediment sources contributing to the bed sediments of the estuary were identified: the Rivers Tay and Earn and the marine sectors immediately to the north (Angus coast) and south (Fife coast) of the mouth (Fig. 1).

METHODOLOGY

Full details of sediment sample collection, treatment and locations are given in Jenkins (2003). End-member sources were characterized from a total of 72 samples: 18 bed sediment samples were obtained from the channel of the River Tay and 17 from the River Earn, from sites upstream of the tidal limit. For the marine sources, 19 beach samples were collected from the Angus coast and 18 from the Fife coast, at locations slightly above mean low water mark. Within the estuary, a total of 431 bottom samples were assembled, including both archival and samples collected in the period 2000–2001. These comprised batches TE-1972 (n = 226), TE-1997 (n = 131), TE-May2000 (n = 15), TE-Aug2000 (n = 17), TE-Dec2001 (n = 18) and TE-TC (n = 24). The latter set of samples were collected from one fixed location, at regular time intervals, on the upper intertidal flats in order to observe changes in the magnetic signature of bed sediments over a spring–neap tidal cycle. Together these batches provide virtually complete coverage of the estuary, with all reaches as defined by Buller *et al*. (1971) represented and particularly high-density coverage in the Navigation Channel.

Magnetic susceptibilities of the sediment samples from the Tay Estuary and its four sources were determined as the mean of five repeat measurements using a Bartington MS2B Dual Frequency sensor, with low and high frequency settings of 0.47 and 4.7 kHz, respectively. A Molspin AF demagnetizer with an ARM attachment and a Molspin 1T pulse magnetizer, induced anhysteretic remanence magnetization (ARM) and isothermal remanance magnetization (*IRM*), respectively, measured subsequently using a Molspin 1A fluxgate magnetometer. *IRM* was measured for forward fields of 40, 100, 300, 500 and 1.0 mT and a reverse field of 100 mT. $IRM_{1.0T}$ is, hereafter, referred to as the saturation isothermal remanent magnetization (*SIRM*). The suite of magnetic measurements, full details of which are given in Jenkins *et al.*

(2002), resulted in six concentration-dependent parameters (χ_{lf}, $\chi_{fd\%}$, χ_{arm}, *SIRM*, IRM_{soft} and IRM_{hard}) and six concentration-independent ratios ($IRM_{soft\%}$, $IRM_{hard\%}$, χ_{arm}/χ_{lf}, $SIRM/\chi_{lf}$, $SIRM/\chi_{arm}$ and *S* ratio). Bulk magnetic measurements were conducted on standard samples, screened to 1 mm, and a series of particle size-based magnetic measurements were conducted for 0.5 ϕ fractions of sediments belonging to the sources and selected estuarine samples.

RESULTS AND ANALYSIS OF MAGNETIC MEASUREMENTS

The magnetic measurements reveal that the magnetic signatures of the bed sediments acquired during this study are dominated by the behaviour of a ferrimagnetic component. The relatively low values of $\chi_{fd\%}$ and χ_{arm} suggest that the ferrimagnets consist of coarse multi-domain minerals rather than ultra-fine, stable single domain minerals. Complete analysis of the results obtained during the investigation is not possible in this paper. A summary of the mean values and 95% confidence intervals for the six concentration-dependent magnetic parameters and the six concentration-independent ratios is provided by Table 1. The concentration-dependent parameters illustrate differences between the fluvial and marine end members, with generally higher values for the fluvial samples as compared with the coastal samples, the exception being the higher value of $\chi_{fd\%}$ for the Angus coastal set. The estuarine sample sets display

Table 1 Mean values and 95% confidence intervals for six concentration-dependent parameters and six concentration-independent ratios.*

Sample set	*n*	χ_{lf}	$\chi_{fd\%}$	χ_{arm}	*SIRM*	IRM_{soft}	IRM_{hard}
River Earn	17	6.74 ± 0.74	1.08 ± 0.14	24.12 ± 2.87	1267.8 ± 137.9	313.33 ± 34.12	146.93 ± 16.17
River Tay	18	6.26 ± 0.76	1.22 ± 0.16	34.49 ± 4.82	765.51 ± 93.48	308.55 ± 38.29	66.27 ± 7.47
Angus coast	19	2.11 ± 0.24	1.36 ± 0.23	6.10 ± 0.72	328.97 ± 37.43	92.51 ± 10.56	57.27 ± 6.74
Fife coast	18	1.63 ± 0.20	0.76 ± 0.13	4.97 ± 0.55	193.92 ± 22.28	60.01 ± 6.92	31.37 ± 3.66
TE-1972	226	2.44 ± 0.26	1.31 ± 0.15	11.49 ± 1.31	312.39 ± 33.24	95.28 ± 10.15	39.05 ± 4.07
TE-1997	131	2.32 ± 0.24	0.57 ± 0.12	9.13 ± 1.04	275.12 ± 29.32	91.59 ± 9.80	41.30 ± 4.34
TE-May2000	15	3.17 ± 0.38	0.92 ± 0.14	17.61 ± 2.62	477.58 ± 60.02	142.05 ± 16.83	53.72 ± 7.02
TE-Aug2000	17	3.32 ± 0.39	1.24 ± 0.16	28.16 ± 4.32	436.13 ± 51.50	150.56 ± 17.95	44.94 ± 5.62
TE-Dec2001	18	2.23 ± 0.27	1.54 ± 0.21	10.91 ± 1.40	260.65 ± 31.68	89.74 ± 10.79	36.62 ± 4.13
TE-TC	24	3.84 ± 0.41	0.78 ± 0.12	18.60 ± 1.44	508.55 ± 54.45	174.51 ± 18.68	72.37 ± 7.09

Sample set	*n*	$IRM_{soft\%}$	$IRM_{hard\%}$	χ_{arm}/χ_{lf}	$SIRM/\chi_{lf}$	$SIRM/\chi_{arm}$	*S* ratio
River Earn	17	24.81 ± 2.60	11.59 ± 1.23	3.75 ± 0.47	188.77 ± 19.71	57.31 ± 6.53	42.23 ± 4.64
River Tay	18	40.45 ± 4.32	9.25 ± 1.03	6.66 ± 0.96	123.05 ± 13.29	39.02 ± 5.36	65.10 ± 6.94
Angus coast	19	28.14 ± 2.89	17.8 ± 1.94	2.96 ± 0.35	155.73 ± 16.65	67.66 ± 9.31	43.58 ± 4.52
Fife coast	18	30.88 ± 3.23	16.21 ± 1.73	3.43 ± 0.42	122.96 ± 13.14	40.66 ± 4.82	47.14 ± 4.99
TE-1972	226	30.39 ± 3.06	13.32 ± 1.36	4.30 ± 0.46	127.48 ± 13.00	35.26 ± 3.67	49.33 ± 5.01
TE-1997	131	33.24 ± 3.41	15.79 ± 1.65	3.83 ± 0.41	117.75 ± 12.11	33.56 ± 3.49	49.22 ± 5.03
TE-May2000	15	31.45 ± 3.41	11.48 ± 1.34	5.14 ± 0.69	146.46 ± 16.07	34.85 ± 4.18	51.81 ± 5.60
TE-Aug2000	17	34.52 ± 3.62	10.63 ± 1.30	7.09 ± 0.97	131.03 ± 18.90	30.16 ± 4.27	55.51 ± 5.97
TE-Dec2001	18	34.58 ± 3.51	14.87 ± 1.61	4.68 ± 0.54	116. 76 ±12.25	27.72 ± 3.28	50.92 ± 5.39
TE-TC	24	34.32 ± 3.46	14.34 ± 1.50	4.72 ± 0.53	132.89 ± 13.51	30.15 ± 3.34	51.17 ± 5.23

*Units: χ_{lf} 10^{-7} m^3 kg^{-1}, $\chi_{fd\%}$ %, χ_{arm} 10^{-7} m^3 kg^{-1}, *SIRM* 10^{-5} A m^2 kg^{-1}, IRM_{soft} 10^{-5} A m^2 kg^{-1}, IRM_{hard} 10^{-5} A m^2 kg^{-1}, $IRM_{soft\%}$ %, $IRM_{hard\%}$ %, χ_{arm}/χ_{lf} dimensionless, $SIRM/\chi_{lf}$ 10^2 A m^{-1}, $SIRM/\chi_{arm}$ 10^2 A m^{-1}, *S* ratio %.

values that tend to be intermediate between those of the fluvial and coastal end-members (e.g. χ_{lf} and χ_{arm}). However, this trend is less distinct for parameters such as $\chi_{fd\%}$ and *SIRM* (Table 1).

Parameter ratios are useful for sample discrimination of sediments with mixed provenance as they remove the masking effects of concentration of magnetic minerals on bulk sediment magnetic properties, allowing evaluation of other controls such as mineral type and grain sizes of ferrimagnetic components (Lees, 1999). The River Earn and River Tay sources appear to be discriminated by the six ratios presented (Table 1). However, the Angus coast and Fife coast end-members are generally less well discriminated by parameter ratios, the most effective in this respect being $IRM_{hard\%}$, $SIRM/\chi_{lf}$ and $SIRM/\chi_{arm}$.

The statistical significance of the distribution of magnetic values of the suite of samples belonging to the end member sets was evaluated using the Student's *t*-test and Levene's test of equality of variance for six pairs of sources. Due to the fact that the magnetic data show some departure from the assumptions of a parametric test, i.e. normality (typically positive skewness) and equality of variances, differences in means were also evaluated using a non-parametric technique (cf. Collins *et al.*, 2001). Both parametric and non-parametric differences in means tests reveal statistically significant differences in the concentrations and types of magnetic minerals that permit discrimination between the sediments belonging to the four sources (Jenkins, 2003). A basis is therefore deemed to exist for the unmixing of the bed sediments of the Tay Estuary. One of the assumptions of fingerprinting studies is that a tracer property does not undergo post-depositional transformation. There is no evidence to suggest that this has affected the estuarine bed sediments and so unmixing is potentially feasible. Analysis of samples from the TE-1997, TE-May2000 and TE-Aug2000 sets showed that neither mean particle size, nor the percentage of material in a specific particle size fraction, controls ferrimagnetic concentration. However, variation of magnetic properties with particle size is observed for the sediments of all four sources. The ferrimagnetic mode of the River Tay sediments resides in the 0.0–0.5 ϕ (coarse sand) fraction, whereas that for the River Earn samples is less pronounced and occurs in the 2.5 to 3.5 ϕ (fine to very fine sand) fraction. The mode for both coastal sample sets lies in the 3.0–4.0 ϕ (very fine sand) fraction, and is characterized by values of concentration-dependent parameters up to two orders of magnitude higher than those of coarser fractions. The degree to which this particle size control adversely affects the accuracy of the unmixing model (see below) is difficult to assess and will be explored in detail in a subsequent paper.

MODELLING OF SOURCE CONTRIBUTIONS TO ESTUARINE BED SEDIMENTS

As a preliminary to quantifying source contributions to the bed sediments of the Tay Estuary, it was necessary to identify those magnetic properties suitable for use in the numerical unmixing procedure. The values of $\chi_{fd\%}$ were consistently low for source and estuarine samples and, as a result of measurement error associated with low values, this parameter was excluded from magnetic fingerprinting. The linear additivity of the remaining 11 magnetic properties was tested experimentally, using mixtures containing known proportions of sediment from the four sources, to select those most suitable for use in an unmixing procedure. Five properties display acceptable linear additivity: χ_{lf}, *SIRM*, IRM_{soft}, $IRM_{soft\%}$ and *S* ratio.

The feasibility of unmixing estuary bed sediments on the basis of a composite signature composed of these five properties was assessed using simultaneous R- and Q-mode factor analysis, and multivariate discriminant analysis (MDA). The former was used to reveal underlying trends in the dataset, whilst the latter showed that further elimination of any of these five properties is detrimental to the correct classification of samples from each of the end-members. While the River Tay and River Earn sources are well discriminated, limited data dimensionality meant that separation of the Angus and Fife coastal samples was less successful. Source contributions were estimated by inputting the data into a multivariate unmixing model based on constrained linear programming (Rowan *et al*., 2000). Two methods of unmixing were adopted: (a) the "traditional" approach used in previous studies (e.g. Jenkins *et al*., 2002) whereby raw or standardized magnetic values were entered into the model, and (b) a novel approach whereby discriminant scores obtained from MDA were used. Model validation confirmed the inability of both approaches to discriminate between the two marine sources and consequently these were amalgamated to form one source group.

The results of the unmixing procedure indicate that the bed sediments of the Tay Estuary are predominantly derived from the marine environment, with a combined contribution of 78 ± 10% attributed to the Angus and Fife coastal sources. Of the 22 ± 10% contribution attributed to fluvial sources, 18 ± 10% is delivered by the River Tay and 4 ± 10% by the River Earn (Fig. 1).

DISCUSSION AND CONCLUSIONS

The above source contribution estimates mask considerable spatial variability both along the estuarine reach and in terms of sub-environments (cf. Jenkins *et al.*, 2002). Nevertheless, the bulk values represent one of the first attempts to quantify the sediment budget of a UK estuary using magnetic fingerprinting. It has previously been suggested (Buller *et al*., 1975) that the River Earn, despite its much smaller discharge, is the dominant source of bed load to the Tay Estuary. The results of the unmixing model suggest that this is not the case and that the dominant fluvial contribution (18 ± 10% of the total estuarine sediment budget, 82 ± 10% of the total fluvial sediment contribution) is derived from the River Tay. This should be considered in the context that the sediment is supplied by Britain's largest river in terms of discharge. This scenario of infilling by dominantly marine-derived sands is consistent with observations by other workers of the sedimentological regimes operating in many temperate estuaries accompanying post-glacial sea level rise (e.g. Dyer, 1986; Anthony, 2000). Furthermore, the findings support the observations of shell fragment migration (Al-Dabbas & McManus, 1987) and bedform asymmetry (Duck *et al*., 2001) in the Tay Estuary.

The magnetic properties of estuarine batch TE-TC suggest that temporal variation of source contributions is significantly smaller than the spatial variation observed across the samples of the other estuarine batches. This finding provides confidence that the spatial trends in bed sediment provenance display temporal constancy. It also validates the decision to combine magnetic data from samples collected during differing sampling phases. The envelope value of approx. ±10% determined by testing the unmixing model is based exclusively on the results of the experiment with controlled mixtures and does not necessarily include uncertainty arising from source variability or the effects of selective transport and erosion. Inaccuracies of the modelling procedure are likely to be caused by departures of the magnetic properties from linear additivity, this in turn resulting from source inhomogeneity and interaction effects within estuarine sediments. Other causes may arise more directly from the optimization procedure used, such as the problem of equifinality (Beven, 1996; Rowan *et al*., 2000).

REFERENCES

Al-Dabbas, M. A. M. & McManus, J. (1987) Shell fragments as indicators of bed sediment transport in the Tay Estuary. *Proc. Roy. Soc. Edin.* **92B**, 335–344.

Anthony, E. J. (2000) Marine sand supply and Holocene coastal sedimentation in northern France between the Somme estuary and Belgium. *Geol. Soc. Spec. Publ.* **175**, 87–97.

Beven, K. J. (1996) Equifinality and uncertainty in geomorphological modelling. In: *The Scientific Nature of Geomorphology* (ed. by B. L. Rhoads & C. E. Thorn), 289–313. John Wiley & Sons, Chichester, UK.

Buller, A. T., McManus, J. & Williams, D. J. A. (1971) Investigations in the estuarine environments of the Tay. Tay Estuary Research Centre (TERC), Report 1, University of Dundee, UK.

Buller, A. T., Green, C. D. & McManus, J. (1975) Dynamics and sedimentation: the Tay in comparison with other estuaries. In: *Nearshore Sediment Dynamics and Sedimentation* (ed. by J. Hails & A. Carr), 201–249. John Wiley & Sons, Chichester, UK.

Collins, A. L., Walling, D. E., Sichingabula, H. M. & Leeks, G. J. L. (2001) Suspended sediment source fingerprinting in a small tropical catchment and some management implications. *Appl. Geogr.* **21**, 387–412.

Duck, R. W. & Wewetzer, S. F. K. (2000) Relationship between current measurements and sonographs of subtidal bedforms in the macrotidal Tay Estuary, Scotland. *Geol. Soc. Spec. Publ.* **175**, 31–41.

Duck, R. W., Rowan, J. S., Jenkins, P. A. & Youngs, I. (2001) A multi-method study of bedload provenance and transport pathways in an estuarine channel. *Phys. Chem. Earth (B)* **26**, 747–752.

Dyer, K. R. (1986) *Coastal and Estuarine Sediment Dynamics*. John Wiley & Sons, Chichester, UK.

Foster, I. D. L. & Lees, J. A. (2000) Tracers in geomorphology: theory and applications in tracing fine particulate sediments. In: *Tracers in Geomorphology* (ed. by I. D. L. Foster), 3–20. John Wiley & Sons, Chichester, UK.

Jenkins, P. A. (2003) Fingerprinting of bed sediments in the Tay Estuary, Scotland: an environmental magnetism approach. PhD Thesis, University of Dundee, UK.

Jenkins, P. A., Duck, R. W., Rowan, J. S. & Walden, J. (2002) Fingerprinting of bed sediment in the Tay Estuary, Scotland: an environmental magnetism approach. *Hydrol. Earth System Sci.* **6**, 1007–1016.

Lees, J. A. (1999) Evaluating magnetic parameters for use in source identification, classification and modelling of natural environmental materials. In: *Environmental Magnetism: A Practical Guide* (ed. by J. Walden, F. Oldfield & J. Smith), 113–138. Technical Guide 6, Quaternary Research Association, London, UK.

McManus, J. (1986) Land-derived sediment and solute transport to the Forth and Tay estuaries, Scotland. *J. Geol. Soc.* **143**, 927–934.

McManus, J. & Wal, A. (1996) Sediment accumulation mechanics on the Tentsmuir coast. In: *Fragile Environments* (ed. by G. Whittington), 1–15. Scottish Cultural Press, Dalkeith, UK.

Rowan, J. S., Goodwill, P. & Franks, S. W. (2000) Uncertainty estimation in fingerprinting suspended sediment sources. In: *Tracers in Geomorphology* (ed. by I. D. L. Foster), 279–289. John Wiley & Sons, Chichester, UK.

Yu, L. & Oldfield, F. (1989) A multivariate mixing model for identifying sediment source from magnetic measurements. *Quatern. Res*. **32**, 168–181.