An evaluation of the qualitative and quantitative approaches used in determining the provenance of the sediment in the River Eden catchment, Scotland

E. Martínez Monasterio

Dpto. de Geología, Facultad de Ciencias del Mar, Universidad de Cádiz, 11510 Puerto Real, Cádiz.

ABSTRACT

Magnetite composition and magnetic measurements are found to be suitable provenance indicators in the River Eden catchment (eastern Scotland). The combined use of chemical and magnetic data lead to a better characterisation and differentiation of sources and sediment samples which set up the basis for sedimentary provenance modelling. Discriminant function analysis of magnetite composition and magnetic measurements provide an environmentally-consistent qualitative provenance model. The sediment transported by each Eden tributary is found to be mineralogically unique as a result not only of mineralogical differences but also of the mixing proportions of the constituting sources. Tributary inputs are recognised downstream the River Eden course in spite of the sediment characteristics in the main course tending to be homogenised during transport. Magnetic parameters are more discriminating than magnetite composition. However, the intra-source magnetic variability and principally the magnetic interdependence of the sediment sources significantly hinder successful modelling of mixtures using linear programming methodology.

RESUMEN

La composición química de la magnetita y los parámetros magnéticos son utilizados con éxito como indicadores de procedencia sedimentaria en la cuenca hidrográfica del Río Eden (Escocia). La utilización combinada de los datos químicos y magnéticos conduce a una caracterización y por tanto a una diferenciación más precisas de los materiales fuente y de los sedimentos, constituyendo las bases para la modelización de la procendencia de los sedimentos. El análisis discriminante de la composición química de la magnetite y de los parámetros magnéticos proporciona un modelo de procedencia sedimentaria consistente en el encuadre medioambiental. El sedimento transportado por cada afluente del Río Eden es mineralógicamente único como resultado de las differencias mineralógicas y de las proporciones en que se mezclan los materiales fuente que lo constituyen. La aportación de los afluentes a lo largo del curso principal del Río Eden es detectada, a pesar de la tendencia de las características del sedimento a homogeneizarse durante su transporte. Los parámetros magnéticos son más discriminantes que la composición química de la magnetita. Sin embargo, la intra-variabilidad magnética y, sobre todo, la interdependencia de las propiedades magnéticas de los materiales fuente imposibilitan la modelización cuantitativa de la procedencia de los sedimentos mediante el uso de métodos de programación lineal.

Key words: *magnetite, magnetic measurements, discriminant function analysis, linear programming, sedimentary provenance*

Geogaceta, 27 (1999), 103-106
ISSN: 0213683X

Introduction

The potential of the Fe-Ti oxide minerals (mainly magnetite, hematite and ilmenite) as provenance indicators has been proven by numerous authors (e.g. Basu and Molinaroli 1989 and 1991; Grigsby 1990 and 1992; Yu and Oldfield 1989 and 1993). The purpose of this paper is to evaluate the combined used of both geochemical and magnetic techniques to sedimentary provenance when using Fe-Ti oxides as provenance indicators. The multivariate statistical analyses (mainly discriminant function analysis) used to model quantitatively sediment provenance on the basis of the Fe-Ti oxide compositional and textural characteristics (e.g. Grigsby, 1990), and the linear programming technique commonly used when modelling magnetic measurements (e.g. Walden *et al.*, 1997) are used in this study in order to determine the provenance and dispersal of the sediment in the River Eden catchment (eastern Scotland) (Fig. 1). In this area the northern, upland part is dominated by Lower Devonian andesitic rocks (basaltic andesites, andesites and dacite-rhyolites). The southern part of the catchment is constituted by a Permo-Carboniferous dolerite sill and Lower Carboniferous sedimentary deposits (sandstone and limestone). The central valley, through which the main channel of the River Eden flows, is underlain by Upper Devonian sandstones. All these bedrock types are variably covered by Quaternary deposits which are dominantly of glacial origin (mainly till), but these deposits are best developed in the topographically lower areas of the

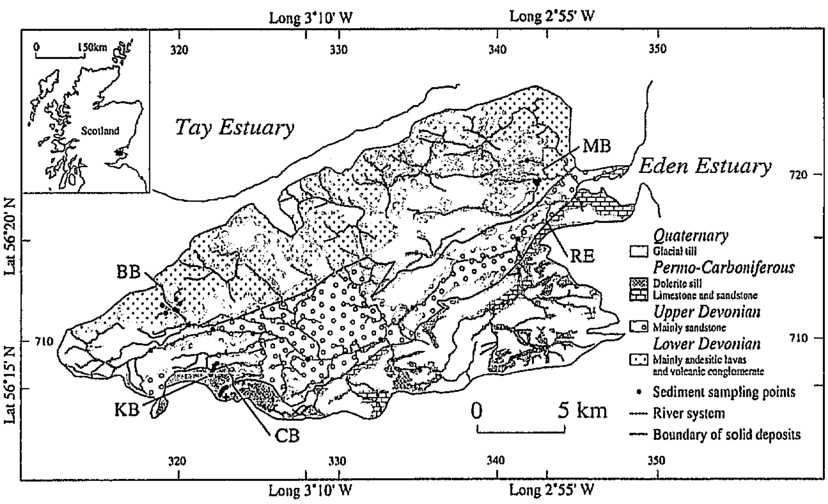


Figure 1. Simplified geological map of the River Eden catchment showing: the 3 main rock units, the Quaternary deposits distribution, the River Eden course, and the sampling points of sediment samples. BB: Barroway Burn, MB: Moonzie Burn, KB: Kilgour Burn, CB: Coalpit Burn, RE: River Eden.

Figura 1.Mapa geológico simplificado de la cuenca del río Eden mostrando las tres principales unidades litológicas, la distribución de los depósitos cuaternarios, el curso fluvial y los puntos de toma de muestras de sedimentos.

catchment. The main channel of the River Eden flows along the central valley of the catchment, being fed by northern tributaries which flow over Lower Devonian andesitic rocks, and southern tributaries which flow mainly over Carboniferous dolerites and sedimentary deposits (Fig. 1). The sources of the sediments transported by the northern and the southern tributaries are then known *a priori* to be different. This fact allows to test the potential of the geochemical and magnetic data, and will assist in the setting up of the basis for quantitative statistical modelling.

Methodology

Sampling. A total of 6 dolerite samples, 15 andesitic rocks samples, 3 sedimentary rocks samples and 3 glacial till samples were collected in the River Eden catchment. Bedload sediment samples were collected along two northern tributaries (7 samples from the Barroway Burn and 4 samples from the Moonzie Burn), two southern tributaries (6 samples from the Kilgour Burn and 8 samples from the Coalpit Burn), and the main channel of the River Eden (6 samples) (Fig. 1).

Geochemical measurements. The chemical and textural analyses of the Fe-Ti oxides were carried out using a JEOL JCXA-733 Superprobe. Accelerating voltage of the instrument was 15 kV and the beam current on the Faraday cup was 20 nA. Seven elements (Si, Ti, Al, Fe, Mn, Mg, Ca) were analysed, and reported as oxide concentrations, on approximately 40 mineral grains from each sample. Total Fe was analysed as FeO and recalculated to weight percent Fe_2O_3 and FeO following the procedure of Droop (1987).

Magnetic measurements. Cores (10 cm^3) of rock samples were prepared. Glacial till and sediment samples were packed into 10 cm^3 plastic pots. Magnetic susceptibility χ was then measured at both low (0.47 kHz) and high (4.7 kHz) frequencies using a Bartington MS2B meter. Samples were exposed to a weak, steady magnetic field (0.04 mT) superimposed on a stronger alternating field (98 mT) applied by a Molspin AC field magnetiser. The anhysteretic remanent magnetisation (ARM) acquired, and the isothermal remanent magnetisation (IRM) acquired by the samples after exposure to forward and then backward magnetic fields of increasing intensity from 20 mT up to 1 T generated by a Molspin pulse magnetiser, were measured by a Molspin Fluxgate magnetometer. The magnetic parameters and ratios derived from these measurements allow the characterisation of the rock and sediment samples in terms of the relative concentrations and grain sizes of the magnetic minerals they contain, as described in Thompson and Oldfield (1986).

Characterisation of sources in the River Eden catchment

A preliminary X-ray diffractometry study and the magnetic measurements determine the presence of Fe-Ti oxides (mainly magnetite and ilmenite) in all igneous rocks and in the glacial till, and their absence or scarcity in the sedimentary rocks. Electron probe microanalysis shows that ilmenite is compositionally homogeneous in all source samples, whereas magnetite presents a wide compositional range within and between samples. However, a simultaneous R- and Q-mode factor analysis of magnetite composition (Fig. 2A) of rock samples shows that there is not a clear differentiation of the rock groups with respect to their magnetite chemistry. On the other hand, magnetic measurements (Figure 2B) suggest an increase in relative proportion of hematite to magnetite together with a magnetite grain size decrease from the dolerite samples towards the more acid andesitic rock samples. Sandstones are dominated by magnetite but both its concentration and grain size are smaller than in the igneous rocks. Glacial till samples are constituted by mixtures of magnetite and hematite showing a wide compositional variability suggesting diverse provenance as expected in such a sedimentary deposit. Thus the sources in the River Eden catchment may be discriminated on the basis of the concentration, composition and grain size of the magnetite constituting them, although such discrimination is difficult as the variability between rock groups is found to be small.

Characterisation of sediments in the River Eden catchment.

Both chemical (Fig. 3A) and magnetic (Fig. 3B) analyses point to the homogeneity in terms of magnetic mineralogy (magnetite and hematite) within each of the tributary sediments of the River Eden. At the same time all streams can be distinguished as independent units. The sediment samples from the northern tributaries (Barroway Burn and Moonzie Burn) present a lower concentration of magnetic minerals, with a greater relative concentration of hematite to magnetite, and smaller and Ti-poorer magnetite than the sediment samples from the southern tributaries (Kilgour Burn and Coalpit Burn). Furthermore, the Barroway Burn sediments show greater hematite concentrations relative to magnetite,

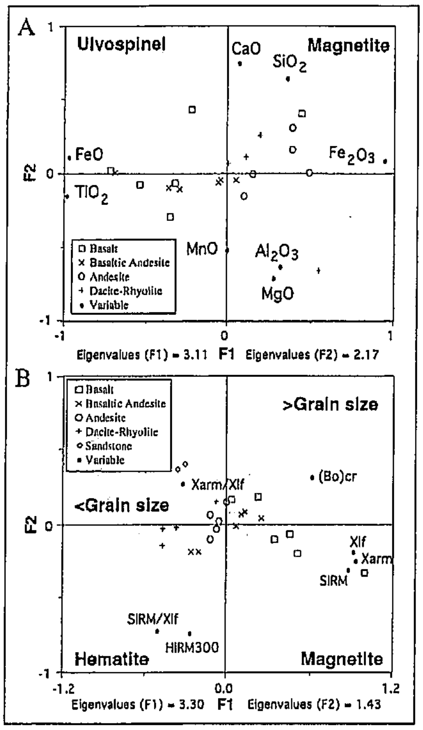
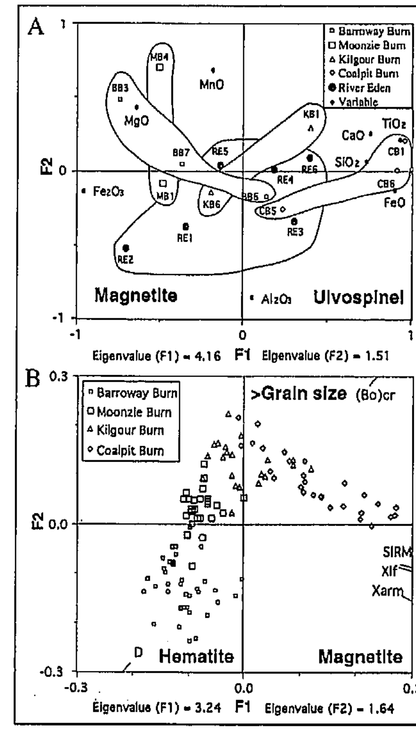


Figure 2. Simultaneous R- and Q-mode factor analysis of: A. The mean composition of all grains of magnetite analysed in each igneous rock sampled in the Eden catchment (Factors 1 and 2 explain 66% of the 8 original variables; B. The main magnetic parameters measured in both igneous and sedimentary rocks sampled in the Eden catchment (Factors 1 and 2 explain 67% of the 7 original variables).

Figura 2. Análisis factorial modo R y Q simultáneo de A: la composición media de todos los granos de magnetita analizados en cada muestra de roca ígnea muestreada en la cuenca del río Eden (Factores 1 y 2 explican el 66% de las 8 variables originales) B: los principales parámetros magnéticos medidos en las rocas ígneas y sedimentaarias muestreadas (Factors 1 y 2 explican el 67% de las variables originales)

Figure 3. Simultaneous R- and Q-mode factor analysis of: A. The mean composition of all grains of magnetite analysed from the stream sediments sampled in the Eden catchment (Factors 1 and 2 explain 71% of the 8 original variables); B. The main magnetic parameters measured in all stream sediments (Factors 1 and 2 explain 98% of the 5 original variables) χ_{lf}: Magnetic susceptibility, χ_{ARM}: Susceptibility of anhysteretic remanent magnetisation, SIRM: Saturation isothermal remanent magnetisation, $(Bo)_{CR}$: Coercivity of remanence, D: Demagnetisation parameter ($=IRM_{-40}/IRM_{300}$).

Figura 3. Análisis factorial modo R y Q simultáneo de A: la composición media de todos los granos de magnetita muestreados en la cuenca del río Eden (Factores 1 y 2 explican el 98% de las 5 variables originales)(1r: susceptibilidad magnética)(ARM: susceptibilidad de magnetización remanente antihistérica. SIRM: Magnetización remanente) parámetro de magnetización



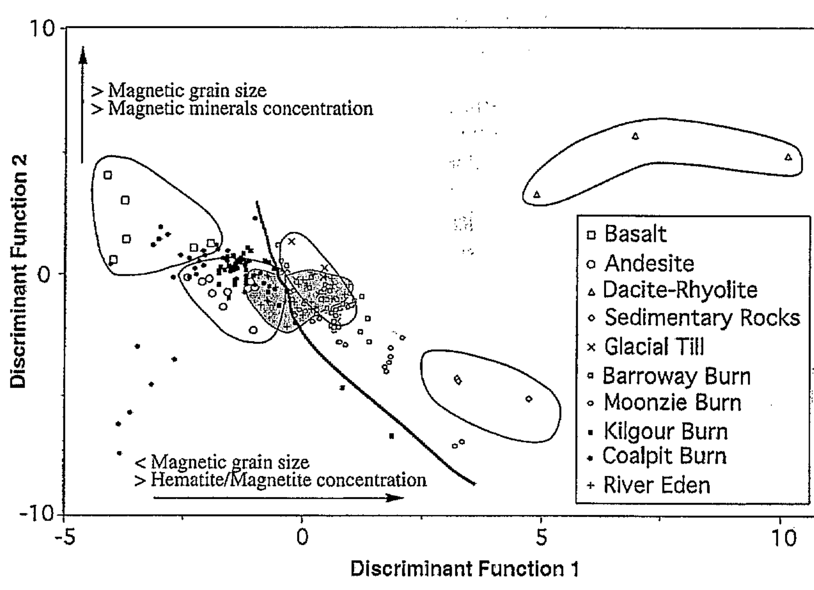


Figure 4. Plot of discriminant Function 1 versus discriminant Function 2 separating samples from five potential sources of stream sediments distinguished in the River Eden catchment (both Functions contain a total of 83% of the information available for separating the 5 source groups). Stream sediment samples are also included in order to see their relationship with the sources. Boundaries for rocks and glacial till groups, as well as for the River Eden sediments (shaded field), are fitted by eye. A line is also drawn which separates 'andesitic' from 'doleritic' stream sediment samples.

Figura 4. Representación de la función discriminante 1 versus Función discriminante 2 separando muestras de cinco áreas potenciales de sedimento de la cuenca del río Eden (ambas funciones contienen el 83% de información disponible para separar los cinco grupos de origen). Los sedimentos fluviales se han incluido para ver interrelaciones entre orígenes, los límites para grupos de rocas y tillitas glaciares y para sedimentos del río Eden (sombreado) se han ajustado visualmente. Se ha dibujado una línea para separar muestras de sedimentos "andesíticos y doleríticos"

smaller grain size and higher Ti-content in magnetite than the Moonzie Burn sediments; and the Kilgour Burn sediments have relatively higher hematite concentrations than the Coalpit Burn sediments, but with similar magnetite composition and grain size. The River Eden sediments show a greater magnetic variability with chemical and magnetic characteristics overlapping those of the tributary streams suggesting a close mineral relationship between the River Eden and its tributaries.

These results indicate that it is possible to discriminate sediments derived from different materials as well as those from a similar source on the basis of their magnetic mineral concentration, assemblages, chemical composition and grain size.

Modelling

Discriminant function analysis provides a good qualitative sedimentary provenance model by establishing the spatial relationships between the sources and the sediment samples. In addition, linear programming (as defined by Walden *et al.*, 1997) is used to estimate quantitatively the relative proportions of the source materials comprising the sediment samples.

Results from the discriminant analysis (Figure 4) suggest that the sediment of the northern Eden tributaries is mainly composed of andesite and glacial till, whilst sediment from the southern tributaries is mainly derived from dolerite and sedimentary rocks. Differences in the sediment transported by streams flowing over similar materials (rocks and till) are due to variations in the relative contribution of the sources. Thus, the Barroway Burn sediment shows a greater contribution from the glacial till than the Moonzie Burn sediment. Similarly, the Kilgour Burn sediment shows a greater contribution from sedimentary rocks than the Coalpit Burn sediment. On the other hand, all sediment samples from the main course of the River Eden show similar characteristics, suggesting a tendency of the mixing fluvial process to homogenise the mineral assemblage. Nevertheless, downstream variation in the tributary supply is detected. All these results set up the basis for linear programming modelling as it highlights the greater discriminant power of the magnetic measurements over the magnetite composition, and also that all sediment sources have been identified, being classified as dolerites, andesites, sedimentary rocks and glacial till. All these sources are clearly differentiated on the basis of their magnetic characteristics, however, their proximity within the discriminant space makes the model interpretation difficult, the detailed information resulting from the interpretation of the analytical data being necessary.

The suitability of linear programming to quantitatively unmix the stream sediments of the River Eden catchment is found to be limited. Results were found to be crude estimates of sediment provenance as significant errors were detected. Neither the use of magnetite composition nor the combination of both magnetic measurements and magnetite chemistry improved the results. Thus, the use of the linear programming model did not provide much more useful information than was obtained using discriminant function. A quantitative estimate of sediment provenance fails, due principally to the interrelationship of the source magnetic characteristics.

Conclusions

1. Discriminant function analysis applied to both geochemical and magnetic data leads to a good qualitative model of the provenance of stream sediments in the catchment. The four main sediment sources (basalts, andesites, glacial till and sedimentary rocks) in the River Eden catchment are identified and their relative contribution to the sediment approximately estimated.

2. Limited success is achieved in the quantitative modelling of sediment provenance when using linear programming, mainly as a consequence of the small compositional contrast between magnetite grains derived from different parent rocks, and the interdependence existing between the magnetic parameters.

Acknowledgements

Special thanks go to Dr. W.E.Stephens, Dr. R.W. Duck and Dr. J. Walden for their supervision, and to Dr. L. Barbero for the oral presentation of this paper. Thanks are extended to A. Calder, D. Herd and A. Mackie for their technical assistance. This research was funded by a grant from the program 'Programa de Formación de Investigadores del Departamento de Educación, Universidades e Investigación' from the Basque Government, which is gratefully acknowledged.

References

Basu, A. and Molinaroli, E. (1989): *J. Sed. Petrol.*, 59: 922-934.

Basu, A. and Molinaroli, E. (1991): *Spec. Publ. Geol. Soc. Lond.*, 57, 56-65.

Droop, G.T.R. (1987): *Mineral. Mag.*, 51: 431-435.

Grigsby, J.D. (1990): *J. Sed. Petrol.*, 60: 940-951.

Grigsby, J.D. (1992): *J. Sed. Petrol.*, 62: 331-337.

Thompson, R. and Oldfield, F. (1986): *Environmental Magnetism.* Allen and Unwin, London, 227 pp.

Walden, J., Slattery, M.C. and Burt, T.P. (1997): *J. Hydrol.*, 202: 353-372.

Yu, L. and Oldfield, F. (1989): *Quater. Res.*, 32: 168-181.

Yu, L. and Oldfield, F. (1993): *Earth Surf. Proc. Land.*, 18: 441-454.