The Application of Environmental Magnetism to Sediment Source Tracing: A New Approach

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Acknowledgements

This work originated from discussions with Andrew Murray and Bob Wasson about how sediment tracers should be tested, and also from the suggestion by Andrew Murray that differences between lithogenic radionuclide ratios could be used to determine the relative contributions of sediment at stream junctions. I thank Andrew and Bob for their early encouragement to continue with the study of using magnetic minerals to trace sediment.

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Abstract

A new approach to sediment tracing using natural mineral magnetism has been developed to determine relative sediment contributions at stream junctions. This method is developed on the basis that well mixed assemblages of magnetic minerals exist in sediment that is delivered to a stream junction, and that relative tributary contributions can be determined at confluences where the magnetic properties of the sediments are distinguishable. The method uses linear relationships between two mineral magnetic parameters to calculate relative tributary contributions to the resultant binary mix in the reach downstream of the confluence. The dominant sediment source catchments may thus be identified by a sequence of confluence measurements along a drainage network. The requirements of this technique are that the tributaries and the downstream reach have constant average magnetic parameter relationships (i.e. the sediments are well mixed) over an appropriate period. This is possible because sediment transport mechanisms have an averaging effect as sediment is delivered first to a stream channel, and then transported within the channel. A simple model was developed to explain how random mixing of fluvial sediment can generate linear magnetic parameter relationships, and how mixing of linear relationships occurs at confluences. The study empirically examines the spatial and temporal constancy of the magnetic mineral component of fluvial sediments using mineral magnetic parameters. Spatial and temporal constancy is important because without it spurious estimates of source contributions can occur because the magnetic properties of sediment are altered in some way between the sources and the sediment sink. Also tested in this study is how representative the magnetic mineral fraction is of sediment as a whole. The binary combination of sediment at a confluence is the simplest possible mixing situation, requiring a relatively simple calculation to determine proportionate contributions along with statistical uncertainties. The tracing method is not affected by the enrichment or dilution of the magnetic mineral component (i.e. concentration changes), with a noted exception of fine suspended sediment transported over large distances. In such circumstances the method cannot be applied. Homogenization processes that occur during sediment transport ensure that representative sampling along river reaches is not difficult. The method is applicable at any scale where two distinguishable sources of sediment exist, including stream junctions, or any location in a drainage basin where sediment is transported.
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CHAPTER 1
INTRODUCTION

Determining the sources of sediment has been the subject of many studies for a variety of reasons. Most interest has centred on the record of environmental change that can be derived from accumulated lake and marine sediment. The sources of sediment associated nutrients and contaminants is also receiving greater attention. The link between erosion and sediment sources is relevant to remedial soil conservation, as well as sediment accumulation problems causing flooding from rivers, and a loss of capacity in water storages.

Sediment sourcing methods include active tracing where a traceable substance is deliberately introduced into the sediment stream, as well as various soil loss and sediment movement models. An inherent difficulty that tracing methods must overcome is the complexity of sediment transport processes. In a spatial context, there may be many intermediate storages between the original point of soil erosion, and the delivery of sediment to the bottom of a drainage basin. Sediment transit times will also vary from minutes to millennia. Making use of a conservative, natural substance that travels with the sediment has some obvious benefits. Direct links can be made between sources and sinks that are not affected by the complexities of sediment transport through space and time. Ideally, such a substance should be ubiquitous in soils and sediments. The tracer also has to be conservative, that is, remain unaltered between source and sink.

Despite the potential complexity, tracing studies have clearly demonstrated that sediment sinks may contain a valuable record of environmental change. However, in many drainage basins the lack of suitable sediment sinks, and the scale of the sediment sourcing problem requires a different approach. Provenance studies based on mineral tracing have been used over many years for mineral prospecting. The method consists of tracing a target mineral up a drainage network by a sequence of measurements at stream junctions. These become decision points at which relative abundance is used to follow the mineral stream to its source. In principal this approach can be used to trace sediment by measuring the relative abundance of a component that is well mixed, and likely to be representative of the bulk of sediment.
Magnetic minerals are ubiquitous in soils, and the sediments derived from them. Measurement of magnetic properties is rapid, inexpensive (provided the equipment is available), and non-destructive, so in principle measuring the magnetic properties of sediment should prove to be a useful method for tracing sediment in fluvial environments. This is the subject of this report.

Mineral magnetic properties have been used for sediment tracing in several previous multi-parameter studies, discussed in the next chapter. However, these have suffered from a number of significant deficiencies including a lack of testing that magnetic properties are conserved within the spatial and temporal scales appropriate to the studies, concentration changes associated with sediment transport, a lack of knowledge about how representative the magnetic fraction is of sediment as a whole, and with the exception of one study discussed in the next chapter, no attempt to determine statistical uncertainties associated with source contribution calculations, and no formal way of measuring the spatial heterogeneity of sources. A study discussed in Chapter 2 has also highlighted the problem of statistically ‘unmixing’ more than four sources, and the masking of magnetically weak sources by stronger ones. There are also a range of linear modelling approaches used for determining source contributions, but as yet there is no consensus about, or evaluation of which is the most appropriate. Given the general lack of information published about the linear modelling algorithms used, there may well be undocumented sources of uncertainty contributing to erroneous outcomes.

These problems have highlighted the need for a simpler, more transparent approach to sediment tracing using mineral magnetism. In this report a new method of determining relative source contributions from two component mixes is presented that makes use of the natural sediment mixing processes in streams to integrate the potentially large number of sources in a catchment. This new approach is developed on the assumption that well mixed assemblages of magnetic minerals exist in sediment that is delivered to a stream junction, and that relative tributary contributions can be determined at confluences where the magnetic properties of the sediments are distinguishable. The innovation of this approach is that only two representative magnetic properties need to be measured, and no interpretation of the data are required to determine what magnetic mineral assemblages are present in the sediment. Also the
binary combination of sediment at a confluence is the simplest possible mixing situation, requiring relatively simple calculations to determine proportionate contributions. This approach is not affected by the enrichment or dilution of the magnetic mineral component (i.e. concentration changes), and homogenization processes that occur during sediment transport ensure that representative sampling is not difficult. The method of calculating binary source contributions is simple compared to multi-parameter modelling approaches, and statistical uncertainties associated with the relative contribution calculations can also be determined.

An important consideration is that magnetic minerals are conserved within the spatial and temporal scales appropriate to tracing studies, otherwise spurious estimates of source contributions can occur because the magnetic properties of sediment are altered in some way between the sources and the sediment sampling site. Previously published tracing studies have assumed that the magnetic properties of sediment are conserved in fluvial environments. Spatial and temporal constancy is empirically tested in this study. Also tested is how representative the magnetic mineral component is of the sediment as a whole.

After a literate review and analysis of the methods used to apply environmental magnetism to sediment tracing (Chapter 2), the method of sediment tracing developed in this report is presented (Chapter 3). Prior to this empirical tests of spatial and temporal constancy are made. In Chapter 4 the contribution of various magnetic mineral fractions in sediment is examined, and conclusions drawn about how representative the magnetic mineral fraction is of sediment as a whole. Chapter 5 gives examples of the application of the method. In Chapter 6 the scope of the method is broadened to determining sediment sources at large drainage basin scale. A summary and conclusions are given in Chapter 7.
CHAPTER 2

ENVIRONMENTAL MAGNETISM AND SEDIMENT SOURCE TRACING

This chapter introduces the subject of environmental magnetism, particularly as it is applied in this report. First, a brief overview is given of what environmental magnetism is. Then the application of environmental magnetism to sediment tracing is discussed. The strengths and weaknesses of previous quantitative source mixing models are examined to highlight the need for a new approach to sediment tracing using environmental magnetism.

2.1 Environmental Magnetism

Iron oxide minerals are ubiquitous soils, and may account for over 50% of the soil minerals in some instances (Taylor et al., 1983). Magnetic forms of iron oxides are also common in soils, although they may be in low concentrations. Because magnetic minerals are believed to be environmentally sensitive, their magnetic properties have been used in a considerable number of environmental studies. Measurement of the magnetic mineral properties is rapid, non-destructive, and a sensitive way of characterizing magnetic mineral assemblages. Discriminating magnetic characteristics can be used to study environmental processes like tracing the sources of sediment in drainage basins.

The principal source of magnetic minerals in fluvial sediments is eroded soil particles. Pedogenic processes produce a variety of iron mineral types and forms, the combination of which may result in unique assemblages of magnetic minerals in soils, and the sediments derived from them. These often unique magnetic characteristics can be used to distinguish sediment from different sources.

Some of the basic aspects of environmental magnetism are discussed in this section. A great deal more detail can be found in Thompson's and Oldfield's (1986) definitive monograph.
2.1.1 Types Of Magnetic Behavior

All substances exhibit some degree of magnetic behavior associated with the motion of electrons. The nature of the magnetic behavior is determined by electron spin interactions, and the nature of electron spin alignment with an applied field. Diamagnetism is the most common magnetic response to an externally applied magnetic field. A very weak, negative magnetization occurs that is lost as soon as the external field is removed. Paramagnetism is another weak form of magnetic behavior. In an applied magnetic field paramagnetic substances acquire a weak, positive magnetization that is also lost upon removal of the field. Many iron minerals are paramagnetic. This is discussed further in the next section.

The most important forms of magnetic behavior as far as environmental magnetism studies are concerned involve iron minerals that are capable of retaining magnetizations in the absence of applied magnetic fields (i.e. remanent magnetization or remanence). One of these forms, known as ferrimagnetism, includes iron oxides which have magnetic moments that are positively aligned in the presence of an applied field. Spontaneous magnetization arises from the parallel alignment of magnetic moments in neighboring atoms. The forces produced are significantly greater than those found in diamagnetic and paramagnetic substances, and one or two orders of magnitude greater than canted antiferromagnetism.

Anti-ferromagnetism occurs in iron oxides where the arrangement of the crystal structure results in self cancellation of parallel but opposite magnetic moments. The net effect is to cancel out any spontaneous magnetization, however, if the magnetic moments are not completely anti-parallel a weak magnetization can result. This is known as canted anti-ferromagnetism. A detailed discussion of the atomic basis of magnetism and the magnetization process is given in O’Reilly (1984).

The forms of magnetic behavior discussed above are modified by magnetic grain size, shape and structure. Magnetic grain size is an important and measurable attribute of ferrimagnetic minerals which tend to dominate magnetic assemblages by virtue of their considerably stronger magnetizations. The approximate magnetic grain size (distinct from sediment particle size) boundaries for magnetite, a common ferrimagnetic
mineral, are given in Figure 2.1a. In a large grain, the magnetostatic energy is minimized by subdivision of the grain into multiple domains (MD), which spontaneously magnetize in one direction. At a critical grain size, also determined by grain shape, only stable single domains (SSD) will be able to form. Since this boundary is not well defined, grains of intermediate properties are termed pseudo-single domain (PSD).

Figure 2.1 (a) Magnetic grain size boundaries. (b) IRM acquisition curve for a mixture of magnetite and haematite (Oldfield, 1987).

The lowest ferrimagnetic grain size threshold is determined by room temperature thermal vibrations of the same order of magnitude as the magnetic energies. These ultra-fine magnetic grains, known as super-paramagnetic (SP), are unable to maintain stable remanent magnetizations in the absence of an applied field due to thermal randomizing effects. Super-paramagnetic behavior is altered by temperature and grain interactions. This also applies to other grain sizes.

2.1.2 Magnetic Minerals

The types of magnetic behavior discussed above are associated with different types of minerals, and soils are the principal source of magnetic minerals found in fluvial sediments. Iron minerals are found in soils in several forms. These include fine discrete particles, iron oxides bound to the surfaces of soil particles, and concretions that may bind soil particles together. The formation of these secondary iron mineral forms is
controlled by pedogenic processes. Primary iron minerals are also ‘inherited’ in soil profiles from the weathering of parent rock. These minerals may occur as discrete heavy mineral particles, or as mineral inclusions within silt and sand sized particles.

Iron minerals, including oxides and sulfides, exhibit some form of magnetic behavior. The most magnetic types are ferrimagnetic minerals like magnetite and maghemite (including titanomagnetites and titanomaghemites), which are commonly found in low concentrations in soils, and the sediments derived from them. Magnetite is an accessory mineral in rocks of igneous origin and in many metamorphic and sedimentary rocks, but it also forms in soils (Maher & Talor, 1988). Maghemite is derived from soil forming processes, and may be prevalent in many soil types but in concentrations too low to be found by normal detection methods (Taylor, et al., 1983).

Common canted anti-ferromagnetic minerals include haematite and goethite. The former is common in soils of arid and tropical regions, while the latter occurs in most soil types (Taylor, et al., 1983). Lepidocrocite, which is paramagnetic, is less common than geothite, and tends to be associated with wetter soil environments. Ferrihydrite is another paramagnetic mineral, but it appears to be confined to very wet soil conditions.

The occurrence of iron sulfides like pyrite (paramagnetic), and greigite (ferrimagnetic) is confined to the reducing conditions found in lake and marine sediments. The latter is attributed to the diagenetic reduction of magnetite (King & Channell, 1991). These minerals are not likely to form in the mainly oxic, fluvial environments that are the focus of this study.

Even from this limited discussion of mineral types, and the previous discussion of types of magnetic behavior, it is evident that soils and sediments are likely to contain complex assemblages of iron minerals that have unique magnetic characteristics. However, it is not necessary to understand this complexity in order to trace sediment sources. All that is required is a means of measuring the overall magnetic characteristics in a discriminating way. In the next section different types of common magnetic measurement are presented, and their value for determining the overall magnetic characteristics of sediment properties is discussed.
2.1.3 Magnetic Measurements

Studies utilizing mineral magnetic properties are concerned with the measurement of magnetic characteristics affected by the concentration, grain size and shape of magnetic minerals. These characteristics are determined by applying artificial magnetic fields and measuring the response. Measurements may be either in-field or remanent, that is, measuring the magnetization remaining (remanence) after a field has been applied (Table 2.1). At low applied field strengths (~0.1 mT) the magnetization process is linear and reversible. This is the range in which mass specific magnetic susceptibility \((\chi)\) is measured in a weak alternating field (e.g. 0.5 kHz in a Bartington instrument). \(\chi\) is sensitive to both non-remanence and remanence holding substances. If another measurement is made at a higher frequency (5 kHz), then the difference between the two is the frequency dependent susceptibility \((\chi_{fd})\), which is normally expressed as a percentage. This parameter is particularly sensitive to grain sizes spanning the stable single domain-superparamagnetic boundary, sometimes referred to as fine-viscous because these grains show a degree of time-dependent loss of remanence.

Beyond the threshold of susceptibility measurements, magnetic substances magnetized in a direct field follow a magnetization acquisition curve (Fig. 2.1b) to a point of saturation. The magnetization that remains upon removal of the magnetizing field is known as isothermal remanent magnetization (IRM). IRMs are commonly imparted in a pulse magnetizer, and measured in some form of magnetometer (Thompson & Oldfield, 1986). Low field IRMs imparted in a field of about 20 mT are indicative of magnetically 'soft' ferrimagnetic grain sizes larger and smaller than magnetically 'harder' stable single domain (SSD) grains (Oldfield, 1991). Maher (1988) showed that synthetic magnetite spanning a range of grain sizes was saturated after being subjected to an applied field of 300 mT. Any further acquisition of remanence in a sample may therefore be attributed to an anti-ferromagnetic component (e.g. haematite). A remanence parameter independent of hysteresis effects is anhysteretic remanent magnetization (ARM), measured by subjecting a sample to an increasing, then decreasing alternating field in the presence of a weak steady field. King et al. (1982) showed that anhysteretic susceptibility (ARM normalized to the applied steady field) is sensitive to the presence of SSD and small PSD grains.
Table 2.1 Commonly measured magnetic parameters.

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<tr>
<th>Magnetic Parameter</th>
<th>Symbol</th>
<th>S.I. Unit</th>
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<tr>
<td>mass specific susceptibility</td>
<td>(\chi)</td>
<td>m(^3)/kg</td>
</tr>
<tr>
<td>frequency dependent susceptibility</td>
<td>(\chi_{fd})</td>
<td>m(^3)/kg (or %)</td>
</tr>
<tr>
<td>isothermal remanent magnetization</td>
<td>IRM</td>
<td>Am(^2)/kg</td>
</tr>
<tr>
<td>anhysteretic remanent magnetization</td>
<td>ARM</td>
<td>Am(^2)/kg</td>
</tr>
<tr>
<td>susceptibility of ARM</td>
<td>(\chi_{ARM})</td>
<td>m(^3)/kg</td>
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The approach to sediment tracing developed in this report requires that representative measurements are made of magnetic minerals in fluvial sediment. As discussed above, \(\chi_{fd}\) and ARM are useful for characterizing fine ferrimagnetic grain sizes, which means that they are not generally representative measures of magnetic mineral assemblages. Low field IRMs are also not generally representative of because they are mainly influenced by magnetically 'soft' ferrimagnetic grain sizes. Of the remanence measurements, this leaves IRMs imparted in fields greater than 300 mT. Such measurements are affected by all remanence holding magnetic minerals, including canted anti-ferromagnetic and ‘hard’ and ‘soft’ ferrimagnetic minerals. The other generally representative magnetic parameter is \(\chi\), which is sensitive to the presence of all of the magnetic minerals in a sample.

Saturating IRM (i.e. IRMs imparted at field strengths large enough to saturate magnetite) and \(\chi\) are most affected by the presence of ferrimagnetic minerals like magnetite, which, depending on grain size, can have measured values 1-3 orders of magnitude greater than a canted anti-ferromagnetic mineral like haematite. The susceptibility of paramagnetic and diamagnetic minerals is even weaker, so ferrimagnetic minerals usually swamp other contributions. Despite this, there is a great deal of possible variation in the relationship between saturating IRM and \(\chi\), as illustrated in Figure 2.2. Here concentrations of the two parameters range over five orders of magnitude, however, there is still a general linear relationship between them.
As will be seen in the next chapter, linear relationships between saturating IRM and $\chi$ are fundamental to the approach to sediment tracing developed in this study. The other important point is that the relationship between these two parameters can be used to characterize the maximum possible range of magnetic mineral assemblages.

**Figure 2.2** Log-log plot of 1000 natural samples (from Thompson and Oldfield, 1986, p30). The IRM is imparted in a magnetizing field strong enough to saturate magnetite.
2.2 Sediment Tracing Studies

Having examined some fundamental aspects of environmental magnetism, sediment tracing studies that have utilized mineral magnetic properties are now considered. This is followed by a discussion about some issues relevant to such studies.

2.2.1 Sediment Tracing Using Mineral Magnetism

One of the first studies to demonstrate the applicability of mineral magnetism for determining sediment sources was conducted in Lough Neagh, Northern Ireland (Thompson et al., 1975). IRM acquisition curves, alternating field demagnetization curves, and the linear relationship between $\chi$ and IRM were used to infer that detrital titanomagnetite was present in the lake sediments. The study inferred that the source of the sediment was Tertiary basalt soil that surrounds the lough. Susceptibility was also positively correlated with grass pollen concentration, so it was inferred that there was also a correlation with the amount of soil delivered from the catchment.

Many subsequent studies have established links between sediment in lakes, and the sources of that sediment in lake drainage basins. Thompson and Morton (1979) investigated the link between sediment in Loch Lomond and potential catchment sources, concluding that changes in magnetic properties are related to rock type. The relationships between saturating IRM ($\text{IRM}_{\text{sat}}$) and $\chi$, $\text{IRM}_{\text{sat}}$ to $\chi$ ratios, and the coercivity of remanence ($B_{\text{CoR}}$, the reverse field required to reduce the saturating IRM to zero) to match the magnetic mineralogy of the lake sediment with that from the major tributary. They also showed a relationship between susceptibility and particle size.

Bradshaw and Thompson (1985) also emphasized the importance of magnetic properties and their relationship with particle size in their study of two Icelandic catchments. IRM and $\chi$ was used to measure changes between source rocks, soils, fluvial sediments, and lake sediment. A combination of magnetic measurements, including IRM, $\chi$, $B_{\text{CoR}}$, and the S ratio (a reverse field $\text{IRM}_{100\text{sat}}$ divided by saturating IRM) were used to determine lake sediment sources.
One of the most comprehensive integrated catchment studies was undertaken in the Rhode River basin that drains into Chesapeake Bay, Maryland, USA (Oldfield et al., 1985). The study was designed to develop a comprehensive approach to magnetic mineral tracing in a relatively complex sedimentary environment. Surface susceptibility surveys were carried out using portable equipment to select representative soil sampling sites. Deposited and suspended sediment from channels was also sampled. A variety of magnetic measurements were made on particle size fractions from the potential sources identified in the initial survey phase of the study, as well as sediment from cores obtained from Chesapeake Bay. Measurements including $\chi$, frequency dependent $\chi$, $\text{IRM}_{\text{sat}}$, ARM, $(\text{Bo})_{\text{CR}}$, and the S ratio, were used to match magnetic characteristics of potential sources with those of sediment sampled from the bay. The main conclusion was that there has been a shift from subsoil derived material to surface soil associated with land clearance and cultivation.

A similar whole basin study was undertaken by Dearing (1992) in the catchment of Llyn Geirionydd, North Wales, based on an 800 year sedimentary record. Magnetic measurements were used for core correlation, and to label potential sources. Part of the analysis included plotting $\text{IRM}_{800}$ against $\chi$ to show relationships between soil, stream sediment, and lake sediment samples. The influence of particle size variation was regarded as the main control on changing magnetic parameter values in lake sediment cores. It was concluded that channel bank erosion dominated the sediment flux until the introduction of mining, when spoil heaps became the dominant source.

While most of the previous sediment source tracing studies have been based on the sedimentary record available in lakes, at least one study has examined the sources of transported sediment based on in-stream sampling. Walling et al., (1979) and Oldfield et al. (1979) measured the change in the magnetic properties of suspended sediment during and between flood events in Jackmoor Brook, and compared these with the magnetic characteristics of soils in the catchment. From this they were able to give a qualitative assessment of sediment sources using magnetic parameter concentrations and ratios, including $\text{IRM}_{\text{sat}}$, $\chi$, $(\text{Bo})_{\text{CR}}$, and $\text{IRM}_{\text{sat}}/\chi$ and S ratios. $\text{IRM}_{\text{sat}}$ vs. $\chi$ was
plotted to show the relationship between surface and subsoil sources, and suspended sediment samples.

### 2.2.2 Some Issues Associated With Sediment Tracing Studies

Studies of this kind offer a powerful way of reconstructing environmental history, but they are restricted in their application by the availability of suitable sinks, and the potential complexity of sediment sources. The number of magnetically distinguishable sources in a catchment may be considerable, and where several sources are involved, determining relative source contributions becomes mathematically and statistically complicated. This is discussed further in the next section.

Another potentially significant impediment to the use of lake and marine sediment records is post-depositional change to magnetic mineral assemblages. There are a significant number of studies that have discussed this problem, mainly in the paleomagnetic literature. Dissolution is a diagenetic process that involves the initial loss of the finest magnetic fraction prior to the gradual loss of coarser magnetic minerals (Anderson & Rippley, 1988; King & Channel, 1991). Chemical reduction of magnetite has been assumed to be the principal process involved, but Kostka and Nealson (1995) have also shown that marine and freshwater bacterium are also able to dissolve and reduce magnetite.

All magnetic parameters are affected to some extent by changes in ferrimagnetic grain sizes. If a sediment source contains a proportion of ultrafine-grained ferrimagnetic minerals, and these are progressively lost in the sediment sink due to dissolution, then the assumption of a entirely detrital origin is no longer satisfied. This assumption requires that magnetic properties must be conserved during transport from the source, and deposition in the sediment sink.

Apart from dissolution, the other diagenetic process that may alter the detrital magnetic record in sediment sinks is the authigenic growth of magnetic minerals. Iron sulfides, such as greigite (ferrimagnetic), have been found in lacustrine (Hilton, 1990; Williams, 1991), and marine sediments (Roberts and Turner, 1993). Karlin, et al.
(1987) have also reported the formation of fine-grained authigenic magnetite in marine sediments.

Fine grained (single domain) biogenic magnetite and greigite are another source of authigenic magnetic minerals in depositional environments. These minerals are produced intracellularly (Blakemore, 1975; Mann et al., 1990), and to some extent extracellularly (Lovely et al., 1987). Magnetic bacteria have also been found in soils (Fassbinder et al., 1990). It is clear from these and other studies that biogenic ferrimagnetic minerals can make a contribution to the assemblage of magnetic minerals present in sediments, although this contribution is likely to be more significant in depositional environments that favour the growth of magnetotactic bacteria.

One of the advantages of using fluvial sediment sampled from streams is that dissolution and the authigenic growth of magnetic minerals unrelated to the original sources is much less likely to occur in mainly oxic fluvial environments, and the original magnetic characteristics of the source material are more likely to be conserved. While chemical transformation is less likely to occur in fluvial environments, there are physical processes associated with sediment transport that will change magnetic mineral concentrations. These include mixing, sorting, abrasion, and sediment particle breakage. Mixing will tend to homogenize sediment magnetic properties (discussed in Chapter 3), but the other three processes may enrich or dilute the original source concentrations.

An important issue associated with sediment transport processes is the relationship between sediment particle size and magnetic properties. Such relationships have been observed in earlier studies, such as that by Thompson and Morton (1979), but, as stated in Thompson and Oldfield (1986, p66), these relationships are not necessarily simple or direct. In one study Manjunatha and Shankar (1994) found that the highest magnetic susceptibility values occurred in the <125 µm fraction of river bed sediment. In this situation, if particle sorting increased downstream, it would be expected that susceptibility will also increase downstream as the sediment became progressively finer. However, this relatively simple process is likely to be complicated by abrasion, particle breakage, or the selective deposition of heavy minerals that contain a high proportion of magnetic minerals like magnetite. In order to reduce the ambiguity
associated with sediment transport, it is necessary to conduct tracing studies on well define particle size fractions. This will not, however, eliminate magnetic mineral dilution or enrichment by fluvial sorting processes. As discussed in the next section, these are processes that may be detrimental to quantitative source tracing models that rely on magnetic concentration parameters.

### 2.3 Quantitative Source Mixing Models

The studies discussed above have mainly attempted determine the contribution of sediment sources to a sediment sink qualitatively (e.g. determine the presence or absence of a contribution from potential sources) or semi-quantitatively (e.g. determine where the majority of the sediment is coming from). In this section several studies are examined that have developed mixing models to quantitatively determine the contributions of catchment source materials (e.g. topsoils and subsoils) to the accumulated sediment in sinks such as lakes and estuaries. The models were empirically developed on a site specific basis. A typical development process involves measuring potential catchment sources, and a sequence of sedimentary deposits in sinks. Then the model is derived by some of the various methods discussed below.

Magnetic enhancement of topsoils is reported by Thompson and Oldfield (1986) to occur over a wide range of rock type and climatic conditions. According to Mullins (1977), this is principally due to the formation of maghaemite by burning of surface vegetation, and the formation of microcrystalline maghaemite or magnetite from weakly magnetic iron oxides and hydroxides. Maher and Taylor (1988) showed that ultrafine-grained magnetite formed in some UK soils by inorganic processes.

Stott (1986) used a demagnetization parameter, the ratio of reverse and forward field IRMs, to determine the relative contributions of topsoil and subsoil in a small reservoir. Proportionate contributions of the two components were estimated from an empirically derived hyperbolic mixing function.

Thompson (1986) modelled the magnetic properties of mixtures of natural materials to develop a more quantitative approach to magnetic mineral fingerprinting. Two approaches were used to mathematically model remanence hysteresis data. The first approach modelled mixtures of source materials using a matrix of the number of
possible source materials, and the number of magnetic parameters measured. Simplex minimization, which is a method for solving linear programming problems, was used to calculate mass mixing. The second approach modelled the magnetic properties of a sample from the measured characteristics of mixtures of magnetite and haematite of various magnetic grain sizes from single to multi-domain.

One of the most involved, multi-parameter approaches to quantitative sediment source tracing was developed by Yu and Oldfield (1989), based on magnetic measurements of soils and sediments from the Rhode River catchment previously reported by Oldfield et al. (1985). As a first step, the sources were classified by cluster analysis using 11 magnetic parameters (concentrations and ratios) in a multi-parameter analysis. Six potential source groups were identified, and representative mixes of these groups were mixed in 25 different proportions for further magnetic measurements. Magnetic parameters and mass proportions of the source mixes were subjected to multiple regression analysis. Proportionate source component contributions were then estimated using linear programming. This is a method for determining optimum values of a linear function that may contain many variables. One of the major weaknesses in the method was the use of ratios that are not linearly additive in the multivariate classification.

In a subsequent study Yu and Oldfield (1993) used the same approach to determine the sources of sediment in a Spanish reservoir. The principle difference between this study and the previous one was that only linearly additive mass specific magnetic parameters were used to determine proportionate source contributions, excluding the significant number of ratios used in the original study. Sand, silt, and clay components were analyzed separately to determine the proportionate contributions of five identified sources types to three sediment profiles from the reservoir. The method of ‘source’ sampling is superficially described, but alludes to finding sites where sediment is retained in the inflowing channels. A range of magnetic parameters were measured on clay, silt, and sand fractions, including $\chi$, $\chi_{fd}$, ARM, and IRMs at 20, 300, and 1000mT. These measurements initially showed that concentrations in the catchment samples were higher than those in the reservoir samples, and further catchment sampling was undertaken to identify an additional source to account for the
discrepancies. In such cases consideration should be given to the possibility that transport related processes, such as sorting due to density differences within the particle size fractions, could account for the concentration differences. Linear programming was used to determine proportionate source contributions to reservoir sediment profiles.

Another method of sediment source modelling was proposed by Shankar, et al. (1994), using a maximum likelihood unmixing algorithm that modelled combined magnetic and radioactivity measurements of soils and mine tailings to determine proportionate contributions to bed-load samples. Thirteen parameters were used in the model, but, like the other models described above, it would be interesting to know if a simpler, more transparent approach could have achieved the same purpose.

In Yu and Oldfield (1993) the authors point out that a major danger in multi-parameter studies is spurious or coincidental source matches. Using a similar approach to sediment tracing, Walling et al. (1993) claim to have minimized this problem by using as many discriminatory parameters as possible. These include $^{210}\text{Pb}_{\text{excess}}$, $^{137}\text{Cs}$, carbon, nitrogen, and four magnetic parameters. They also use cluster analysis to classify the topsoil and subsoil sources, and a linear programming algorithm to determine source contributions to suspended sediment samples collected at the outlet of two catchments. The results show considerable source variation in the contributions of cultivated topsoil, pasture topsoil, and channel banks between the sampled flow events. A weakness of the study identified by the authors is inclusion of as yet unidentified sources such as ditches, gullies and road material. However, the issues of the spatial heterogeneity of source types, and transport related enrichment or dilution of the source concentrations are not considered. Either or both of these issues could result in spurious outcomes.

In a subsequent paper, Collins et al. (1997) measured trace and heavy metals, base cations, C, N, and P, $^{210}\text{Pb}_{\text{excess}}$, and $^{137}\text{Cs}$, from the range of source types used by Walling et al. (1993). Suspended sediment samples were collected from several sites within the drainage networks of two catchments. The Mann-Whitney U-test was used to determine if the mean values of the surface and subsurface soils were significantly different, however, this took no account of the range of variation in the measured properties of these potential sources, so no statistical uncertainties were given. Further
discrimination analysis was used (multivariate discriminant function analysis) to
determine the parameters that could best distinguish between all of the sources. These
included Ni, Co, K, P, and N in one catchment, and N, Cu and $^{137}$Cs in the other. A
linear mixing algorithm was used to determine source contributions to suspended
sediment samples, including correction factors to account for particle size and organic
matter content differences between the soils and sediments. This just introduces another
element of uncertainty, and it would have been better if the study was conducted on
particle size fractions consistent with the suspended sediment samples. More
fundamentally however, spurious outcomes are more likely to occur because of
unaccounted source variation, and transport related enrichment or dilution (i.e.
concentration differences).

One of the most comprehensive and systematic studies of the multi-parameter
approach to sediment tracing using environmental magnetism was undertaken by Lees
(1994). Significant aspects of the approach were studied including the linear additivity
and statistical distribution of magnetic parameter measurements, determining the
number of sources that can be successfully ‘unmixed’ (Lees, 1997), a formalized
approach to determining the spatial variability of potential sources, estimating statistical
uncertainties associated with determining proportionate source contributions, and
evaluating which magnetic parameters give the best source discrimination. The process
of determining sediment sources included representative sampling of soil sources and
fluvial sediments, a range of magnetic measurements, classification of sources by
cluster analysis and principal component analysis, and linear modelling to quantify the
source contributions.

Lees presented the first formal approach to spatial source sampling for whole
catchment tracing studies. This involved measuring the volume susceptibility of surface
soils with a field sensor at regular intervals along predefined transects at relatively
coarse and fine scales. The data were then analyzed using variograms (semi-variance
plotted against distance) to identify significantly different source units for sampling.
While it may be practical to do this on transects several hundreds of meters long in
small catchments, this approach is not practical in larger basins.
The linear additivity of magnetic parameters was checked by artificially mixing natural and man-made substances that represented the full range of magnetic behavior. Up to six different components were mixed, and predicted and measured values compared. Lees (1997) found that magnetic susceptibility ($\chi$) was linearly additive within 2%, however IRM measurements of the mixtures deviated from predicted values by an average of 15%. It was concluded that this was probably the result of complex magnetic interactions that occurred when strong ferrimagnetic, and weakly magnetic components were mixed. In Chapter 3 the results of a two component mixing experiment are given to show that $\chi$ and IRMs are linearly additive.

The artificial mixtures were also used to determine the number of sources that could be successfully ‘unmixed’. Linear modelling was use to predict component contributions, and it was found that 96% of two source components could be successfully predicted, but this fell to less than 20% for five components. It was concluded that no more than four components could be successfully discriminated under ideal circumstances where the right balance of source component characteristics was achieved. The mixing of magnetically similar components, followed by mixing of magnetically strong and weak components caused the greatest number of failed predictions. This experiment clearly showed that only two component mixes could be ‘unmixed’ with close to 100% certainty.

In the approach that Lees evaluated, cluster analysis was used to determine the closest associations between source types. This analysis was used to group the number of source types to a manageable number (i.e. <4). Principal component analysis was used to determine which magnetic parameters gave the best source discrimination. A requirement of this approach is that well correlated parameters cannot be used in the analysis, otherwise spurious outcomes can occur due to what is termed ‘ill-conditioning’. This refers to systems of highly correlated explanatory variables whose influences cannot be disentangled to determine their separate effects. To obtain a measure of statistical uncertainty associated with the estimates of relative source contributions, Lees ran the linear modelling on mean source values plus and minus one standard deviation. An important related issue is that frequency distributions of magnetic parameter data from natural sources are positively skewed (Thompson &
Oldfield, 1986), so log-transformed data should be used to determine statistical uncertainties in the way that Lees has done.

The most significant deficiencies associated with the approaches to sediment tracing reviewed include lack of testing that magnetic properties are conserved within the spatial and temporal scales appropriate to the studies, concentration changes associated with sediment transport, a lack of knowledge about how representative the magnetic fraction is of sediment as a whole, and apart from Lees (1994) study, no attempt to determine statistical uncertainties associated with source contribution calculations, and no formal way of measuring the spatial heterogeneity of sources. Lees work has also highlighted the problem of statistically ‘unmixing’ more than four sources, and the masking of magnetically weak sources by stronger ones. There are also a range of linear modelling approaches used for determining source contributions, but as yet there is no consensus about, or evaluation of which is the most appropriate. Given the general lack of information published about the linear modelling algorithms used, there may well be undocumented sources of uncertainty contributing to erroneous outcomes.

Any one of the problems identified above could lead to spurious or coincidental source matching, and there is an obvious need for a simpler, more transparent approach to using mineral magnetism for sediment source tracing. This is the purpose of this report.

In the following chapters the magnetic properties of fluvial sediment are measured to test spatial and temporal constancy. A method of determining relative source contributions from two component mixes is presented that makes use of the natural sediment mixing processes in streams to integrate the potentially large number of sources in a catchment. This approach is not affected by the enrichment or dilution of the magnetic mineral component, and homogenization processes that occur during sediment transport ensure that representative sampling is not difficult. The method of calculating binary source contributions is simple compared to the modelling approaches discussed above, and it also provides statistical uncertainties associated with the relative contribution calculations. Also tested is how representative the magnetic mineral component is of the sediment as a whole.
2.4 References


3.1 Introduction

A new approach to sediment tracing using mineral magnetism has been developed, principally to determine relative sediment contributions at stream junctions, although the method is applicable to any binary mixing situation. In the previous chapter a number of significant problems with the whole-catchment, multi-parameter approach to sediment source tracing were identified. The approach developed here tests assumptions that until now have been not been examined, and substantially overcomes the problems associated with the whole-catchment, multi-parameter approach.

The method uses numerical signatures in the form of linear relationships between mineral magnetic parameters to label sediment delivered to a confluence and in the reach downstream. These linear relationships are used to determine relative sediment contributions to the resultant binary mix in the reach downstream of a confluence. The dominant sediment source catchments may thus be identified by a sequence of confluence measurements along a drainage network.

The requirements of this technique are that the confluence tributaries and the downstream reach have constant average signatures (i.e. the sediments are well mixed) over an appropriate period. This is possible because sediment transport mechanisms have an averaging effect as sediment is delivered first to a stream channel, and then transported within the channel for some distance over some period of time. The amount of time and length of channel in which an average sediment mix may occur will depend on the size and other characteristics of the catchment. Given that constant magnetic signatures occur in stream sediments, then the tracing technique must also be able to distinguish between, and quantify relative sediment contributions at a confluence in the majority of cases.

The principal advantages of this approach are that it is relatively easy to obtain channel bed or suspended sediment samples that are representative of the sediment
transported along a reach, and, with the exceptions discussed in Chapter 6, the method is not affected by changes in concentration. The approach is also applicable at any scale where there are two magnetically distinguishable sources of sediment. Another advantage is that it is relatively easy to calculate the proportionate contributions of two sources to a binary mix, along with statistical uncertainties, so confidence in the outcome is quantified.

In this chapter an empirical test of the spatial and temporal constancy of the magnetic mineral component of fluvial sediments using environmental magnetism parameters is presented. Then the technique of determining relative sediment contributions at stream junctions is discussed, with examples from different types of catchment.

3.2 Method

3.2.1 Sampling

The spatial sediment source tracing technique presented in this chapter depends on representative sampling of stream sediments at confluences from which the proportionate contributions of tributary catchments are estimated. Sediment transport mechanisms in rivers are very complex, however, mixing and sorting processes are likely average out the different rates of sediment supply and transport along river reaches. With the exception of suspended sediment samples from the Murrumbidgee River (discussed later), all samples were collected from deposited channel bed sediment. Sub-samples from different channel bed-forms (e.g. lateral and point bars) along and across channels were combined so that a minimum of 5 representative samples was obtained along a sampled reach. Samples were collected downstream of confluences at distances estimated to be sufficient for total mixing. While this was a subjective assessment, no other test of complete mixing was available.

To test spatial constancy, channel reaches were selected where it was judged that no significant sediment inputs occurred other than from the upstream channel (i.e. no significant bank erosion or other direct contributions). The locations of the sampled reaches are shown in Figure 3.1. These reaches ranged from 2 km to 1150 km long, draining catchments that contained as much variety of rock types, and by inference
source types as possible. Inspections of each sampled reach were made to estimate what the most abundant particle size fraction being transported in the bed load was, and samples from these reaches were subsequently wet sieved to approximately match these fractions. A 6.5 km reach of concrete lined, 2 m wide by 1 m deep, irrigation channel was also sampled at regular intervals to provide a more controlled test of spatial constancy. Suspended sediment samples were collected from along a 1050 km reach (distance measured along the channel centre line) of the Murrumbidgee River at 12 sites spaced at regular intervals (see Figure 5.7). A continuous flow centrifuge was used to collect <15 μm samples under low flow conditions on four occasions between March 1991 and July 1992, and during a moderate flood in July 1991 (Olley et al. 1996).

Figure 3.1 Locations of sampling sites.

Given that a tracer's characteristics may be constant with distance as measured in a stream channel, it is likely that relatively stable catchments may also yield consistent signatures with respect to time. In large catchments the likelihood of such signatures occurring increases because localised sources are integrated over longer transport
distances. Also, factors that have a long-term influence on sediment delivery, such as climate, are likely to be better averaged. Temporal constancy is empirically tested by taking core samples at sites of sediment accumulation where it is believed that catchment sediment delivery processes produce relatively uniform sediment mixes. Details about the two selected sites on the Murrumbidgee River are given in the section on tracer constancy.

3.2.2 Sample Treatment

Channel samples were wet sieved to obtain the size fraction observed to be the most common particle size being transported, although, for the reasons discussed below, relatively narrow particle size ranges were normally selected. Samples from the drowned reach of the Murrumbidgee River in Burrinjuck Reservoir (Figure 3.1) were also wet sieved where natural sorting had not adequately fractionated the sediment. Grab samples from the Namoi River were treated in an ultrasonic bath and fractionated by settling in a water column to recover the very fine silt and clay fraction (<10 µm).

There are two main reasons for sample fractionation. The first is that clay and silt are mainly associated with the suspended load, even though a proportion of this fraction is deposited with coarser bed-load. The hydraulic transport characteristics of suspended and bed-load sediment fractions are such that they generally separate into two populations and should, therefore, be considered separately. Secondly, as discussed in the previous chapter (section 2.2.2), relationships may exist between particle size and mineral magnetic characteristics, particularly those relating to magnetic grain size (Thompson and Oldfield, 1986). After wet sieving samples were dried at <50°C so that no magnetic enhancement occurred due to heating, and firmly packed into 2 x 2 x 2 cm non-magnetic plastic containers prior to being measured.

3.2.3 Measurements

The principal benefits of using environmental magnetism for sediment tracing are that measurements are easily made, rapid compared to other forms of analysis, and non-destructive. As discussed in Chapter 2, mass specific susceptibility (χ) is measured by subjecting a 5-10 g sample to a weak alternating field. This gives a result that is affected by the total assemblage of magnetic minerals. Remanence measurements are
also very useful for characterising the general magnetic properties of sediments.

Isothermal remanent magnetisations (IRMs) are imparted in a steady field and the magnetisation measured after the sample is removed from the field. At applied field strengths >300 mT magnetite is saturated (Maher, 1988), and any additional magnetisation is attributed to canted antiferromagnetic minerals such as haematite (Oldfield, 1991). In this study IRMs were imparted at 850 mT, so IRM$_{850}$ is a measure of all of the remanence holding magnetic minerals. Together, $\chi$ and IRM$_{850}$ represent the total assemblage of magnetic minerals, and it is the relationship between these two parameters that is used in this study.

In a previously published paper (Caitcheon, 1993), the relationship between IRM$_{850}$-IRM$_{20}$ and IRM$_{20}$ was also used, the former being a parameter that can be regarded as magnetically independent of IRM$_{20}$. The relationship between these two parameters gave results that were statistically indistinguishable from the relationship between IRM$_{850}$ and $\chi$, but as discussed in the previous chapter, $\chi$ and IRM$_{850}$ are preferred because they best represent the total assemblage of magnetic minerals.

Samples were subjected to mass specific susceptibility ($\chi$) measurements at low frequency (0.45 kHz) using a Bartington meter and MS2B dual frequency sensor. IRMs were imparted with a Molspin pulse magnetiser at 850 mT, and remanence measurements made on a Molspin fluxgate magnetometer after a regular, 15 second delay. Reproducibility was checked by measuring 10 homogenised sediment samples, giving standard deviations of 3% and 5% for specific susceptibility and remanence measurements respectively (Fiona Dyer, pers. comm.). In most cases measurement errors are insignificant compared to the natural variability between samples.

The silica concentrations of the Namoi River samples was measured by X-ray fluorescence (XRF) using the standard method (Norrish and Chappell, 1977).

3.3 Tracer Constancy

An essential criterion for determining sediment sources is that magnetic minerals are conserved within the spatial and temporal scales appropriate to tracing studies, otherwise spurious estimates of source contributions can occur because the magnetic properties of sediment are altered in some way between the sources and the sediment
sampling site. In this section, empirical tests of the spatial and temporal constancy of the magnetic properties of sediment are presented. Previously published tracing studies have assumed that the magnetic properties of sediment are conserved in fluvial environments. This is the first time that this assumption has been tested.

For tracing in fluvial environments two empirical tests of tracer constancy are possible. First, by sampling along a channel reach where there are no bank or other direct sediment contributions, an empirical check of spatial constancy can be made (i.e. invariance of tracer properties with transport). Second, by measuring tracer properties in a sediment core, a check for invariance in time is made where contributions from the source catchment are believed to be relatively stable. In such cases magnetic parameter relationships should not change with depth, and by inference time.

3.3.1 A Test of Spatial Constancy Under Controlled Conditions

Spatial constancy was first tested under relatively controlled conditions by obtaining sediment samples at regular intervals along a 6.5 km section of concrete lined irrigation channel in the Murrumbidgee Irrigation Area near Griffith, NSW (Figure 3.1). The predominant sediment source is probably unlined channel upstream of the lined section. Data from six particle size fractions are plotted in Figure 3.2, and the regression relationships are given in Table 3.1. In each case $\text{IRM}_{850}$ and $\chi$ are well correlated ($r^2 > 0.8$), showing that spatially constant linear relationships exist. It is also apparent that magnetic concentrations are not constant. As discussed below, this is an outcome of sediment transport where sorting processes randomly mix sediment with more or less magnetic mineral content. In the fine sand fractions (63-250 $\mu$m) concentration generally increases downstream, but there are no concentration trends with distance in the other particle size fractions. The critical test of constancy here is one of the linear relationships between $\text{IRM}_{850}$ and $\chi$, that is, that conservative linear relationships exist that are substantially independent of changes in concentration.

In Figure 3.2 it can be seen that the spread in concentration generally increases with particle size, as does the scatter in the data. These increases indicate that the coarser fractions are not as well mixed, an outcome consistent with heavier particles being
transported more sporadically so the opportunity for mixing is less than it is for finer particles. The significance of this is discussed below.

Figure 3.2 Data relationships for the (a) <63 µm, (b) 63-125 µm, (c) 125-250 µm, (d) 250-500 µm, (e) 0.5-1.4 mm, and (f) 1.4-2 mm sediment fractions sampled at regular intervals along the 6.5 km, concrete lined irrigation channel at Griffith.
Table 3.1  Linear relationships for particle size fractions from the concrete lined irrigation channel near Griffith, NSW. Subscripted values are 1 standard error.

<table>
<thead>
<tr>
<th>Size fraction</th>
<th>IRM$_{850}$ vs. $\chi$ regression relationships</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;63 $\mu$m</td>
<td>$y = 10.27_{1.02} x - 2.49_{0.26}$</td>
<td>0.96</td>
</tr>
<tr>
<td>63-125 $\mu$m</td>
<td>$y = 11.22_{1.24} x - 2.95_{0.41}$</td>
<td>0.95</td>
</tr>
<tr>
<td>125-250 $\mu$m</td>
<td>$y = 11.25_{2.05} x - 2.23_{0.87}$</td>
<td>0.88</td>
</tr>
<tr>
<td>250-500 $\mu$m</td>
<td>$y = 11.00_{2.79} x - 1.37_{1.03}$</td>
<td>0.80</td>
</tr>
<tr>
<td>0.5-1.4 mm</td>
<td>$y = 14.69_{2.24} x - 0.89_{1.62}$</td>
<td>0.91</td>
</tr>
<tr>
<td>1.4-2 mm</td>
<td>$y = 12.73_{3.46} x + 1.28_{2.42}$</td>
<td>0.81</td>
</tr>
</tbody>
</table>

3.3.2 The Occurrence of Linear Relationships in Fluvial Sediment

It is apparent from the results presented above that constant linear relationships exist between IRM$_{850}$ and $\chi$ that can be defined by two constants, the slope ($a$) and the intercept ($b$), where

$$IRM_{850} = ax + b.$$  

According to Hilton (1986) linear relationships will only occur under special circumstances. If only one magnetic mineral is present with uniform attributes, then changes in concentration will result in a line that passes through the origin. Thompson et al. (1975) concluded that sediment data from Lough Neagh had a highly linear relationship between IRM$_{850}$ and $\chi$ with a zero intercept because either a single mineral was present (with varying concentration), or dominant minerals mixed in constant proportion. In this case the slope of the line is the same as the ratio of the two parameters, that is

$$\frac{IRM_{850}}{\chi} = a.$$
This is the only situation when the ratio of IRM_{850} and $\chi$ is constant. If $b \neq 0$ then obviously the ratio is not constant. Hilton (1986) cautioned that normalised magnetic parameters (i.e. ratios) are only independent of changes in concentration in special circumstances, such as when only one magnetic mineral is present. In such circumstances any relationship between magnetic parameters should have a zero intercept.

Sediment can potentially contain a range of magnetic minerals from many different sources with different concentrations, resulting in a range of possible $\chi$ and IRM_{850} values that may vary by up to 5 orders of magnitude (see Figure 2.2). A general model that explains how linear relationships can develop by mixing of fluvial sediment is graphically illustrated in Figure 3.3. If the sediment contains different types of magnetic minerals, including ferrimagnetic minerals with different grain sizes, then a range of different $\chi$ and IRM_{850} values could occur. Here it is assumed that each of the randomly generated points in Figure 3.3 represents a sediment particle that has an associated magnetic mineral component (the magnetic components of sediment are considered in Chapter 4). According to Hubell and Sayre (1964), and Hung and Shen (1976), particle movement is a random phenomena, so mixing and sorting processes will occur at random. It is apparent from Figure 3.3 that if particle mixing is allowed to continue between all points at random, then the outcome of complete mixing will be a cluster of data at the means of the original unmixed IRM_{850} and $\chi$ values. Concurrent with this homogenisation process will be random mixing and sorting of sediment with varying magnetic mineral concentrations, so there is also a tendency for linear relationships to develop about the mean value.

This model proposes that the mean x and y positions of IRM_{850} and $\chi$ are the outcome of a stochastic fluvial mixing process. The slope of the line is controlled by the relationship between the two magnetic parameters. Bradshaw and Thompson (1985, Fig. 9) presented results that show for pure magnetite the slope of the IRM_{saturating} vs. $\chi$ line is greatest for fine magnetic grain sizes, and reduces sharply for coarse grain sizes.
The development of linear relationships proposed by the model in Figure 3.3 is best described by the point-slope form of linear equation. In this form the linear relationship is defined by a line with slope $a$ that passes through a defined point $(x_1, y_1)$, so that

$$y - y_1 = a(x - x_1).$$

Defining linear relationships in this way is simply a variation of the standard slope-intercept form, that is,

$$y = ax + b.$$ 

But because it is not operationally possible to determine the defined point $(x_1, y_1)$ the linear relationship must still be expressed in the slope-intercept form.

Hilton’s first condition for the development of linear relationships will apply if a well mixed average magnetic component is also mixed with non-magnetic sediment. In such cases the intercept will be zero, and the slope of the line will be controlled by the x and y position of the mean $\chi$ and IRM$_{850}$ values. This is illustrated by the dashed line in Figure 3.3.

While there are examples of linear relationships that have intercepts consistent with zero (e.g. the two coarsest sand fractions in Table 3.1), there are also cases where they are not. The two finest fractions (<63 µm and 63-125 µm) from the Griffith irrigation channel do not have intercepts consistent with zero at the 99% confidence interval (i.e. 3 standard errors, Table 3.1). In these cases the slope of the lines cannot be controlled by mixing with a non-magnetic component. In such situations it can be assumed that two or more magnetic components are present. One possibility is that non-zero intercept relationships arise from mixing between two well mixed concentration end points that would graphically plot as clusters. This would explain how the otherwise inexplicable negative linear relationship shown in Figure 5.9c occurs. Figure 6.12a also shows a linear relationship that is probably the result of mixing between two end points. However, if mixing between end points commonly controlled linear relationships then it would be expected that inexplicable situations such as negative relationships would be observed more frequently, given the potentially
very large range of end points that could occur (see Figure 2.2). The negative linear relationship shown in Figure 5.9c is the only one that has been encountered.

The most likely general explanation for the occurrence non-zero intercept relationships is found in the model illustrated in Figure 3.3. This shows that the intercept is an incidental outcome of the x and y positions of the mean $\chi$ and $\text{IRM}_{850}$ values in combination with the slope of the line. This is an inherent property of the point-slope form of linear equation discussed above.

**Figure 3.3** Random data used to illustrate the effect of complete random mixing towards mean x and y values. The line results from a constant linear relationship between magnetic parameters that are a measure of varying concentrations of magnetic minerals. The dashed line shows that if mixing only occurred between the mean values and a diluting property not detected by the measurement of x and y, then the resultant mixing line will pass through the origin.
Given that this mechanism controls the intercept when two or more magnetic minerals are present, it is also possible that some zero-intercept relationships may be controlled by magnetic components alone, and coincidentally have zero intercepts. While it is apparent from this that a zero intercept is not an unequivocal indication of control by the non-magnetic sediment component, in fluvial environments it is likely that both possible controlling processes operate with varying degrees of influence.

The model proposed above is a general one that explains how linear relationships originate from random concentration values. In natural soils and sediments there may be more order, as can be seen in the linear relationships that occur in soil data in Chapter 6. The mixing of linear relationships is discussed later in this chapter.

The other situation that Hilton identified where a linear relationship could occur was a single mineral with constant attributes changing concentration while a second mineral has constant magnetic properties (including constant concentration). In this case the intercept may not be zero. It is much less likely that Hilton’s second condition for the development of linear relationships will occur in fluvial environments because it requires that one mineral is a constant, well mixed average while a second mineral alone changes in concentration. The combined fluvial processes of homogenisation and dilution/enrichment will operate on all of the magnetic components in sediment, so it is unlikely that one component will remain constant while another changes.

A fundamental aspect of the fluvial mixing model discussed above is that the better mixed the sediment and its associated magnetic mineral fraction is, the less the scatter in the data will be away from the regression line, and the less spread in concentration there will be along the regression line. Conversely, less well mixed sediment will result in more dispersed data away from the regression line as well as along it. Given that finer sediment is likely to be better mixed, and coarser sediment less well mixed, then there should be more or less scatter and more or less spread in concentration in these fractions. This is what occurs in the Griffith irrigation channel data (Figure 3.2).

By using some of the diagnostic magnetic parameters discussed in the previous chapter it may be possible to gain a qualitative understanding of attributes such as ferrimagnetic grain size and magnetic mineral composition, but all of the linear
relationships shown in Table 3.1 are consistent within two standard errors, indicating that all of these fractions contain a uniform mix of magnetic minerals. Using the approach developed in this report, it is not necessary to know what the magnetic mineral composition is. The linear relationships apparent within each of the fractions is sufficient to demonstrate spatial constancy.

### 3.3.3 Tests of Spatial Constancy in Natural Stream Channels

Natural channel reaches were sampled as described in section 3.2.1. Data from seven streams that include a range of size fractions (selected to approximately match what was observed to be the most common particle size being transported), catchment sizes and rock types, as well as climatic conditions ranging from temperate to monsoonal tropics, are summarised in Table 3.2 and plotted in Figure 3.4. While concentrations vary considerably, the well-correlated linear relationships show that spatially constant mixes occur along the sampled reaches. It is also apparent that most of the linear relationships are statistically different, which means that such relationships have the potential to distinguish different sediment sources. However, the critical point here is that the mixing processes in fluvial environments are able to generate constant linear relationships between magnetic properties in sediment.

The results presented in Figure 3.4 come from a considerable range of fluvial environments, including small creeks (e.g. Crooked Creek), and large rivers (e.g. the Murrumbidgee River), draining catchments in different climatic environments and geological provenances. Duck Creek (site 1, Figure 3.4a) is a small channel that drains a small catchment on the south coast of News South Wales. Crooked Creek (site 2, Figure 3.4b) is a narrow, moderately incised channel that mainly transports medium sand, however, the data from the sampled reach are still reasonably well correlated despite the outlying value below the line, and inclusion of almost the entire sand fraction in the analysis (0.063-2 mm). The South Alligator River has a c.10 m wide, incised channel where the sandy bedload is mainly transported during the wet season when very large flows can occur. In the Molonglo River mainly sandy bedload is transported, and the channel is a similar in size to the South Alligator, while the Snowy River has a broad channel where the bedload is mainly coarse sand. The Murrumbidgee and Namoi rivers are discussed further below, and in Chapters 5 and 6 respectively. No
downstream trends in concentration are present in any of the data sets with the exception of the Murrumbidgee and Namoi data. These are discussed below.

**Table 3.2** Magnetic parameter relationships from selected channel reaches. Site locations are given in Figure 3.1. Subscripts are 1 standard error.

<table>
<thead>
<tr>
<th>Site</th>
<th>Catchment area (km²)</th>
<th>Length of reach (km)</th>
<th>Catchment rock type</th>
<th>Size fraction</th>
<th>IRM&lt;sub&gt;850&lt;/sub&gt; vs. χ</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>20</td>
<td>2.5</td>
<td>Permian sediments and igneous tuffs</td>
<td>&lt;63 μm</td>
<td>y = 9.45&lt;sub&gt;0.29&lt;/sub&gt; x - 0.62&lt;sub&gt;0.37&lt;/sub&gt;</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>2</td>
<td>Silurian granite</td>
<td>0.063 -2 mm</td>
<td>y = 7.65&lt;sub&gt;1.27&lt;/sub&gt; x + 0.12&lt;sub&gt;1.11&lt;/sub&gt;</td>
<td>0.80</td>
</tr>
<tr>
<td>4</td>
<td>1240</td>
<td>6</td>
<td>Proterozoic sediments and dolerite</td>
<td>250-500 μm</td>
<td>y = 4.45&lt;sub&gt;0.58&lt;/sub&gt; x + 0.65&lt;sub&gt;0.67&lt;/sub&gt;</td>
<td>0.88</td>
</tr>
<tr>
<td>5</td>
<td>1535</td>
<td>16</td>
<td>mid-Palaeozoic sedimentary and igneous</td>
<td>0.5-1.4 mm</td>
<td>y = 10.92&lt;sub&gt;0.38&lt;/sub&gt; x - 0.04&lt;sub&gt;0.28&lt;/sub&gt;</td>
<td>0.99</td>
</tr>
<tr>
<td>6</td>
<td>13600</td>
<td>7</td>
<td>Tertiary basalt Palaeozoic - sedimentary and igneous</td>
<td>0.5-1.4 mm</td>
<td>y = 16.95&lt;sub&gt;1.58&lt;/sub&gt; x -1.94&lt;sub&gt;1.69&lt;/sub&gt;</td>
<td>0.91</td>
</tr>
<tr>
<td>7</td>
<td>25000</td>
<td>200</td>
<td>sedimentary, igneous and metamorphic</td>
<td>&lt;10 μm</td>
<td>y = 12.60&lt;sub&gt;0.17&lt;/sub&gt; x - 0.92&lt;sub&gt;0.36&lt;/sub&gt;</td>
<td>0.99</td>
</tr>
<tr>
<td>8</td>
<td>35000</td>
<td>1050</td>
<td>sedimentary and igneous</td>
<td>&lt;15 μm</td>
<td>y = 10.08&lt;sub&gt;0.23&lt;/sub&gt; x - 0.71&lt;sub&gt;0.27&lt;/sub&gt;</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Flows in the Murrumbidgee River are substantially regulated by two large irrigation water storage reservoirs, so, with the exception of the occasional flood, discharge tends to be relatively uniform. Along the sampled reach there is an exponential decrease in χ values with distance downstream (Figure 3.5). This is probably due to sorting as particles with higher density are preferentially deposited, particularly those particles containing a higher proportion of heavy iron minerals, which also includes magnetic minerals. The three outlying values above the main group of data down to
Figure 3.4 Magnetic data relationships from natural channel reaches of (a) Duck Creek [site 2], (b) Crooked Creek [3], (c) South Alligator River [4], (d) Molonglo River [5], (e) Snowy River [6], (f) Namoi River [7], and the (g) Murrumbidgee River [8].
about 420 km (at Narrandera shown in Figure 5.7) were sampled during the July, 1991 flood when it would be expected that the opportunity for deposition is much less than it would be during low flow when the other samples were collected. Based on the fitted exponential curve in Figure 3.5, 65% of the susceptibility is lost by Narrandera, a result consistent with that of Olive et al. (1996), who analysed sediment loads for two floods and found that 63% of the suspended sediment load is deposited upstream of Narrandera. While concentration decreases exponentially downstream, there is no change in the linear relationship between IRM$_{850}$ and $\chi$ (Figure 3.4g).

![Figure 3.5](image_url)

**Figure 3.5** Suspended sediment samples from the Murrumbidgee River downstream of Burrinjuck Reservoir (see Figure 5.7) showing the exponential reduction in $\chi$ values.

The lower reaches of the Namoi River are substantially different to the Murrumbidgee, particularly in terms of the flow conditions. Regulated river flows are considerably lower and less frequent in the lower Namoi, where the lower basin is often affected by drought, so sediment transport is very sporadic. Four representative channel sediment samples (fractionated to $<10$ µm) were obtained from each of three sites along
a 200 km reach between Narrabri and Walgett (see Figure 6.1). In Figure 3.4f the three values with the highest concentration are from Narrabri, and only one of the measurements from Narrabri groups with the rest of the data. The three high concentration values have high leverage on the linear relationship, however, if the regression is calculated without these values, the result \( y = 11.1_{1.2} x - 0.5_{0.3}, r^2 = 0.91 \) is indistinguishable from that shown in Table 3.2. Along the sampled reach there is a general negative correlation with silica (Figure 3.6), which, according local information, may originate from silicious material on the floodplain. Despite the apparent influence of silica acting as a dilutant, the intercept of the linear relationship given in Table 3.2 is only consistent with zero at 3 standard errors.

All of the sampled reaches, including natural channel and concrete lined irrigation channel, have yielded data that indicate that constant linear relationships exist between IRM\(_{850}\) and \( \chi \). It will be seen throughout this report that such relationships are sufficiently common to provide a basis for tracing sediment.

![Figure 3.6](image-url)  
**Figure 3.6** General negative correlation between silica and \( \chi \) from the sampled reach of the lower Namoi River.
3.3.4 Tests of Temporal Constancy

The second possible test of tracer constancy is invariance through time. To test this magnetic measurements are made of core sub-samples where it is believed that a constant mix of sediment has been accumulating for a period of time. Temporal constancy was empirically tested at two sites of sediment accumulation on the Murrumbidgee River at Burrinjuck Reservoir and Hook Billabong (Figure 3.1).

Burrinjuck Reservoir is an irrigation water storage that has three major tributaries, the Murrumbidgee catchment (12,000 km²) being the largest. Sediment in this arm of the reservoir was sampled in 1983 when a monolith was obtained at a time when the water level was very low. Sub-samples were taken from a monolith at 1 cm intervals to a depth of 24 cm. In 1992, 7 regularly spaced grab samples were obtained between the original sampling site and the head of the reservoir, a distance of approximately 13 km. Samples from the upper part of the drowned reach that were not already naturally sorted were wet sieved to obtain the <63 \mu m fraction. Bi-variate magnetic parameter plots (Figure 3.7a) show that the linearly correlated data from the reach is consistent with that from the accumulated sediment profile, indicating temporal constancy of the magnetic mineral assemblage for a period of at least 9 years.

There is no trend in concentration along the sampled reach of the Murrumbidgee arm of Burrinjuck Reservoir. The linear relationships of the two sets of data are consistent, but it would be expected that the concentration values would overlap more. There is a very slight decrease in concentration with depth in the monolith data, so it is possible that there has been some dissolution of the magnetic component similar to that found by Canfield and Berner (1987) in a study of magnetite dissolution in marine cores (see also the discussion in Chapter 2). However, this is unlikely to be sufficient to fully explain the separation of the two groups of data.

The second test of temporal constancy was undertaken at Hook Billabong, a cut-off meander loop of the Murrumbidgee River that receives over-bank flood flows at a return interval of about 2 years. The catchment area of the Murrumbidgee at this location is approximately 35,000 km². A 67 cm core of predominantly clay size sediment was obtained from the billabong in 1992. The first appearance of $^{137}$Cs, a
radionuclide produced by atmospheric nuclear weapons testing, at 35 cm in the core shows that sediment has been accumulating in the billabong from at least 1960 (Olley et al., 1996). Suspended sediment samples were obtained from the river on five separate occasions (March 1991 - July 1992) at five sites upstream of the billabong to the first major tributary, a distance of approximately 450 river kms. The suspended sediment data are well correlated and consistent with the linear relationship of the core data within two standard errors (Figure 3.7b). This indicates that the assemblage of magnetic minerals, represented by the magnetic parameter relationships, has, on average, been constant for at least 32 years.

The word ‘average’ is used because there are variations down the core which may be due to subtle changes in the source composition, or some form of post-depositional change. Of the three intervals selected (Figure 3.7c), only the bottom interval (29-67 cm) has a linear regression equation consistent with the overall linear relationship. The regression equations from the upper two intervals (0-18 cm and 18-29 cm) are not consistent with the overall relationship. These differences are more likely to be due to subtle source composition changes than post-depositional alteration. If the latter was responsible for the differences it would be expected that sediment at the bottom of the core would be altered more than sediment at the top. Also inspection of Figure 3.7c shows the changes to be quite distinct rather than a gradual trend as would be expected from some form of diagenetic change. The differences in the linear relationships of the upper two sections are not regarded as significant because, as will be seen in the next section and in subsequent chapters, substantial differences in sources result in distinctly different linear relationships. Taken as a whole the data from the Hook Billabong core and the upstream reach of the river are consistent.

In both of the above examples the concentration ranges of the source and sink data are different. This does not diminish the conclusion that the magnetic component of the river sediments is temporally constant, because on average both groups have consistent magnetic mineral compositions. If significant transformations or source changes had occurred in either the source material or the sinks, the overall linear relationships between the source and sink groups would not be consistent. The lower concentrations in the sinks may in part be due to the effects of transport related sorting as discussed previously, although it would be expected that some concentration overlap would occur.
At this stage this issue cannot be resolved, however well correlated linear relationships show that mineral magnetic properties in fluvial environments are spatially and temporally constant. In the next section the question of how these relationships can be used for spatial tracing is considered.
Figure 3.7 Linear relationships between cores and upstream reaches at Burrinjuck Reservoir (a), and Hook Billabong (b and c) demonstrating average temporal constancy.
3.4 Spatial Tracing At Confluences

It has been empirically demonstrated, using two representative magnetic parameters, that magnetic mineral assemblages are spatially and temporally constant in stream sediments from a range of geological and climatic conditions, and so may be regarded as a reliable tracer in fluvial environments. Now the method of determining relative sediment contributions to binary mixes is described, with particular reference to stream junction mixing. To be able to determine relative sediment contributions at confluences the method must be able to distinguish between sub-catchment sediment contributions in the majority of cases if it is to be generally applicable. The magnetic components in sediment must also be linearly additive. According to Hilton (1986), in dilute mixtures where magnetic minerals act independently of each other, a magnetic measurement will be the sum of the contributions from each magnetic component. As sediment normally contains very dilute mixtures of magnetic minerals, it can be assumed that this criterion will be met. To test linear additivity, two sediment samples with different magnetic concentrations were separately mixed so they were homogeneous, and then mixed with each other in different proportions. Each of the mixed samples was then measured. The results given in Figure 3.8 clearly show that the magnetic measurements are linearly additive in proportion to the weights of the two original samples.

Having satisfied the test of linear additivity, confluence mixing is examined by considering three examples of magnetic parameter relationships. The first two examples are taken from the Ord River in the monsoonal tropics of Western Australia and the third example is from the Queanbeyan River in southern New South Wales (Figure 3.1). Each of the tributary catchments in these examples contains a mix of sedimentary, metamorphic and igneous rock types. The sand fractions analysed are approximately the modal grain size observed to be transported in the channel bed sediment.

Inspection of the data presented in Figure 3.9 shows linear resultant mix relationships intersecting distinct tributary linear relationships close to the origin. The discussion in the previous section has shown how linear relationships develop through fluvial mixing processes. At confluences the same processes operate to generate linear relationships in the downstream reach. Such a hypothetical mixing situation is illustrated in Figure 3.10. Three points (a, b, c) from the first tributary are mixed with
all of the points from the second, assuming a 50:50 mix. It is apparent that if random mixing between all possible tributary points occurred then the outcome would be a rhombic arrangement of points between the tributary lines. Further random mixing in varying proportions will ultimately produce a cluster of data at the centroid of the rhombus. However, as previously discussed, fluvial mixing processes will also randomly mix sediment with varying concentrations of magnetic components, resulting in a line of data with varying concentrations passing through the centroid. This is the same process illustrated in Figure 3.3 in the previous section, except in this case the sources are defined by linear relationships.

![Figure 3.8 Linear additivity of magnetic parameters. The lines represent conservative mixing.](image-url)
Figure 3.9 Magnetic parameter relationships from the Ord - Negri (a), Ord - Panton (b), and Queanbeyan - Towney (c) confluences.
Figure 3.10 Hypothetical confluence mixing situation (50:50 mix). Arrows indicate direction of random mixing towards centroid and along the line of concentration.

Having developed a simple model for the mixing of linear tributary relationships at confluences, it is necessary to formulate a method for determining proportionate tributary contributions. A simple procedure is to establish a mixing origin, the point of intersection of the tributary regressions, and fit the downstream resultant mix regression through this point. If the mixing origin \((x_1, y_1)\) is reset to zero by subtracting \(x_1\) and \(y_1\) from the data, then fitted regression lines have gradients equivalent to mean \(\frac{IRM_{850}}{\chi}\) ratios. The percent proportionate tributary contributions \((C_p)\) can then be determined by a proportion calculation where

\[
C_p = \frac{\bar{x}_{\text{tributary}} - \bar{x}_{\text{downstream mix}}}{\bar{x}_{\text{tributary}} - \bar{x}_{\text{tributary}}} \times 100
\]

However, because neither of the parameters are statistically dependent, it is equally valid to regress \(IRM_{850}\) against \(\chi\), and vice versa. This means that there are two equally
valid proportionate contribution estimates possible, an outcome that is not ideal. A procedure that produces one result, where no dependent variable is assumed, was developed by Morton (1991), and applied in Murray et al. (1993). The data are standardised so that variations within each of the two source components are the same. Three concurrent straight lines were fitted to the data from the two sources and the resultant mix by a method similar to that of Morton, but which allowed for greater variability in the resultant than in the sources (Jeff Wood, pers. comm.). A mixing line at 45° to the axes was used for estimating the proportionate contributions to the resultant. As the estimated proportions are a ratio of linear combinations of estimated parameters, Fieller’s theorem (Finny, 1964) was used to calculate confidence intervals and standard errors. The Genstat (NAG, 1987) routine for determining this is given in the Appendix. Using this procedure the proportionate contributions of the tributaries from Figure 3.9 were determined and given in Table 3.3.

Table 3.3 Relative contributions of the tributaries from Figure 3.9. Uncertainties are one standard error.

<table>
<thead>
<tr>
<th>Tributary (size fraction)</th>
<th>Percent contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negri (63-125 µm)</td>
<td>19 ± 6</td>
</tr>
<tr>
<td>Panton (63-125 µm)</td>
<td>43 ± 7</td>
</tr>
<tr>
<td>Towney (125-500 µm)</td>
<td>81 ± 2</td>
</tr>
</tbody>
</table>

While the above examples are typical of the confluence data relationships examined in this study and presented in subsequent chapters, not all tributaries can be distinguished by differences between linear relationships. An example given in Figure 3.11 is from the confluence of the Snowy and Maclaughlin Rivers in southern NSW (Figure 3.1). Coarse sand was observed to be the most common bed-load particle size, so the 0.5-1 mm fraction was analysed. All the data are consistent with a single line passing through, or close to the origin, which means that, apart from concentration, the magnetic mineral characteristics of the tributaries are indistinguishable. Despite this, the tributary concentration ranges of the samples clearly differentiate the sources. In this
case, use of a measure of central tendency, such as the mean, is the only way to estimate relative contributions. Using mean tributary and downstream mix values of χ and IRM$_{850}$, the relative contribution by the Maclaughlin River is calculated using the proportionate contribution equation given above, and the results shown in Table 3.4. The χ and IRM$_{850}$ results are consistent within statistical uncertainty, indicating a 50% contribution. However, while the statistical uncertainties are low, they take no account of possible systematic errors associated with concentration variation. It is probable that if the number of samples was increased, or they were taken from different locations, then a different outcome could occur. This example highlights the fact that the use of linear relationships for determining relative tributary contributions is much more reliable because they are substantially independent of variations in concentration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Percent Contribution (0.5-1 mm fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>χ</td>
<td>46 ± 7</td>
</tr>
<tr>
<td>IRM$_{850}$</td>
<td>56 ± 8</td>
</tr>
</tbody>
</table>

**Table 3.4** Proportionate contributions by the Maclaughlin River. Uncertainties are 1 standard error.
3.5 Conclusion

The constancy of magnetic parameter relationships, and by inference magnetic mineral assemblages, has been empirically demonstrated spatially in channel reaches, and temporally as measured in accumulated sediment deposits. It has also been shown that mineral magnetism can be used to trace sediment sources at stream junctions where two catchments deliver magnetically distinguishable, averaged source mixes to a trunk stream. The method depends on obtaining representative bed-load or suspended sediment samples from tributary and downstream reaches at a confluence. Magnetic parameters are measured after sample fractionation. If bi-variate plots show the tributary data are linearly related, and distinguishable, then proportionate tributary contributions can be calculated.

Using this approach, relative source changes through time can be monitored by re-sampling at junctions, and by measuring down profile changes in age-dated alluvial
deposits. An example of the latter is given in Chapter 5. The method is not restricted to stream junctions. It can be applied wherever there is a binary mix of two distinguishable sources. In principle, different source materials in relatively complex catchment systems can be traced by reducing the complexity to two component mixes. This approach is considered in Chapter 6. Finally, this method of sediment tracing is easy to understand, and the results are easily interpreted. Confidence in the outcomes is quantified by the calculation of statistical uncertainties.

While this method shows promise there are still some unanswered questions. For example, what is the origin of the differences observed in magnetic parameter relationships? This question is answered in the next chapter and further in Chapter 6. A more significant question that has not been considered by any tracing method study to date is, does it give the right answer? This is a difficult question to answer with any certainty because it requires an independent and reliable method of verification. To some extent this problem is dealt with in the next chapter when the relative composition of the magnetic constituents of sediment are determined to quantify how well the magnetic mineral component represents the total transported sediment. Also at the end of Chapter 6 the possibility of spurious source matches in large catchments is considered.


3.6 References


Chapter 4

The Significance of Various Sediment Magnetic Mineral Fractions for Tracing Sediment Sources in Killimicat Creek

4.1 Introduction

In the previous chapter it was shown that if two streams of magnetically distinguishable sediment are delivered to a confluence, then the sediment's magnetic properties can be used to determine the relative sediment contributions. The spatial and temporal stability of the magnetic components of transported sediment was also demonstrated, however, there are no known studies that have measured the relative contributions of the magnetic constituents of sediment (i.e. components associated with surface-bound Fe, the heavy mineral fraction, and mineral inclusions in particles) to determine how well they represent fluvial sediment. Addressing this question is central to understanding how good the magnetic mineral component is as a tracer of fluvial sediment as a whole.

Hounslow and Maher (1996) examined magnetic mineral extracts to determine the efficiency and representative nature of the extraction process, as well as the types of mineral present in extracts. They found that some ferrimagnetic minerals (e.g. magnetite) may be present as discrete particles. These individual minerals are part of the heavy mineral fraction, and they may make a significant contribution to the total magnetic measurement. However, because heavy minerals are a discrete component, they may not necessarily be derived from the same source as the rest of the sediment. Common heavy minerals, such a magnetite, may have different transport histories to the rest of the sediment because of their higher density (Fletcher and Wolcott, 1991).

Mineral inclusions within particles, and magnetic minerals associated with surface-bound Fe oxide on sediment particles are the other possible magnetic constituents. Magnetic minerals associated with surface-bound Fe are a product of secondary mineralisation, mainly due to pedogenic processess (see for example Taylor et al.,
1983), while primary mineral inclusions within sediment particles originate from rocks (Thompson and Oldfield, 1986).

This chapter contains a report on experiments to measure the relative contributions of the magnetic constituents of sediments. First, the proportionate contributions of heavy and light mineral components of two different sediment streams delivered to a confluence are determined from mineral magnetic measurements of heavy liquid separates. The light mineral component is then digested in HCl to remove surface-bound Fe, so that the relative contribution of magnetic minerals associated with surface-bound Fe can be measured. The remaining magnetic component is attributed to mineral inclusions within sediment particles.

**4.2 Sample Collection and Treatment**

Killimicat Creek is a tributary of the Tumut River in south-east New South Wales. Sediment grab samples were collected from the channel along a 10 km reach downstream of the junction with an unnamed tributary, and also from along 1-2 km of the tributary channels. The larger tributary, Killimicat Creek, drains a 22 km² catchment containing rocks of mainly volcanic origin. These are mostly dacite and volcaniclastic sediments. The western edge of the basin includes relatively small areas of metabasalt, serpentinite, and granodiorite. Channel bank erosion is likely to be the major sediment source, but this does not appear to be very extensive or active (Figure 4.1).

In contrast, the other, smaller tributary catchment sampled has significant channel incision, as well as extensive gully erosion. Sheet erosion also occurs in a few areas. The 7 km² drainage basin is made up almost entirely of quartz rich sedimentary rocks. Sediment delivery from this catchment is likely to be more efficient due to relatively higher channel gradients compared to Killimicat Creek.

Before magnetic measurements were made on the sediment samples, they were wet sieved to obtain 6 particle size fractions including, <63 μm, 63-125 μm, 125-250 μm, 250-500 μm, 500 μm - 1.4 mm, 1.4-2 mm. As previously discussed, the reason for fractionating the samples is that the transport history of fine and coarse sediment is potentially quite different, so relative source contributions could be different. Also, the
magnetic mineral properties of these fractions may be different, particularly for clay-silt (<63 µm) and sand fractions.

Figure 4.1 Rock types and channel sediment sampling sites in the tributary catchments and downstream reach (not all downstream sites shown).

The 63-125 µm fraction was selected for heavy liquid separation because it is likely to contain a relatively high proportion of fine grained heavy minerals (Selley, 1976). All of the fractionated samples were thoroughly mixed in a sodium polytungstate solution made up to a specific gravity of 2.85, and allowed to stand until the heavy mineral fraction had settled. The light fractions, which should include all of the quartz and feldspar, was decanted off, washed, and then dried at <50°C before packing into plastic cubes for magnetic measurements. The small quantity of heavy minerals recovered (average, 0.5 g per sample) was washed, dried, and then mixed with finely ground sugar so that the sample filled the plastic cubes. This method of sample dispersion reduces interactions between magnetic grains during the measurements.
After heavy liquid separation, each of the light mineral sample fractions was digested in concentrated HCl at 50°C for more than 1 hour to remove surface-bound Fe. This method is similar to that of Berner (1970), who digested samples in concentrated HCl for 1 minute at 100°C.

Mass specific magnetic measurements (see Chapter 3) were made on all samples after they had been particle size fractionated. Measurements were then made on the light and heavy, 63-125 µm fractions after the heavy liquid separation. A final set of measurements was made on the residue of the light mineral fractions after the HCl digest.

**4.3 Results and Discussion**

**4.3.1 Proportionate Tributary Contributions**

The relationship between $\chi$ and IRM$_{850}$ from all of the particle fractions is shown in Figure 4.2. In all but the two coarsest fractions a linear mix of sample data from the reach downstream of the confluence plots between the two sets of linearly correlated tributary data. The concentration ranges increase with particle size, particularly in the coarsest fractions. There is also a noticeable merging of the data in the 250-500 µm fraction, while in the 0.5-1.4 mm and 1.4-2.0 mm fractions the linear relationships are indistinguishable. The significance of this is discussed later in this chapter.

The proportionate contributions of particle size fractions from the smaller, sedimentary rock catchment were calculated using the method developed by Morton (1991), discussed in Chapter 3. The results given in Table 4.1 show that the clay-silt, and fine to medium sand fractions (<500 µm) are consistent with about a 70% contribution from the smaller, although apparently more eroded, sedimentary rock tributary basin. No useful result could be determined for the two coarse sand fractions (0.5-1.4 mm, and 1.4-2 mm) due to the similarity of the data from the two tributaries.
Figure 4.2 Killimicat Creek confluence data from the (a) <63 µm, (b) 63-125 µm, (d) 125-250 µm, (e) 250-500 µm, (f) 0.5-1.4 mm, and (g) 1.4-2.0 mm fractions.
Table 4.1 Proportionate contributions of sediment from the sedimentary rock tributary basin.

<table>
<thead>
<tr>
<th>Particle Size Fraction (µm)</th>
<th>Contribution (%)</th>
<th>standard error (%)</th>
<th>95% confidence limit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;63</td>
<td>76</td>
<td>28</td>
<td>19-100</td>
</tr>
<tr>
<td>63-125</td>
<td>70</td>
<td>12</td>
<td>45-94</td>
</tr>
<tr>
<td>125-250</td>
<td>71</td>
<td>6</td>
<td>59-82</td>
</tr>
<tr>
<td>250-500</td>
<td>63</td>
<td>23</td>
<td>17-100</td>
</tr>
</tbody>
</table>

4.3.2 Heavy Liquid Separation Results

All of the fine sand fraction (63-125 µm) samples were subjected to heavy liquid separation as described above. The 63-125 µm fraction data obtained prior to heavy liquid separation, and after removal of the heavy mineral component are plotted together for comparison in Figure 4.3. Apart from a reduction in concentration in the fraction with the heavy minerals removed, the two sets of data relationships are very similar. Magnetic measurements of the light mineral fraction gave a proportionate contribution result similar to that of the total fraction, 73 ± 13% from the sedimentary rock catchment.

For the heavy mineral fraction, the relationship between the magnetic parameters is more uncertain, giving a contribution from the smaller catchment of 78 ± 38%. This estimate excludes a sample from downstream of the confluence, highlighted by the open square in Figure 4.4. This sample plots within the well defined linear correlation from the Killimicat tributary, indicating that it has probably not been mixed with the heavy mineral fraction from the sedimentary rock tributary. Although the data from the sedimentary rock tributary are linearly correlated, the heavy mineral fraction is not as well mixed as it is in the Killimicat tributary, and so the downstream mixing is not as complete as it is in the light mineral fraction. Apart from the downstream data point excluded from the relative contribution calculation, some of the other lower concentration downstream data are also consistent with the Killimicat tributary data, however, it is not possible to determine if these are exclusively from one tributary or the other, so they have been included in the contribution calculation.
Figure 4.3 Comparision of the 63-125 µm sediment fraction (a) prior to heavy liquid separation, and (b) after removal of the heavy mineral component. Note that the Killimicat tributary data in (a) have the same regression relationship with or without the value with high leverage \[y = 15.0x - 0.2\] and \[y = 15.3x - 0.3\] respectively.]
The downstream sample highlighted in the open square has been excluded from the proportionate contribution calculation.

Another estimate of the relative contribution can be calculated from the weight of heavy minerals in each sample taken as a percentage of the total sample weight. The mean values from each tributary and the downstream reach (using all of the data) were used to calculate a proportionate contribution, using the proportion equation in section 3.4, of $55 \pm 14\%$ from the sedimentary rock catchment. The two calculated heavy mineral fraction contributions ($78 \pm 38\%$ and $55 \pm 14\%$) are both consistent (within 1 standard error) with the light mineral fraction contribution of about 70%.

The heavy mineral component is 0.2-1.4\% by weight of the 63-125 $\mu$m fraction from the sedimentary rock tributary, and 1.6-4\% of the volcanic tributary. However, the
relative contributions to the total magnetic susceptibility average 14% and 32% respectively, with respective ranges of 5-23% and 26-40% (Table 4.2). It is apparent that, depending on the characteristics of the source material, the heavy mineral component can make a significant contribution to magnetic component of sediment, although it is not the dominant constituent in this case.

Table 4.2 Magnetic susceptibility data from the volcanic and sedimentary rock tributaries (63-125 μm fraction) used to calculate the relative heavy mineral $\chi$ contribution to the $\chi$ of the total fraction.

<table>
<thead>
<tr>
<th>Weight % Heavy Mineral</th>
<th>$\chi$ (total fraction)</th>
<th>$\chi$ (heavy mineral fraction)</th>
<th>$%\chi$ (heavy mineral fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sedimentary</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>0.38</td>
<td>3.90</td>
<td>12.9</td>
</tr>
<tr>
<td>1.4</td>
<td>0.40</td>
<td>6.78</td>
<td>23.0</td>
</tr>
<tr>
<td>1.1</td>
<td>0.22</td>
<td>3.03</td>
<td>14.7</td>
</tr>
<tr>
<td>1.2</td>
<td>0.41</td>
<td>3.06</td>
<td>9.2</td>
</tr>
<tr>
<td>1.0</td>
<td>0.41</td>
<td>9.31</td>
<td>22.8</td>
</tr>
<tr>
<td>0.6</td>
<td>0.20</td>
<td>6.52</td>
<td>19.3</td>
</tr>
<tr>
<td>0.2</td>
<td>0.19</td>
<td>6.64</td>
<td>6.2</td>
</tr>
<tr>
<td>0.2</td>
<td>0.08</td>
<td>1.88</td>
<td>5.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.29</td>
<td>7.80</td>
<td>12.6</td>
</tr>
<tr>
<td><strong>Volcanic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>0.25</td>
<td>2.52</td>
<td>39.8</td>
</tr>
<tr>
<td>2.4</td>
<td>0.24</td>
<td>3.01</td>
<td>30.1</td>
</tr>
<tr>
<td>2.0</td>
<td>0.24</td>
<td>3.69</td>
<td>31.7</td>
</tr>
<tr>
<td>1.8</td>
<td>0.23</td>
<td>3.34</td>
<td>26.2</td>
</tr>
<tr>
<td>3.2</td>
<td>0.55</td>
<td>6.36</td>
<td>36.8</td>
</tr>
<tr>
<td>1.6</td>
<td>0.22</td>
<td>3.97</td>
<td>29.6</td>
</tr>
<tr>
<td>2.3</td>
<td>0.25</td>
<td>3.28</td>
<td>30.4</td>
</tr>
<tr>
<td>1.8</td>
<td>0.20</td>
<td>3.43</td>
<td>30.6</td>
</tr>
</tbody>
</table>

Another interesting outcome is the similarity of the linear regression coefficients from the light and heavy mineral fractions. The sedimentary rock tributary light and heavy mineral regression coefficients are $7.8 \pm 0.7$, and $9.2 \pm 1.3$ respectively, while the volcanic rock tributary coefficients are $12.6 \pm 0.5$ and $14.5 \pm 1.1$ respectively. The light and heavy mineral fraction coefficients from the sedimentary rock tributary are consistent within one standard error, while the coefficients of the light and heavy mineral fractions from the volcanic rock tributary are almost within one standard error.
of each other. This indicates that there is a common controlling influence on the magnetic characteristics of these fractions in their respective catchments.

The heavy mineral fraction will influence the magnetic characteristics of sediment due to the combined effects of magnetic concentration, and the amount of heavy mineral present. But it will also influence the slope of the regression line of the sediment as a whole if the slope of the heavy mineral fraction regression line is different to that of the light mineral fraction. Such a difference was not observed in this study, but it is a possible outcome. From the results given above it can be seen that combination of the light and heavy mineral fractions produces a linear resultant mix relationship (Figure 4.3a), even though the concentration ranges of the two fractions are different by an order of magnitude (Figure 4.3b and Figure 4.4).

While the weight concentration of the heavy mineral component is likely to be low, it is clear that it can have a significant influence on the magnetic characteristics of the sediment as a whole. It is possible that in particular situations the heavy mineral fraction may be the dominant influence on magnetic parameter relationships, in which case it may be the heavy minerals that are being traced rather than the sediment as a whole.

4.3.3 Digest Results

Magnetic measurements were made on the light mineral component before the samples were chemically treated to remove the surface-bound Fe. The measurements were repeated after the digests, and they show that an average of 3% (range, 0.7-7%) of the total magnetic susceptibility of the 63-125 µm fraction (including the heavy mineral component) from the sedimentary rock catchment is attributable to particles chemically stripped of surface-bound Fe. The equivalent average from the volcanic tributary sediments is 16% (range, 12-19%).

These results are summarised in Table 4.3, and they show that the largest magnetic component is associated with surface-bound Fe. The heavy mineral fraction accounts for the next largest component, while mineral inclusions within sediment particles make a relatively minor contribution to the total magnetic susceptibility. However, the highest heavy mineral contribution is 40%, so in the sediments measured in this study,
>60% of the magnetic component is associated with the bulk of the sediment, either as part of surface-bound Fe, or as particle inclusions.

Table 4.3 Mean values of the heavy mineral, surface-bound Fe, and sediment particle mineral inclusion components as a proportion of the total magnetic susceptibility. The component contributions do not sum to 100% because of experimental uncertainties. Internal statistical uncertainties are 1 standard error. The method of calculating the percent contribution of the three components of the total magnetic susceptibility in each sample is also shown, where H is the percent heavy mineral fraction, S is the percent surface-bound Fe component, L is the percent light mineral fraction, P is the particle inclusion component (after the surface-bound Fe component has been chemically stripped), \( \chi_T \) is the total susceptibility of each 63-125 \( \mu m \) sample, \( \chi_H \) is the susceptibility of the heavy mineral fraction, \( \chi_L \) is the susceptibility of the light mineral fraction, \( \chi_P \) is the susceptibility of the light mineral particles stripped of surface-bound Fe, \( H\% \) is the weight proportion of the heavy mineral fraction, and \( L\% \) is the weight proportion of the light mineral fraction.

<table>
<thead>
<tr>
<th>Tributary catchment rock type</th>
<th>Heavy mineral fraction (H)</th>
<th>Surface-bound Fe component (S)</th>
<th>Light mineral fraction after surface-bound Fe removed (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sedimentary</td>
<td>14 ± 2</td>
<td>73 ± 1</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>volcanic</td>
<td>32 ± 2</td>
<td>46 ± 2</td>
<td>16 ± 1</td>
</tr>
</tbody>
</table>

\[
H = 100.H\% . \chi_H / \chi_T \\
S = L - P \\
P = 100.\chi_P / \chi_T \\
where \\
L = 100.L\% . \chi_L / \chi_T
\]

Figure 4.5 shows the results of magnetic measurements made on the samples after the HCl digests. While there is some spread in the sedimentary rock tributary data, the clear differences between the linear relationships of the light mineral fractions from the two tributaries (Figure 4.3b) have now been removed, which means that they are attributable to the magnetic component of the surface-bound Fe oxides. According to Taylor et al. (1983) these are a product of soil forming processes. The similarity of the linear regression coefficients from the light and heavy mineral fractions from each tributary, discussed in the previous section, also show that the magnetic properties of
these mineral fractions are a product of soil forming processes that must be substantially influenced by the geochemical characteristics of the parent rock. This observation is consistent with the results in Chapter 6, where mineral magnetic data from soils developed on basalt and sedimentary rocks are clearly different. Maher (1986) also highlighted the influence of parent material on the mineral magnetic characteristics of soils.

Figure 4.5 The magnetic characteristics of the light mineral fraction after surface-bound Fe was chemically removed.

Because of the removal of the linear relationships between the HCl digested samples, the average magnetic parameter concentrations from the tributaries and downstream reach data in Figure 4.5 were used to determine the relative sedimentary rock tributary contribution. The relative contributions are 77 ± 5% and 70 ± 6% for IRM_{850} and $\chi$ respectively. These results are consistent with the other proportionate contribution estimates given above.
The data in Figure 4.5 is generally consistent with a single regression line passing through the origin, which indicates that the sediment particles mainly contain one type of magnetic mineral, probably primary magnetite, mixed with a non-magnetic component (see section 3.3). Magnetite is a relatively common accessory rock mineral. At the end of section 4.3.1 it was stated that the data from the coarse sand fractions could not be distinguished. The magnetic mineralogy of the coarse sand fraction is probably dominated by primary mineral particle inclusions, rather than surface-bound Fe oxides or heavy minerals. The similarity of the regression coefficients from the digested light mineral fraction (63-125 µm), and the untreated 0.5-1.4 mm sand fraction (14 and 14.6 respectively) indicates that this is probably the case.

As previously discussed, the heavy mineral fraction is a relatively important contributor to the magnetic component of the fine sand fraction (63-125 µm) analysed. The heavy mineral fraction is likely to make its greatest contribution as a magnetic component in fine sands because heavy minerals are mainly fine grained (Selley, 1976). Indirect evidence presented above indicates that mineral particle inclusions may be the most significant magnetic component of coarse sand. For finer particles, fine silts and clays, the magnetic component of surface-bound Fe oxides probably increases in relative importance as particle size decreases. This is because, assuming particles are spherical, smaller particles have a greater relative surface area, so in relative terms there is likely to be more surface found Fe. Also clay minerals are a chemical weathering product, so there are no residual internal primary minerals in the particles.

**4.4 Conclusion**

The experiments reported here show that in the fine sand fraction (63-125 µm), most of the magnetic mineral component is associated with either surface-bound Fe or particle inclusions, although the discrete heavy mineral component does make a significant contribution. There is good indirect evidence that mineral particle inclusions are the most significant magnetic component in coarse sand.

Surface-bound Fe oxides, including the magnetic component, are mainly a product of soil forming processes. This was shown by the chemical stripping of surface-bound Fe that completely removed the distinct differences between the linear relationships in...
the light mineral fractions from the two tributary catchments. The heavy mineral components from each tributary were also distinctly different, and consistent with the magnetic parameter regression relationships of the light mineral fractions. These differences must be substantially influenced by the geochemical properties of the parent rock, given that this is the principal difference between the two tributary catchments.

While the results indicate that most of the magnetic mineral component is associated directly with sediment particles, a question remains about what proportion of sediment particles have magnetic minerals associated with them. The experiments reported in this chapter have shown that clay-silt, and fine to medium sand from two different catchments have distinct magnetic parameter relationships, which, according to the results from the 63-125 µm fraction, are mainly due to the magnetic characteristics of surface-bound Fe. Given that this originates from pedogenic processes acting on all soil particles, it is likely that the great majority of sediment particles will also have some surface-bound Fe, a proportion of which will be magnetic mineral. From this it is concluded that the magnetic component is broadly representative of sediment as a whole (with a possible exception discussed below), and that the tracing method developed in this study is a reliable way of determining relative sediment contributions at confluences.

The situation for coarse sand may be somewhat different. The uniformity of the magnetic parameter relationships in the 0.5-1.4 mm and 1.4-2.0 mm fractions, and the similarity of these to the linear regressions from the digested, 63-125 µm, light mineral fraction, indicates a common, dominant type of magnetic mineral. It will also be noted that these linear relationships have zero intercepts, which, as discussed in the previous chapter, may indicate mixing of a single magnetic component with a non-magnetic component such as quartz. If this is the case then the method will not be tracing the diluting, non-magnetic component if this includes particles that have no magnetic mineral inclusions. However, it will be difficult to test if individual particles have no magnetic mineral inclusions, or just a very small amount below the limit of detection. A simple test if silica was the principal dilutant would be to plot $\chi$ against SiO$_2$ as in Figure 3.6. It is possible that the relationship shown here is an inverse one, rather than a negative correlation. If more data showed this to be the case, then it would demonstrate
that a substantial proportion of the sediment particles had low concentrations of magnetic minerals (at the high SiO$_2$ tail of the inverse relationship), rather than no magnetic mineral particle inclusions at all.

The results also show that different rock types can be used as a basis for distinguishing sediment sources. This means that while stream junctions receiving sediment from distinguishable sources may be useful locations for determining relative sediment contributions, other sites of sediment deposition in stream networks that only receive eroded soil from two distinct rock types can also be used to determine relative contributions. The potential for extending the confluence tracing method is explored further in Chapter 6, and to some extent in the next chapter.
4.5 References


5.1 Introduction

In the previous chapters a simple, binary mixing method to trace sediment was developed, and the major assumptions involved tested. While there are limitations to this approach in that it is restricted to tracing two sources at a time, it has a major advantage over multi-parameter methods because the data are evaluated in the simplest possible way, that is, a bi-variate plot. However, as will be seen in this chapter, more than two sources can be analysed in the same plot, and downstream trends evaluated by summarising the outcomes in innovative ways.

In this chapter three examples are given of how the spatial tracing method can be applied. The first example involves tracing fine sand in the Ord River, a large, remote catchment in the monsoonal tropics of Western Australia. Then a suspended sediment tracing study in the Murrumbidgee River, and a coarse bedload tracing study in the Snowy River are presented (Figure 5.1).

![Study site locations.](image-url)
5.2 Sampling and Sample Treatment

In the Ord River deposited bed sediment samples were collected from the dry channels of tributary and downstream reaches at confluences during the 1991 dry season. These samples were normally made up of many sub-samples collected from different bedforms along and across the channels. Bed sediment samples were wet sieved to obtain the fine sand fraction (63-125 µm) which was judged to be the modal grain size delivered to Lake Argyle. Suspended sediment samples from the Murrumbidgee River (section 5.3.2) were obtained with a continuous flow centrifuge. The median grain size of these samples is about 2 µm, and does not normally exceed 30 µm (Jon Olley, pers. comm.). Bedload samples from the Snowy River were sieved to recover the 0.5-1 mm fraction. All samples were dried at <50°C. Magnetic measurements were made as described in Chapter 3.

5.3 Sediment Tracing Applications

5.3.1 The Ord River

The 46 000 km² Ord River catchment is in the monsoonal tropics of Western Australia (Figure 5.1). Flow, and associated sediment transport is ephemeral, particularly at the beginning and end of the wet season when runoff results from discrete thunderstorms. During the wet season very large floods can occur. Outside the wet season most of the sand bed channels dry out leaving a few semi-permanent pools. Each of the major tributary catchments contains a complex range of rock types including Precambrian sediments, metasediments, and volcanics, Cambrian sediments and basalt, and Devonian sediments.

Extensive erosion has occurred in the catchment since the introduction of cattle grazing late last century. In 1972 the Lake Argyle dam was constructed on the Ord River for irrigation water storage. The sediment tracing method developed in this report was applied to see if the sources of sediment delivered to the reservoir could be determined. Deposited bed sediment samples were collected at eight major tributary junctions during the 1991 dry season along the extensive dry channel reaches (Figure 5.2).
The results of the confluence measurements are presented in Figure 5.3. At each of the confluences magnetic mineral characteristics, expressed as linear relationships between $\text{IRM}_{850}$ and $\chi$, clearly distinguish the tributary sources. The possible exception is Osmond Creek where the concentration range in the sample data is limited compared to the Ord River data. Even so, the tributary and resultant mix linear relationships are well defined. The regression relationships plotted in Figure 5.3 may vary slightly from the linear relationships used to determine the proportionate contributions discussed in
Section 3.4 because this method constrains the linear relationships to pass through a common point.

Relative tributary contributions, determined by the method described in Chapter 3, are given in Table 5.1. The results show that the Panton River and Osmond Creek have relatively high contributions, although confidence in the Osmond Creek result is low due to the large statistical uncertainty. At the three confluences where there is no detectable tributary contribution to the Ord and Panton rivers, the resultant downstream mix regression relationship lies outside the tributary inputs. An explanation for this is that the mix of bed sediment (characterised by the magnetic regression relationships) is not uniform along the channel because of the spasmodic nature of flow and sediment transport, particularly at the end of the wet season when flow is associated with individual thunderstorm events. In such circumstances bed sediment can move as discrete ‘slugs’.

Table 5.1 Relative tributary contributions to the Ord River and the Panton River at the Elvire River junction (63-125 µm fraction). Uncertainties are 1 standard error, or where the contribution is zero the upper 95% confidence limit value is given (as % in brackets) if it is >0.

<table>
<thead>
<tr>
<th>Tributary</th>
<th>Proportionate Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panton - Elvire</td>
<td>0 (4)</td>
</tr>
<tr>
<td>Panton</td>
<td>43 ± 7</td>
</tr>
<tr>
<td>Nicholson</td>
<td>0 (5)</td>
</tr>
<tr>
<td>Forrest</td>
<td>14 ± 14</td>
</tr>
<tr>
<td>Osmond</td>
<td>73 ± 31</td>
</tr>
<tr>
<td>Negri</td>
<td>19 ± 6</td>
</tr>
<tr>
<td>Spring</td>
<td>8 ± 12</td>
</tr>
<tr>
<td>Bow</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 5.3 Magnetic parameter relationships from the (a) Panton-Elvire, (b) Panton, (c) Nicholson, (d) Forrest, (e) Osmond, (f) Negri, (g) Spring, and (h) Bow river confluences (63-125 µm fraction).
The spatial variability of the channel bed sediment, as indicated by the variation in mineral magnetic properties, is illustrated in Figure 5.4. Here the IRM$_{850}$ vs. $\chi$ regression coefficients from the tributaries and main channel are plotted against distance downstream of the Panton River to a core site downstream of the Bow River confluence. Vertical lines connect tributary values with the corresponding upstream value from the Ord. Short horizontal lines point to the resultant downstream value. The horizontal dash-dot lines from 5-87 km, and 105-173 km are means of Ord River values for these reaches. The variation in the Ord values indicates that the mix of sediment varies along the river, as well as clearly showing the contributions from the Panton, Osmond and Negri tributaries.

Also plotted in Figure 5.4 (at 65 km) are data from a sediment profile located immediately downstream of the Forrest Creek confluence (OG-B). This profile was sampled to a depth of 1.5 m from a sequence of lateral bars on the same side of the main channel as the Forrest Creek tributary, so the site will preferentially receive sediment from the creek. Trees growing on the lateral bar sequence indicate that sediment has been accumulating for several years. In Figure 5.5a there are only four sample data available from Forrest Creek due to an error during sample preparation, however the available data are highly correlated. It can be seen that the OG-B profile site receives a consistent contribution from the Forrest River, averaging 56 ± 11%. This probably defines an upper limit of sediment contributions to the Ord River given that the site will preferentially receive Forrest Creek sediment.

Additional channel samples from the Panton River, and the Ord upstream of the Panton, were obtained in 1992. The data from these samples are almost indistinguishable from those obtained the previous year, indicating that over this period at least, relative sediment delivery from the two sub-catchments is a fairly constant.

An 8 m deep core was obtained at a site 4 km downstream of the Bow River at the head of Lake Argyle, where sediment has been accumulating since the early 1970s when the dam was constructed. The data show a high degree of consistency with depth (Figure 5.5b), and also with contemporary channel samples obtained from upstream of the core site. This indicates that the mix of sediment that has accumulated at this site has been remarkably constant for a period of about 20 years. However, it is not possible
to say where this mix of sediment has come from. The core data are not consistent with
the relatively uniform data trends upstream of the Bow River. It may be that the
sampled Bow River sediment is the product of local, late wet season storm activity, and
not representative of what is normally transported during the major part of the wet
season.

![Figure 5.4](image)

**Figure 5.4** Variation in $\text{IRM}_{850}$ vs. $\chi$ regression coefficients along the Ord River
downstream of the Panton River. While this diagram shows the downstream
trends in tributary contributions, it only approximately represents the
proportionate contributions.

The results presented here demonstrate the applicability of the tracing method in a
drainage network. Results from the two sequences of alluvial deposits show that such
sequences contain a useful record of temporal information. Re-sampling at confluences is also a way of obtaining temporal information about the constancy of, or changes in sediment delivery. Further sampling of alluvial sequences on the major tributaries and downstream reaches would provide a more complete understanding of changes in sediment delivery along the drainage network, particularly at Lake Argyle where the principal source has yet to be determined.

Figure 5.5  (a) Data from the lateral bar sequence downstream of Forrest Creek plotted with data from Forrest Creek and the Ord River upstream of the confluence; (b) the Lake Argyle core and upstream reach data.
5.3.2 The Murrumbidgee River

The Murrumbidgee River was selected to test how well the tracing method could determine the sources of fine suspended sediment. The reach of the river studied extends from the Burrinjuck Reservoir to Balranald, just upstream of the confluence of the Murray River (Figure 5.6), a distance along the channel of approximately 1150 kms. There is one major tributary, the Tumut River, at 130 km downstream of the reservoir, and a number of minor ones to about 400 km. The Tumut River is dammed at Blowering Reservoir, about 50 km upstream of the Murrumbidgee confluence. Downstream of the minor tributaries there are several irrigation water diversions. The principal rock types in the catchment below the dams are granite and sedimentary rocks.

Suspended sediment samples were collected at 12 locations along the main channel downstream of Jugiong Creek on 5 separate occasions, and from the tributaries at 3-5 different times during 1991-92. To obtain longer term suspended sediment data, a 67 cm clay sediment core was obtained from a cut-off meander loop known as Hook Billabong just downstream of Narrandera (previously discussed in Chapter 3), about 440 km downstream of Burrinjuck Reservoir. The billabong receives overbank flood flows at a return period of <2 years. The first appearance of $^{137}$Cs in the core at 35 cm shows that suspended sediment has been accumulating from at least 1960 (Olley, 1996).

The magnetic parameter data obtained from measurements of the suspended sediment samples are presented in Figure 5.7. In Figure 5.7a the Murrumbidgee River data from multiple samplings under different flow conditions form a well defined linear relationship. Data from the Tumut River form another, distinctly different linear relationship. This indicates that, on average, the Tumut River does not make a significant suspended sediment contribution, a conclusion that agrees with the sediment budget results of Olive et al. (1996, 1994) who showed from an analysis of turbidity and flow data that there is a very small contribution of suspended sediment from the Tumut River.
Figure 5.6 The Murrumbidgee River showing main channel sampling sites.
There are no data from the Murrumbidgee River upstream of the first tributary, Jugiong Creek. However, during the July 1991 flood, a large release of water from Burrinjuck Reservoir was sampled at two sites upstream of Narrandera, and then at Narrandera before and after the Burrinjuck flood peak arrived. It is apparent from the data shown in Figure 5.7a that the suspended sediment from Burrinjuck is different to that normally found in the Murrumbidgee. Conversely, sediment sampled from 'local' water prior to the arrival of the Burrinjuck discharge is entirely consistent with the rest of the Murrumbidgee data.

These results indicate that suspended sediments derived from the Tumut River and Burrinjuck Reservoir do not make a significant contribution to the Murrumbidgee, consistent with the results reported by Olive et al. (1996, 1994). The data obtained from samples collected at Narrandera during the 1991 flood, before the arrival of the Burrinjuck release water (known from monitoring of the hydrograph), indicate that the suspended sediment is derived from more local sources. This conclusion is supported by the data from catchments downstream of Jugiong Creek, shown in Figure 5.7b. With the exception of Billabung Creek, all of these catchments yield sediment with characteristics consistent with the sediment in the main channel. The consistency of the data from Hook Billabong (Figure 5.7a) also indicate that catchments downstream of the major dams have been the dominant sediment sources since at least 1960. Finally, the main channel sediment does not substantially originate from a mix of Tumut River and Burrinjuck derived sediment because some of the main channel data were collected upstream of the Tumut confluence, and are consistent with a contribution from Jugiong Creek (Figure 5.7a).

While the data show that the minor tributaries downstream of Jugiong Creek are the principal sources of suspended sediment, it is not possible to say what their relative contributions are because, with the exception of Billabung Creek, they are indistinguishable. The Hillas, Tarcutta, and Kyeamba tributaries mainly drain sedimentary rock catchments. Jugiong and Adelong catchments are mainly granodiorite, with some mixed sedimentary rocks in Jugiong, and volcaniclastic sediments and meta-basic igneous rocks in the Adelong Creek catchment.
Figure 5.7 (a) Magnetic parameter relationships of suspended sediment sample data from the main channel, the Tumut River, and the Hook Billabong core; (b) data from the main channel and the smaller tributaries of the Murrumbidgee River.
Billabung Creek catchment contains mainly mixed sedimentary rocks with some volcanics, which may account for the different magnetic characteristics. However, further discrimination of source areas would require sediment data from subcatchments that only drain a particular rock type to determine if soils developed on these rock types are magnetically distinguishable. From the results presented in Chapter 4, it would be expected that sediments derived from volcanic and sedimentary rocks should be readily distinguishable. As will be seen in the next chapter, granite rock source areas are also likely to produce magnetic parameter relationships different from those derived from volcanic and sedimentary rocks. If these source areas are distinguishable in the Murrumbidgee catchment, then the uniformity of the results may indicate a dominance of sediment originating from a particular rock type.

The Murrumbidgee study demonstrates that simple magnetic parameter relationships can be used to distinguish more than two different sources in situations other than confluence mixing. The potential of this approach is developed further in Chapter 6.

5.3.3 The Snowy River

The aim of this study was to see if coarse bedload contributions could be determined at major tributaries of the Snowy River. It was shown in Chapter 4 that the coarse sediment fraction could not be distinguished, despite the fact that the parent rock source areas (sedimentary and volcanic rocks) were very different. It was concluded that the lack of difference was due to the magnetic component being dominated by a common type of magnetic mineral inclusion within the sand particles.

In the Snowy River catchment the principal rock types in order of abundance are granite, sedimentary, and volcanic rocks. Tertiary basalt outcrops in the northeast of the catchment, while granite is most common in the north and west. Most of the southeastern third of the basin is made up of sedimentary and metamorphic rocks. There is therefore considerable diversity of rock types across the catchment.

The Snowy River flows through a narrow, steep sided valley along most of its length. According to a study by Brizga and Finlayson (1992) that mainly used analysis of historical and contemporary aerial photographs, sand is mostly being delivered to the
river from the Delegate River and tributaries further upstream (Figure 5.8), particularly granite areas. This is consistent with extensive erosion observed in the New South Wales part of the Snowy River basin.

Representative bed load samples were obtained from the six major tributaries of the Snowy River and reaches upstream and downstream of the junctions. The modal particle size range was determined by sieve analysis of sediment sampled from the reach below the Buchan River. As a result, all samples were sieved to recover the 0.5-1 mm fraction.

![Figure 5.8](image_url)  
**Figure 5.8** Major tributaries of the Snowy River sampled to determine their relative coarse bedload contributions.

Data from the six confluences studied are shown in Figures 5.9, and estimates of relative sediment contributions to the Snowy River given in Table 5.2. The Wullwye Creek data have a moderate amount of scatter, but the tributary and downstream relationships are still well defined, and sufficient to determine the proportionate contribution. As discussed in section 3.4, the Maclaughlin confluence data are
consistent with a common linear relationship that passes through, or close to the origin. In this case the mean tributary and downstream mix values of $\chi$ and $\text{IRM}_{850}$ were used to calculate the proportionate contribution, giving a mean value of 51%. However, while the statistical uncertainty is low, it takes no account of possible systematic errors associated with sampling. Sampling different locations along the reaches, or increasing the number of samples may result in a different range of concentration values, so there is much more uncertainty about this result.

<table>
<thead>
<tr>
<th>Tributary</th>
<th>Proportionate Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wullwye</td>
<td>70 ± 15</td>
</tr>
<tr>
<td>Maclaughlin</td>
<td>(51 ± 8)</td>
</tr>
<tr>
<td>Delegate</td>
<td>62 ± 9</td>
</tr>
<tr>
<td>Jacobs</td>
<td>15 ± 18</td>
</tr>
<tr>
<td>Deddick</td>
<td>4 ± 5</td>
</tr>
<tr>
<td>Buchan</td>
<td>5 ± 6</td>
</tr>
</tbody>
</table>

The linear relationships from the Delegate River junction are distinct and well defined. However, the Delegate River linear relationship is negative ($y = -1.3x + 8.3$), which can only be explained by the mixing of two end points. This was discussed in Chapter 3, and thought to be an unlikely mixing option because it would be expected that negative correlations or relationships with large intercepts would be more common if linear relationships originated in this way. As there are no other circumstances under which $\chi$ and $\text{IRM}_{850}$ can be negatively correlated, then the mixing of two data end points must occur, albeit infrequently. This is the only known example of a negative relationship between the two magnetic parameters.
Figure 5.9 Magnetic parameter relationships from the (a) Wullwye, (b) Maclaughlin, (c) Delegate, (d) Jacobs, (e) Deddick, and (f) Buchan river junctions on the Snowy River (0.5-1.0 mm fraction).

At the Jacobs, Deddick, and Buchan junctions the concentration ranges are restricted, however, it is clear that the relative contributions of these rivers are low. These outcomes are consistent with the conclusions of Brizga and Finlayson (1992)
who concluded that sand is mainly being delivered to the Snowy River from the Delegate River and tributaries further upstream where granite is common and erosion is extensive.

This study has demonstrated that it is possible to trace coarse sand bedload based on confluence sampling. This will probably work best where the tributary catchments are relatively large, and have a diverse mix of rock types.

5.4 Conclusion

The examples of stream network confluence tracing given in this chapter demonstrate the applicability of the method. The Ord River and Snowy River studies showed that measurements of fine and coarse sand fractions can be used to determine relative sediment contributions in large, remote catchments where no previous data existed, and monitoring of sediment delivery would have been very expensive to set up and maintain. Data from sequences of alluvial deposits proved to contain a valuable record of temporal information.

In the Murrumibidgee River it was shown that simple magnetic parameter relationships can be used to infer the sources of suspended sediment along an extensive reach of channel. While this approach was only quantitative in that it showed the presence or absence of a particular source (i.e. 0% or 100%), it demonstrated that a simple method of analysis is sufficient to confidently identify sediment sources. The results obtained were also consistent with the outcome of the sediment budget derived from turbidity and flow data.

In the next chapter the tracing method is developed beyond confluence mixing situations to tracing source types in medium to large catchments.
5.5 References


CHAPTER 6

A NEW APPROACH TO SEDIMENT TRACING IN LARGE CATCHMENTS

6.1 Introduction

The studies presented so far have mainly relied on spatially limited mixing situations, such as at confluences where the possible source inputs are obvious. In principal the method can be applied to any two component mixing situation, so even in a large catchment, if there is reasonable confidence that only two distinguishable types of sediment are being produced from areas with different rock types, then it should be possible to determine their relative contributions to reaches downstream.

In Chapter 4 it was shown that sediments derived from soils developed on different rock types were magnetically distinguishable. Sediment transport processes are also likely to promote the occurrence of sediment that is typical of soils developed on particular rock types, because transport processes will tend to average out any local heterogeneity. The confluence examples presented previously indicate that complete mixing can occur within relatively short distances downstream of the combination of two distinct streams of sediment, so tracing sediment along reaches at small to large scale should be possible.

In this chapter the scope of the method is extended to sediment tracing at whole catchment scale. The first part of the study looks at a 420 km² sub catchment of the Namoi River basin where the contributions to a water storage of two distinct soil types derived from two different rock types is determined. The method is further expanded in concept, and in spatial extent to larger areas of the basin by characterising the magnetic properties of sediment derived from areas that only contain a particular rock type, and estimating the contribution of these sediments to major rivers. Included in this chapter is a study of the Darling-Barwon River that drains a large area of southern Queensland and northern and central New South Wales, as well as some of its major tributaries, including the Namoi River.
6.2 The Sources of Sediment Delivered to Chaffey Reservoir

In this part of the study the sources of fine sediment reaching Chaffey Reservoir are determined. Rather than tracing sediment along the drainage network, the mineral magnetic properties of soils developed on the two major rock types are characterised. The possible origins of sediment delivered to the reservoir are basalt derived soil eroded from the steep uplands of the catchment, and soils developed on the sedimentary rock lowland parts of the catchment. The aim is to determine the relative contributions of these soils to sediment in the reservoir. It is assumed that because of the relatively short transport distances involved, the magnetic properties of the soils are conserved after they are eroded and transported to the reservoir.

The catchment of Chaffey Reservoir is 420 km², and rises from 520 m elevation at the full storage level to over 1300 m in the headwaters. The topography ranges from low to moderate gradients in the lower catchment, grading to steep in the headwaters of the Peel River and many of its tributaries. The rock type found in most of the upland catchment is Tertiary basalt. Most of the alluvial deposits along streams in the lower valley are dark reddish-brown, and appear to originate from basalt soils. Alluvium derived from soils developed on sedimentary rocks is yellowish brown. Sedimentary rocks of Carboniferous to Devonian age are the dominant rock type in the lowland catchment, accounting for about 70% of the total catchment area (Figure 6.1).

6.2.1 Sampling and Sample Treatment

A 65 cm core that penetrated to the pre-reservoir soil was obtained from exposed sediment deposited at the head of Chaffey Reservoir during a period of low water level. The reservoir is highly eutrophic, and the bottom sediments are normally anoxic and reducing, so the core location was chosen as close to the inflow of fresh water as possible. The core was subsampled at contiguous 5 cm intervals, and no trends were observed in the magnetic data down the core that would indicate post-depositional alteration, or the formation of authigenic magnetic minerals.

Tertiary basalt and sedimentary rock derived soils were sampled by shallow coring to 20 cm at 15 sites, and 0-5cm surface samples from 11 sites (Figure 6.1). The soil cores were subsampled in 4 cm increments. All samples were wet sieved to recover the
fraction finer than 20 µm (clay and fine silt), and dried at 50°C. This size fraction was selected because sediment in the reservoir core consisted of fine silt and clay. The samples were measured as described in Chapter 3.

**Figure 6.1** Chaffey catchment showing sampling sites and the extent of the basalt.

**6.2.2 Results**

As discussed in Chapter 2, magnetic enhancement of topsoils can occur by inorganic pedogenic processes. Data from the soil cores were plotted to see if there were any significant trends that might influence the soil source tracing results. Examples from soils developed on both rock types are shown in Figure 6.2. No consistent patterns
emerged, with data from soil profiles either tending to group together or form linear relationships. In the linearly related data from the soils derived from sedimentary rocks, some profiles had decreasing concentration with depth, although this trend was not universal. However, the relationship between IRM and $\chi$ remained constant. The soil cores may not have penetrated deep enough to observe substantial changes in magnetic characteristics, although Maher and Taylor (1988) showed significant reductions in IRM and $\chi$ concentrations by 20 cm depth in an Exmoor soil. The lack of consistent changes with depth in the soil profiles from Chaffey catchment indicates that there is unlikely to be significant variation in magnetic properties at greater soil depths.

The results of the catchment and reservoir sample measurements are given in Figure 6.3. All the data from the soils developed on sedimentary rocks plot as a well defined linear relationship. Data from the basalt soils form a distinct linear relationship with much higher concentrations. The reservoir core values plot close to the basalt soil data, clearly showing that the reservoir sediment is mainly derived from basalt soils.

Using the procedure described in Chapter 3, the relative basalt-soil derived sediment contribution to the reservoir core is calculated to be $83 \pm 3\%$. This result is consistent with that obtained by Caitcheon et al. (1995), where linear relationships between Fe/Ti and Al/Ti were used to determine a basalt-derived soil contribution of $88 \pm 4\%$.

While it is apparent that basalt-derived soil is the principal sediment source, the tracing method cannot distinguish between sediment delivered directly from the upland basalt areas of the catchment, and basalt-derived valley fill alluvium eroded from the banks of the Peel River on the lowland floodplain. The alluvium has the distinct dark reddish-brown colour of basalt-derived soil, and its origin was confirmed by plotting data from a lowland floodplain soil core with the other basalt-derived soil data (Figure 6.4).

In the study reported by Caitcheon et al. (1995), $^{137}$Cs was used to estimate that about 50% of the sediment in the reservoir core had come from surface soils, so the remaining 50% must originate from subsoils. As gully or channel bank erosion was not prevalent in the uplands, it was concluded that most of the subsoil had come from lowland...
channel bank erosion. The combination of a spatial tracing, and a topsoil tracing method demonstrates the benefit of using more than one approach to sediment sourcing.

Figure 6.2 Soil profile data from (a) sedimentary rock, and (b) basalt rock areas in Chaffey catchment.
Figure 6.3 Magnetic parameter relationships between the basalt and sedimentary rock source areas, and the sediment in Chaffey Reservoir.

Figure 6.4 Floodplain alluvium from the lower Peel River showing a clear basalt origin.
6.3 Tracing the Sources of Sediment in the Namoi River

The Chaffey study showed that the magnetic properties of soils developed on two different rock types are distinguishable, and that these magnetic characteristics can be used to determine the relative contributions to a binary sediment mix in the reservoir. In the Namoi basin the relationship of soils and sediments is examined further by comparing the characteristics of sediment derived from other basalt and sedimentary rock areas of the catchment to the Chaffey soils. The characteristics of sediment derived from areas of different rock types is then used to estimate the relative contributions of fine sediment in the Namoi River.

The importance of basalt source areas has been demonstrated in the Chaffey study. In the Namoi Basin extensive lowland plains of Quaternary alluvium have developed from soils and sediments principally derived from basalt. Basalt outcrop has been much more extensive in the past, there being many outlying remnants of Tertiary, Jurassic, and Permian basalts in the basin (Figure 6.5).

The other major rock types are complexes of sedimentary rocks ranging from Jurassic to Devonian in age. In the far west of the basin there are Silurian-Devonian sedimentary and metamorphic rock complexes. Granitic rocks are the principal rock type along the north-eastern margin of the basin.

The object of this part of the study is to first sample sediment derived from areas that only contain a particular major rock type, or complex of related rock types. Given that these areas produce magnetically consistent and distinguishable sediment, then it should be possible to determine the relative contributions of these source areas to sediment in the Namoi River if the sources can be resolved as two component mixes.
Figure 6.5 The Namoi River basin geology and river sampling sites.
6.3.1 Sampling and Sample Treatment

Deposited channel sediment samples from the principal rock type source areas were collected at the sites shown in Figure 6.5, and fractionated by settling in a water column to recover the very fine silt and clay fraction (<10 µm). By observation, this is the predominant sediment size fraction transported and deposited in the lower part of the Namoi River. Samples were pre-treated in an ultrasonic bath to disperse the particles before being thoroughly mixed in a water column. After 50 minutes the sediment remaining in suspension above 25 cm depth was siphoned off and dried at 50°C. The samples were measured as described in Chapter 3.

6.3.2 Results

A comparison of soils and sediments is made between the soils derived from basalt and sedimentary rocks in Chaffey catchment, and sediments derived from other basalt and sedimentary rock areas in the uplands of the Namoi basin. Basalt derived sediment was sampled from four subcatchments along the base of the Liverpool Range that defines the southern margin of the basin (Figure 6.5). Sediment originating exclusively from the Silurian-Devonian sedimentary and metamorphic complex subcatchments in the south-east of the basin was compared with the soils in Chaffey catchment derived from Carboniferous-Devonian sedimentary rocks.

Figure 6.6 shows that there is a close relationship between the soils and sediments derived from similar rock types. The offset of the sediments from the soils may be due to the slightly different particle size fractions analysed, where the fractionated soil samples (<20 µm) are likely to have slightly more silt than the sediment samples (<10 µm). Differences may also arise from variations within the soil and rock types from different parts of the catchment, however, the fundamental relationships defined by the regression coefficients are indistinguishable. The basalt derived soils and sediments have regression coefficients of 14.0 ± 0.4, and 14.4 ± 2.2 respectively, while the sedimentary-metamorphic complex rocks have respective coefficients of 5.6 ± 0.2, and 6.6 ± 0.3.
Apart from basalt and sedimentary rocks, the other possible major source rock-type in the eastern Namoi basin is granite. In Figure 6.7a the data from granite-derived sediment plots between the basalt and sedimentary-metamorphic source data. Data from sedimentary-metamorphic rock complexes from the upper McDonald River is included with the other data from this source. In the lower parts of the river where it flows through granite rocks the data show that the river sediment is dominated by granite (Figure 6.7b). The granite derived sediment, and MacDonald River linear relationships are substantially levered by one point in each case, but their consistency indicates that these relationships are genuine. The MacDonald River becomes the Namoi River further downstream, and at the confluence of the Manilla River the sediment is clearly dominated by sedimentary-metamorphic complex rocks. Data from Keepit Reservoir are also consistent with this source, as are the data from the Manilla River, although the latter may also contain an additional component from an unidentified source.

**Figure 6.6** Magnetic parameter relationships showing the close relationship between soils and sediments derived from similar rock types.
Figure 6.7 (a) Granite-derived sediment data plots between the basalt and sedimentary-metamorphic source data; (b) expanded scale of view graph (a) showing the MacDonald, Namoi, and Manilla river sediment data plotted with sediment derived from basalt, granite, and sedimentary-metamorphic rock sources.
It is clear from these results that sediment in the Namoi River down to Keepit Reservoir is dominated by sedimentary-metamorphic complex rock sources. The Peel River drains a catchment containing mainly Carboniferous-Devonian sedimentary rocks. The Peel River data plotted in Figure 6.8a were obtained from samples taken at a site on the lower river in 1995, and at four sites downstream of Tamworth in 1997 sampled immediately after a significant flood in February. All of these data are consistent with the results from sediment derived from sedimentary-metamorphic complex rocks, as are the data from the Namoi River upstream of the Mooki River confluence. The results show that, with the exception of the MacDonald River where it flows through granite, sediment in the major tributaries and the Namoi upstream of the Mooki River is derived from areas that contain sedimentary, or sedimentary-metamorphic complex rocks.

Sediment derived from major rock types in the southern and eastern uplands of the Namoi Basin have internally consistent magnetic properties that are distinguishable between rock types. In the eastern part of the basin the most common rocks are sedimentary or sedimentary-metamorphic complex rocks, and sediment derived from these rock types are also the dominant sediment sources. In the central part of the basin basalt and sedimentary rocks predominate, so it would be expected that the Namoi River and its tributaries in this part of the catchment will transport a mix of sediment derived from these two sources.

In Figure 6.8b data from four sites on the Lower Mooki River are plotted. There is a very close relationship between these data and results from six sampling sites downstream of the Mooki-Namoi confluence to Wee Waa. These samples were all collected immediately after the February, 1997 flood. Using the method described in Chapter 3, the proportionate contribution of the Mooki to the Namoi is calculated to be 80 ± 7%, taking the Peel River as the other source. The Mooki data also appear to be derived from a mix of sources. The basalt derived sediment samples (Figure 6.8) were collected from the headwaters of the Mooki River, however, there may be variations in the Mooki catchment basalt not accounted for by the existing data. There may also be a sedimentary rock derived sediment component in the Mooki samples, but more data are required to determine what the mix of sources types in the Mooki is.
Figure 6.8 (a) Peel River and downstream Namoi River data plotted with sediment derived from basalt, granite, and sedimentary-metamorphic rock sources; (b) Mooki River, downstream Namoi River, and Coxs Creek data plotted with sediment derived from basalt and sedimentary-metamorphic rock sources.
The Coxs Creek data (Figure 6.8b) are also from samples obtained immediately after the 1997 flood. This sediment appears to be mainly basalt in origin. Apart from basalt, sedimentary rocks are the other major rock type in the Coxs Creek catchment (Figure 6.5). Assuming that the sedimentary-metamorphic and basalt rock derived sediment data represent the two sources, then the relative basalt rock contribution to the Coxs Creek sediment is 83 ± 5%.

Further evidence of the consistency of the sedimentary rock derived source characteristics comes from samples collected from Bohena Creek that drains an area that almost exclusively contains sedimentary rock (Figure 6.5). These results are shown in Figure 6.9a, along with data from Namoi River samples obtained in 1995 at Narrabri, near Pilliga, and about 10 km upstream of Walgett at Six Mile Reserve.

Like the Coxs Creek data, the three Narrabri sediment samples with the highest concentrations (regression line shown in Figure 6.9a) have a substantial basalt rock derived contribution, calculated to be 70 ± 4% by the method described in Chapter 3. Also potted in Figure 6.9a are data from Quirindi Creek, a tributary of the Mooki River. The upper part of Quirindi Creek catchment where the sediment samples were collected only contains basalt and sedimentary rocks. The Quirindi Creek data are consistent with the Narrabri data, which is further evidence that these sediment samples contain a mix of sediment derived from basalt and sedimentary rocks.
Figure 6.9 (a) Data from Bohena Creek sediments are consistent with the other Namoi sedimentary-metamorphic rock derived sediments. A regression line is drawn through the Narrabri data only, and does not include the Quirindi results. (b) Data from the lower Namoi River sediments.
The basalt source contribution calculated above used three of the four samples obtained from Narrabri in 1995. The fourth sample has a much lower concentration than the basalt data, and plots with the lower Namoi sample data from Pilliga and Walgett shown in Figure 6.9b. The reason for this significant concentration difference was introduced in Chapter 3, where it was shown that there is a negative correlation with silica (Figure 3.6). In Figure 6.10 silica concentrations from sites along the Namoi River are plotted in relative downstream order from the Peel River to Walgett. All of these results, including the averaged values from the Peel, Mooki, and Coxs tributaries were obtained immediately after the 1977 flood referred to above. The other averaged results (with standard error bars) from Narrabri, Pilliga and Walgett were sampled in 1995. There is a general trend of decreasing silica concentration downstream to Wee Waa in the post 1997 flood data. At the two most downstream sites (Pilliga and Walgett) the silica concentration is significantly higher, indicating that there may be a source of silicious sediment along this reach of the river, or possibly upstream of Narrabri if the single very high value shown in Figure 6.10 is also considered. From this it is concluded that the high silica and low $\chi$ concentration results from the lower river show that there is a discontinuity in the characteristics of the sediment downstream of Wee Waa.

Plotted in Figure 6.9b are data from a 70 cm deep core of channel deposits from Six Mile Reserve that has been age dated by Olley et al. (1998) using optically stimulated luminescence, the dates showing that sporadic deposition has occurred from the present to 146 $\pm$ 17 years. These results indicate that the source mix has been consistent for an extended period.

It can also be seen in Figure 6.9b that the data from the Pilliga and Six Mile Reserve samples have a regression line slope similar to the basalt source line, while the slope of the core data regression line is consistent with a mix of the two principal sources. However, the low magnetic concentrations of the lower river sediments are more consistent with the low concentration end of the sedimentary rock source line. The low concentrations in the lower river could occur by the same sorting process observed in the Murrumbidgee River (see section 3.3.3), where it was concluded that suspended sediment particles with higher density, and a higher proportion of associated heavy
mineral such as surface-bound Fe minerals, were preferentially deposited upstream, while lower density, lower magnetic concentration particles were preferentially transported to the lower river. Transport distances in the lower Namoi are large and flows tend to be very low, so it is possible that only the lowest density particles, almost devoid of any associated heavy mineral (and magnetic) component reach the lower river. If this is so, then the lower Namoi sediment regression lines may still retain the original magnetic basalt and sedimentary-metamorphic components (at much lower concentrations), but not show the contribution of a third, but significant magnetically undetectable component.

**Figure 6.10** Trends in silica concentrations down the Namoi River.
As shown above, the lower Namoi sediment regression relationships have slopes consistent with a relatively high basalt source contribution. Martin and McCulloch (in press) used the isotopic composition of strontium and neodymium to infer that a sample collected from Six Mile Reserve upstream of Walgett predominantly originated from sedimentary-metamorphic complex or granitoid rock sources. This result and the relatively high silica content of the lower Namoi sediment indicates that they are unlikely to contain a significant basalt component. Basalt typically has a silica content of 45-50% (Nockolds et al., 1978). The large difference in concentration between the lower Namoi and basalt source data is an indication that there is likely to be a significant contribution from a diluting, non-magnetic component.

6.3.3 Conclusion

The results presented above show that the magnetic characteristics of soils and sediments derived from major rock types have internally consistent properties that are distinguishable. In the Namoi Basin the principal rock types are basalt and sedimentary-metamorphic complex rocks, and the relative contributions of sediment derived from these two sources can be determined in the main channel and its major tributaries. This study has shown that the confluence tracing method can be applied more generally, but with greater caution. Major source types can be identified by sampling channels that integrate sediment delivered from these sources, and traced along the drainage network. Significant concentration differences between one or more of the source types, and sediment further down the stream network may indicate a contribution by an undetected, non-magnetic sediment component.
6.4 Tracing the Sources of Fine Sediment in the Darling-Barwon River

This part of the study builds on the results from the Namoi River, which is a tributary of the Barwon River. Data from two other basalt and sedimentary-metamorphic rock sources are presented to demonstrate source consistency with other parts of the Darling basin. The relationship between these data and data from the main Darling-Barwon channel, major tributaries along the studied reach, and core samples is examined to try to ascertain where the main channel sediment has come from.

The Darling River and its tributaries drain a substantial part of south eastern Australia. From its junction with the Murray River, the Darling extends 1500 km upstream to the first major tributary, the Culgoa River. Upstream of this junction it becomes the Barwon River that drains large tributaries in New South Wales and Queensland (Figure 6.11).

Basalt outcrops in the headwaters of all of the major tributaries of the Darling River, with the exception of the Bogan River (Figure 6.11). The original extent of basalt is unknown, but it is likely to have been much more extensive than the highly dissected present-day outcrop, which is about 27% of the outcropping rock in the eastern uplands of the major tributaries. Along the rest of the eastern margin of the Darling River Basin, outcrops of sedimentary, low grade metamorphic, and acid to intermediate igneous rocks (e.g. granite) of mainly Permian to Silurian age occur. West of the major rock type outcrops, the remaining areas of the major tributary basins are mainly alluvium derived from the uplands.

The Namoi River basin is typical of most of the other major eastern tributaries of the Darling River where basalt is present in the headwater catchments. Sedimentary and sedimentary-metamorphic complex rocks are the most common rock types. Relatively small areas of granitic rocks occur in the headwaters of the Namoi, as they do in some of the other major tributary basins of the Darling (Figure 6.11), however it is assumed that, like the Namoi, granite sources do not make a significant contribution to sediments in the lower reaches of the Darling’s tributaries. For these reasons, the basalt and sedimentary-metamorphic rock source data from the Namoi are used to try to determine the origin of sediment in the Darling-Barwon River. It is also assumed that all of the
sediment delivered to the river comes from the major eastern catchments, because, as discussed below, this is where the great majority of the flow comes from. The basin north and west of the Culgoa-Condamine River channel is semi-arid, and runoff is very infrequent.

Figure 6.11 Geology of the Darling River basin also showing river sampling sites.
The major tributaries of the Darling River originate in the eastern highlands along the Great Dividing Range. These rivers generally flow west from steeper uplands of over 1500 m, down to low relief plains with well developed distributary systems (Riley & Taylor, 1978). Most water is delivered from the Macintyre-Boomi Rivers, followed in order by the Namoi, Culgoa, Macquarie and Bogan Rivers (Short et al., in prep). The total basin area is 650,000 km².

The prevailing rainfall regime is semi-arid (mean annual rainfall, 400 mm), the driest areas being the western plains (median annual rainfall <200 mm). Highest rainfall occurs along the Great Dividing Range on the eastern edge of the basin (750 mm, with higher local maximums). There are north-south gradients of decreasing temperature, solar radiation, and summer rainfall, as well as increasing winter rainfall. East-west gradients are increasing temperature, and decreasing rainfall (Walker, 1986).

6.4.1 Sampling and Measurements

Surface grab samples of recently deposited sediment were collected from 8 locations along the Darling-Barwon River from Bourke to upstream of Collarenebri (Figure 6.11). Sediment grab samples were also taken from 5 sites along the Bogan River channel from the upper catchment down to its confluence with the Darling River. The Bogan River basin has no basalt outcrops. A further 5 sediment samples were obtained from one of the basalt headwater catchments of the Condamine River in southern Queensland. Channel bed grab samples were obtained from the lower reaches of the Mehi, Macquarie, Culgoa, and Warrego rivers relatively close to their confluences with the Darling-Barwon. A bench upstream of the Namoi River and beside the main channel was cored to 118 cm, and an infilled channel downstream of Namoi River, also beside the main channel was cored to 126 cm. Both coring locations are below the bank full level, and so would be inundated by floods relatively frequently. A 55 cm sediment core was obtained from Bourke Weir.

All of the sediment samples were treated in an ultrasonic bath to disperse the particles before settling in a 25 cm water column for 50 minutes to recover the <10 µm fraction. Like the Namoi River, most of the sediment transported in the Darling-Barwon is very
fine and predominantly <2 \(\mu\)m (Woodyer, et al., 1979). Magnetic measurements were made as described in Chapter 3.

6.4.2 Results

The data from sediment derived from the basalt and sedimentary-metamorphic rocks in the Namoi catchment are shown in Figure 6.12. Also plotted are data from basalt derived sediments from the headwaters of the Condamine River in southern Queensland. These data are entirely consistent with those from the Namoi catchment basalt, increasing confidence in the spatial continuity of the magnetic characteristics of sediment from this source. Data from the Bogan River sediments are also shown in Figure 6.12. This catchment contains no basalt outcrop, the predominant rock types being a mix of sedimentary, and acid to intermediate volcanic rocks (rhyolite and andesite), with less common outcrops of granite and metamorphic rocks. The Bogan River data linear relationship is similar to that of sedimentary-metamorphic rock source catchments in the Namoi Basin (Figure 6.12 and Table 6.1). These results increase confidence that the parent rock type, soil, and sediment relationships observed in the Namoi catchment are consistent with those found elsewhere the Darling River basin. In particular, the sediment from basalt source areas is magnetically distinct, and readily distinguishable from sediment derived from other major rock types.
Figure 6.12 (a) Magnetic data from the Namoi basin and the upper Condamine River catchment. (b) Magnetic data from the Darling-Barwon and Bogan rivers.
Table 6.1 Regression relationships between IRM$_{850}$ and $\chi$ from sources and resultant mixes in the Darling River basin.

<table>
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<th>Source Description</th>
<th>Regression Relationship</th>
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<th>n</th>
</tr>
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<td>Bourke Weir core</td>
<td>$14.9x - 0.9$</td>
<td>0.96</td>
<td>20</td>
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<tr>
<td>Barwon River core upstream Namoi River</td>
<td>$10.9x - 0.9$</td>
<td>0.63</td>
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<td>Barwon River core downstream Namoi River</td>
<td>$18.8x - 2.2$</td>
<td>0.93</td>
<td>14</td>
</tr>
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<td>Darling-Barwon channel sediment</td>
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</tr>
<tr>
<td>lower Namoi River core</td>
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<td>0.97</td>
<td>7</td>
</tr>
<tr>
<td>sediment from lower Namoi River (downstream Narrabri)</td>
<td>$12.6x - 0.9$</td>
<td>0.99</td>
<td>8</td>
</tr>
<tr>
<td>sediment derived from soil developed on sedimentary-metamorphic rocks (Namoi catchment)</td>
<td>$6.5x + 0.9$</td>
<td>0.96</td>
<td>17</td>
</tr>
<tr>
<td>soils developed on sedimentary rocks (Chaffey catchment)</td>
<td>$5.3x + 0.2$</td>
<td>0.97</td>
<td>35</td>
</tr>
<tr>
<td>Barwon River core upstream Namoi River</td>
<td>$12.6x + 4.0$</td>
<td>0.91</td>
<td>6</td>
</tr>
<tr>
<td>sediment derived from soil developed on basalt (Namoi catchment)</td>
<td>$14.4x - 2.2$</td>
<td>0.81</td>
<td>12</td>
</tr>
<tr>
<td>soils developed on basalt (Chaffey catchment)</td>
<td>$10.6310.9x - 0.9$</td>
<td>0.97</td>
<td>35</td>
</tr>
<tr>
<td>sediment derived from soil developed on basalt (Condamine catchment)</td>
<td>$12.6x + 4.0$</td>
<td>0.91</td>
<td>6</td>
</tr>
<tr>
<td>sediment derived from soil developed on basalt (Namoi catchment)</td>
<td>$14.4x - 2.2$</td>
<td>0.81</td>
<td>12</td>
</tr>
<tr>
<td>sediment derived from soil developed on basalt (Namoi catchment)</td>
<td>$12.6x + 4.0$</td>
<td>0.91</td>
<td>6</td>
</tr>
<tr>
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<td>0.81</td>
<td>12</td>
</tr>
<tr>
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<td>0.91</td>
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<tr>
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<td>$14.4x - 2.2$</td>
<td>0.81</td>
<td>12</td>
</tr>
</tbody>
</table>
The available data shows that areas of the Darling-Barwon basin with the same or similar rock types produce sediment with magnetic properties that are the same or similar. The aim now is to see whether relative contributions from these sources to the sediment in the river can be determined. Data from bed samples collected along the Darling-Barwon channel from upstream of the Mehi River near Collarenabri, to Bourke about 600 km downstream are shown in Figure 6.12b. The data form a linear relationship (Table 6.1), however, closer inspection (Figure 6.13a) shows that a group with higher concentrations (group 1) are from the reach of the Barwon River downstream of the Namoi River to the Macquarie River. A second group with lower concentrations (group 2) is from the reach of the main channel between the Macquarie River to Bourke. The last group (group 3) from the Barwon upstream of the Namoi River has the lowest concentrations. The concentrations in group 1 can be explained by adding sediment from the Namoi that has a higher average concentration, to sediment from the Barwon upstream that has a lower concentration. However, the lower concentrations in group 2 can be explained by contributions from the Namoi River, the Barwon upstream of the Namoi, and the Macquarie River (Figure 6.13c). The mean concentration values of the Namoi, and Barwon immediately upstream and downstream (groups 1 and 3) of the Namoi confluence can be used to calculate a proportionate contribution of 38 ± 15% for $\chi$, and 47 ± 14% for IRM$_{850}$, giving an overall mean contribution from the Namoi of 43%. This result is consistent with that of Olley and Caitcheon (1996), who found that the Namoi sediment contribution was 44 ± 4% using geochemistry data.

The grouping of data from different reaches of the Darling-Barwon channel to form a linear relationship (Figure 6.13a) raises the question about whether the linear relationship genuinely reflects the mixing of original sources that have distinct linear relationships, or whether this is due to the incidental mixing of groups with different concentrations. In Figure 6.13c the Namoi and Bogan rivers are the only tributaries that have consistent linear relationships. All of the other tributary data tends to cluster about, what is termed here, a concentration ‘end-point’. This may be the result of a number of transport related processes. For example, in Chapter 3 it was shown that $\chi$ concentrations in the Murrumbidgee River declined exponentially with transport distance, probably due to sorting of the suspended sediment. Dilution by particles that
Figure 6.13 (a) Grouped data from three reaches of the Barwon River. Dashed regression lines are from lower Namoi River data and extrapolations of the basalt and sedimentary-metamorphic data. (b) Core data from the Darling-Barwon. (c) Darling-Barwon tributary data with extrapolated major source
do not have a detectable magnetic component is another possibility. This was thought to be the reason for the low magnetic concentrations in the lower Namoi sediments. A third option is that because transport distances in river systems like the Darling-Barwon are long, there is a greater likelihood that sediment will be deposited and stored in the channels for extended periods. If the sediment is deposited in the bottom of pools that become anoxic and reducing during the droughts that frequently occur, then there is an opportunity for dissolution of the magnetic, surface-bound Fe component. Any or all of these processes could result in low magnetic concentrations that no longer form distinct linear relationships.

Sediment cores were obtained from Bourke Weir, and sites on the Barwon River immediately upstream and downstream of the Namoi River confluence to see if any temporal trends in sediment delivery could be detected. The core from Bourke Weir was not age dated, but it probably represents several years deposition. Core sites on the Barwon river were above the bed of the main channel but below bank-full level. The downstream core site was an old, infilling channel, while the upstream site was a broad depositional bench. Both of these cores were dated by optically stimulated luminescence, giving basal dates of 132 ± 12 years for the upstream core, and 223 ± 20 years for the downstream core (Jon Olley, pers. comm.). Top of core dates were consistent with recently deposited sediment.

The data from these cores is given in Figure 6.13b, and the regression relationships shown in Table 6.1. All of the data from the cores are internally consistent and linear, indicating extended periods of deposition of well mixed sediment. There were no concentration trends down the cores. While the mix of sediment may be fairly constant at particular sites, the linear relationships generated may arise from the mixing of low concentration end-points as occurred in the Barwon data, so the core linear relationships may not be related directly to the original sources. Also the core data have very low concentrations, and matching the source and deposited sediment linear relationships would require an unacceptable amount of extrapolation. Under these circumstances it is likely that spurious source matches could occur.
6.5 Conclusion

The Darling-Barwon core and channel sediment samples have magnetic mineral concentrations that are significantly less than those of the basalt source type identified in this study. Transport related processes are likely to be responsible for this reduction in concentration. The linear relationship observed in the Darling-Barwon channel data appears to be the result of mixing between two concentration end-points, that is, from the lower Namoi River and the Barwon upstream of the Namoi confluence. This means that this linear relationship is not directly a result of the mixing of the principal source types. The core data obtained from along the channel are internally consistent and linear, but these linear relationships may also result from the mixing of low concentration end points, particularly downstream of confluences, so that they also may not be directly related to the source types. Given that this is a possibility, and that it will be difficult to know what processes are involved in generating the linear relationships where concentration differences may have a significant effect, then their use to determine source contributions must be treated with caution.

In the Darling-Barwon river the problems discussed above mean that it has not been possible determine the sources of the sediment based on the binary mixing of linear relationships. At this end of a large river system concentrations have reached an end-point so that linear relationships either do not exist, or if they do, they may not directly result from the source types that the sediments originate from. In such a large river system all of the major tributaries must by sampled in as much detail as the Namoi and Bogan rivers were sampled. Otherwise it cannot be assumed that all of the major source types have been identified, and their relative contributions along their respective tributary systems adequately determined. In large river systems studies are also required to understand transport related processes, particularly concentration reduction, and the possible generation of linear relationships that are not directly related to source types.

This study has also demonstrated that large concentration differences between the sources and the depositional sinks will probably mean that source matches cannot be made reliably. In this respect the method developed in this report is not independent of concentration changes.
In the Namoi River basin, however, it was shown that the binary tracing method could be used, at least in the upper to mid-basin. Here sediments derived from soils developed on different rock types are magnetically distinct, and these differences could be traced down through the river system. In the lower part of the river there appears to be a significant contribution by a diluting, non-magnetic component, an outcome that is probably due to the preferential transport of less dense, low magnetic concentration suspended sediment particles. As was shown in the Darling study, a significant difference in concentration between one or more of the sources and the sediment downstream, probably indicates that source matches cannot be made reliably. In such cases measuring geochemical parameters such as silica concentration may indicate the presence of a significant non-magnetic component.
6.6 References


CHAPTER 7

SUMMARY AND CONCLUSION

In Chapter 2 a review of previous studies that made use of the natural mineral magnetic properties of sediment to determine sediment sources identified a number of problems with many of the tracing methods. These included a lack of testing that magnetic properties are conserved within the spatial and temporal scales appropriate to the studies, concentration changes associated with sediment transport, a lack of knowledge about how representative the magnetic fraction is of sediment as a whole, and with the exception of Lees (1994) study (ref. Chapter 2), no formal way of measuring the spatial heterogeneity of sources, and no attempt to determine statistical uncertainties associated with source contribution calculations. The problem of statistically ‘unmixing’ more than four sources, and the masking of magnetically weak sources by stronger ones was also identified in Lees study. The range of multi-parameter, linear modelling approaches used for determining source contributions, and the lack of concessus about, or evaluation of which method is the most appropriate highlights a weakness in the multi-parameter modelling approach. There was a general lack of information published about the linear modelling algorithms used, so there may well be undocumented sources of uncertainty contributing to erroneous outcomes. These problems highlighted the need for a simpler, more transparent approach to sediment tracing using mineral magnetism.

A major difference between the multi-parameter approaches to sediment tracing, and the method developed in this report, is that the approach developed here is applicable at any scale where there are two distinguishable sources of sediment. Previous approaches have relied on being able to characterise all of the potential sediment source types in a catchment, a requirement that is difficult to meet when there are a large number of sources. This can be a problem in small catchments, but it is more likely to be a problem as catchment size increases.

Many of the previous multi-parameter approaches to sediment tracing have relied on developing site-specific models based on parameters able to distinguish sediment sources in a particular situation. This may introduce inconsistencies in the outcomes between different sites, because, for example, some parameters may vary in terms of
how representative they are of the sediment as a whole. The consistent application of the method developed in this report significantly reduces or eliminates this uncertainty.

While the studies discussed in Chapter 2 showed that particular parameters (including major and minor element chemistry, and some radionuclides) may discriminate between particular sediment sources in particular situations, in the method developed in this report, only two representative magnetic parameters were used ($\chi$ and $\text{IRM}_{850}$). This is because they are easy to measure, they are known to be collectively sensitive to all of the variations in magnetic mineral characteristics, and, as shown in this study, they measure the properties of magnetic minerals that are conserved in fluvial environments, and they are broadly representative of sediment as a whole.

In Chapter 3 the constancy of magnetic parameter relationships, and by inference magnetic mineral assemblages, was empirically demonstrated spatially in channel reaches, and temporally as measured in accumulated sediment deposits. It was shown that mineral magnetism can be used to trace sediment sources at stream junctions where two catchments deliver magnetically distinguishable, averaged source mixes. The method depends on obtaining representative bed-load or suspended sediment samples from tributary and downstream reaches at a confluence. Magnetic parameters are measured after particle size fractionation. If bi-variate plots show the tributary data are linearly related, and distinguishable, then proportionate tributary contributions can be calculated. This method of sediment tracing is easy to understand, and the results are easily interpreted. Confidence in the outcomes is quantified by the calculation of statistical uncertainties associated with the estimates of relative sediment contributions.

A model was developed to explain how random mixing of fluvial sediment can generate linear magnetic parameter relationships. This model was developed further to explain how mixing occurs at confluences where well mixed streams of sediment combine in proportion to the relative tributary contributions, and results in a well mixed average in the reach downstream of the confluence. Measurement of particle size fractions accounts for differences in the delivery of different particle sizes. A new method was adopted to calculate relative contributions.

The experiments reported in Chapter 4 showed that in the fine sand fraction (63-125 µm), most of the magnetic mineral component is associated with either
surface-bound Fe or particle inclusions, although the discrete heavy mineral component does make a significant contribution. There was indirect evidence that mineral particle inclusions are the most significant magnetic component in coarse sand.

Surface-bound Fe oxides, including the magnetic component, are mainly a product of soil forming processes. Chemical stripping of surface-bound Fe completely removed the distinct differences between the linear relationships in the light mineral fractions of the sediment from the two tributary catchments. The heavy mineral components from each tributary were also distinctly different, and consistent with the magnetic parameter regression relationships of the light mineral fractions. These differences must be substantially influenced by the geochemical properties of the parent rock, given that this is the principal difference between the two tributary catchments. In subsequent chapters, differences in rock types also provided a basis for discriminating between sediment sources.

While the results presented in Chapter 4 indicate that most of the magnetic mineral component is associated directly with sediment particles, the question remains about what proportion of sediment particles have magnetic minerals associated with them. The experiments showed that clay-silt, and fine to medium sand from two different catchments have distinct magnetic parameter relationships, which, according to the results from the 63-125 µm fraction, are mainly due to the magnetic characteristics of surface-bound Fe. Given that this originates from pedogenic processes acting on all soil particles, it is likely that the great majority of sediment particles will also have some surface-bound Fe, a proportion of which will be magnetic mineral. From this it is concluded that the magnetic component is broadly representative of sediment as a whole, and that the tracing method developed in this study is a reliable way of determining relative sediment contributions at confluences.

The situation for coarse sand may be somewhat different. The uniformity of the magnetic parameter relationships in the coarse sand fractions, and the similarity of these to the linear regressions from the digested, 63-125 µm, light mineral fraction, indicates a common, dominant type of magnetic mineral. It was also noted that these linear relationships have zero intercepts, which, as discussed in Chapter 3, may indicate mixing of a single magnetic component with a non-magnetic component such as quartz.
If this is the case then the method will not be tracing the diluting, non-magnetic component if this includes particles that have no surface-bound magnetic minerals or inclusions.

In Chapter 5 two examples of stream network confluence tracing were presented that demonstrate the applicability of the method. The Ord River and Snowy River studies showed that measurements of fine and coarse sand fractions can be used to determine relative sediment contributions in large, remote catchments where no previous data existed, and monitoring of sediment delivery would have been very expensive to set up and maintain. The Snowy River study also showed that coarse sand can contain distinct, traceable magnetic properties. Data from sequences of alluvial deposits proved to contain a valuable record of temporal information. In the Murrumbidgee River it was shown that simple magnetic parameter relationships can be used to infer the sources of suspended sediment along an extensive reach of channel. While this approach was only quantitative in that it showed the presence or absence of a particular source (i.e. 0% or 100%), it demonstrated that a simple method of analysis is sufficient to identify sediment sources.

Results from the reported studies show that different rock types can be used as a basis for distinguishing sediment sources. This means that while stream junctions receiving sediment from distinguishable sources may be useful locations for determining relative sediment contributions, other sites of sediment deposition in stream networks that only receive eroded soil from two distinct rock types can also be used to determine relative contributions. The potential for extending the confluence tracing method was explored in Chapter 6.

The Namoi River basin study showed that the binary tracing method can be generally applied at large basin scale. Here sediments derived from soils developed on different rock types were magnetically distinct, as were the sediments derived from them, and these differences could be traced down through the river system to determine relative contributions along river reaches down to middle part of the catchment. This study also showed that sediment derived from soils developed on different rock types can be used to trace sediment at any scale where there are two distinguishable sediment sources. However, a significant difference in concentration between one of the sources and the sediment in the lower river was probably due to the preferential transport of less
dense, low magnetic concentration suspended sediment particles, so source matches could not be made reliably.

The Darling-Barwon River study showed that core and channel sediment samples have magnetic mineral concentrations that were significantly less than one of the major sediment source types. As in the lower Namoi River, transport related processes are likely to be responsible for this reduction in concentration. The linear relationship observed in the Darling-Barwon channel data appears to be the result of mixing between two concentration end-points. This means that this linear relationship was not directly a result of the mixing of the principal source types. The core data obtained from along the channel are internally consistent and linear, but these linear relationships may also result from the mixing of low concentration end-points, particularly downstream of confluences, so that they also may not be directly related to the source types.

In the Darling-Barwon river it was not possible determine the sources of the sediment based on the binary mixing of linear relationships. In this part of the river system concentrations are all relatively low, so that linear relationships either do not exist, or if they do, they may not directly result from the source types that the sediments originate from. It was also concluded that in such a large river system all of the major tributaries must be sampled in as much detail as the Namoi and Bogan rivers were sampled. Otherwise it cannot be assumed that all of the major source types have been identified, and their relative contributions along their respective tributary systems adequately determined. In large river systems studies are also required to understand transport related processes, particularly concentration reduction, and the possible generation of linear relationships that are not directly related to source types.

The Darling-Barwon and lower Namoi studies also showed that where large concentration differences occur, source matches cannot be made reliably. In this respect the method developed in this report is adversely affected by concentration differences. Otherwise the method depends on changes in concentration to form the linear relationships that characterise different sediment sources. Where there are similar concentration ranges in sediment from different sources, such as those observed at stream junctions, this research has shown that the method can be confidently applied. The method has also passed empirical tests of spatial and temporal constancy, and the balance of evidence indicates that magnetic minerals are representative of sediment as a
whole. As to the question about whether the method gives the right answer, such confirmation requires an equally well tested, independent approach to determine proportionate contributions to a binary mix. The evidence from the research presented here is that the method can be reliably used to determine the relative contributions of two sediment sources.

No tracing method can compensate for inadequate sampling that does not fully represent the temporal and spatial variations in the sources. In this respect the method developed in this report is probably more robust than others, because the occurrence of linear relationships in the data is an indication of constancy. Also, sediment transport processes are likely to promote the occurrence of sediment that is typical of soils developed on particular rock types, because the transport processes will tend to average out any local heterogeneity. The same sediment transport processes mix sediment so reaches of channel contain well mixed averages. For these reasons fluvial sediment is likely to present the best opportunity for obtaining samples that are representative of different source types.

The method developed here is limited to tracing two sources at a time, but this has a major advantage over multi-parameter modelling methods because the data can be evaluated in the simplest possible way, that is, a bi-variate plot. Also the relative contributions to a binary mix can be easily calculated with statistical uncertainties.

Finally it must be recognised that no one tracing method is likely to provide all of the answers, and independent verification of outcomes should be made if possible using other well tested, reliable tracers. Further developments in the new tracing method developed in this report could include experiments designed to determine the circumstances in which sediment may not have a magnetic component, the processes that result in reductions in concentration in large river systems, and the relationships between soils and sediments.
APPENDIX

GENSTAT PROGRAM FOR DETERMINING PROPORTIONATE CONTRIBUTIONS

job 'job name'
output [width=105 ; print=""] 1

"DECLARATIONS"
matr[12;12] B
vari[3] n,beta,sxi,ybar,xbar,syy,sxy,sxx,xibar,sdel
vari[12] h,se
scal xi0,eta0,lambda,seps,Plow,Phigh,gfiel,crit,df[1,2,3]
poin[3] y,x,res
text[12] pname ; !t(xi0,eta0,beta1,beta2,beta3,sxi1,\n   sxi2,sxi3,sdel1,sdel2,sdel3,lambda)

"DATA"
open 'filename' ; 2
for i=1...3
  read[pr=s,e ; ch=2;setn=y] x[i],y[i]
calc df[i]=nval(x[i])-1
endfor
calc wx=df[1]*var(x[1])+df[3]*var(x[3]) & wx=wx/(df[1]+df[3]) & wx=sqrt(wx)
calc wy=df[1]*var(y[1])+df[3]*var(y[3]) & wy=wy/(df[1]+df[3]) & wy=sqrt(wy)
for i=1...3
  calc s[x][i]=x[i]/wx & y[i]=y[i]/wy
  sspm[terms=x[i],y[i]] sspm ; s ; m ; num
  fsspm[p=*] sspm
calc s=s/(num-1)
calc sxx[i]=s[i;1] & sxy[i]=s[i;2] & syy[i]=s[i;2]
  & xbar[i]=m[i;1] & ybar[i]=m[i;2] & n[i]=num
endfor
  prin n,xbar,ybar,sxx,sxy,syy

"INITIAL VALUES"
read[pr=d] xi0,eta0,lambda
  0.5142 0.6269 1
read[pr=d] sdel
  0.10 0.01 0.02
  calc beta=sqrt(syy/sxx)
  for [10]
    calc sxi=sxx*(1-2*sdel*sdel*lambda/(sdel*syy+lambda*sdel*sxx))
    exit (min(sxi).gt.0)
    prin [or=a] sxi
calc sdel=sdel*(0.5+0.5*(sxi.gt.0))
endfor
vari[12] par ; !(#eta0,#xi0,#beta,#sxi,#sdel,lambda)
prin beta,sxi & xi0,eta0,sdel,lambda
calc B=0 & V=0
scalarm outer ; 10 & inner ; 5 & step ; 0.2
lrv [rows=12] lrvm

"ITERATION ; PRINT CRITERION t(h)*+MINV*+h"
for [outer]
  for [inner]
    calc xibar=(beta*sdel*(ybar-xi0+beta*xi0)+lambda*sdel*xbar)\
calc g1 = ybar - eta0 - beta*(xbar - xi0)
& g2 = syy - sxi*beta**2 - lambda*sdel
& g3 = sxy - sxi*beta
& g4 = sxx - sxi - sdel

vari[12] g ; !(#g1,#g2,#g3,#g4)

calc v1 = (lambda + beta*beta)*sdel/n
& v2 = 2*lambda*sdel*(2*(beta**2)*sxi + lambda*sdel)/(n-1)
& v3 = (sxi*((beta**2)*sdel + lambda*sdel) + lambda*sdel*sdel)/(n-1)
& v4 = 2*sdel*(2*sxi + sdel)/(n-1)
& v34 = 2*beta*sxi*sdel/(n-1)
& v23 = v34*lambda

vari[12] diag ; !(#v1,#v2,#v3,#v4)

calc V[1...12;1...12] = diag[1...12]
& V[7...9;4...6] = v23[1...3]
& V[10...12;7...9] = v34[1...3]

calc B[1...3;1] = beta[1...3]
& B[1...3;2] = -1
& B[1...3;3...5] = xibar[1...3] + xi0
& B[4...6;3...5] = -2*sxi*[1...3]*beta[1...3]
& B[7...9;3...5] = -sxi*[1...3]
& B[4...6;6...8] = -(beta[1...3]**2)
& B[4...6;9...11] = -lambda
& B[7...9;6...8] = -beta[1...3]
& B[10...12;6...8] = -1
& B[10...12;9...11] = -1

calc VINV = i(V)
calc M = qproduct(t(B); VINV)
& h = t(B)**VINV**+g

calc MINV = i(M)
calc par = par-step*MINV**+h
& par[9] = par[9]*((par[9],gt.0)+0.01*(par[9],le.0))
& par[10] = par[10]*((par[10],gt.0)+0.01*(par[10],le.0))
& par[11] = par[11]*((par[11],gt.0)+0.01*(par[11],le.0))
& par[12] = par[12]*((par[12],gt.0)+0.01*(par[12],le.0))
calc crit = qproduct(t(h);MINV)
& sxi[1...3] = par[6...8] & sdel[1,2,3] = par[9,10,11] & lambda = par[12]
endfor

print [rlw=4 ; or=a] crit,par ; fi=8
flrv M ; lrvm

endfor

vari [nv=12] gscal
for ii=1...12
    calc gscal[ii] = g[ii]*sqrt(VINV[ii;ii])
endfor

print [orient=across ; rlw=5] gscal ; fi=8 ; de=3
print[pr=*,rlpr=*,clpr=*,sq=y] crit,par ; f=8,7 ; d=5,3

"FINAL PRINT-OUT"
calc se[1...12] = sqrt(MINV[1...12;1...12])
calc C = corrmat(MINV)
calc fit = qproduct(t(g); VINV)
"ESTIMATION AND INTERVAL FOR P"

"N.B. THE FOLLOWING PROCEDURE ASSUMES THAT THE BETAS ARE IN INCREASING OR DECREASING ORDER"

scal a,b,c,P,d13,d23,seP,b1,b2,b3
calc b1,b2,b3=beta[1,2,3]
print b1,b2,b3
calc d13,d23=b1,b2-b3
calc P=d23/d13

calc a=MINV[3;3]-2*MINV[5;3]+MINV[5;5]
& b=MINV[4;3]-MINV[5;3]-MINV[5;4]+MINV[5;5]
& c=MINV[4;4]-2*MINV[5;4]+MINV[5;5]

" Application of Fieller's theorem "

scal [val=2] t
calc gfiel=t*t*c/(d13*d13)
calc wx=sqrt(a-2*P*b+P*P*c-gfiel*(a-b*b/c))
calc Plow=(P-gfiel*b/c-t*wx/d13)/(1-gfiel)
calc Phigh=(P-gfiel*b/c+t*wx/d13)/(1-gfiel)
calc seP=P*sqrt(a/(d13**2)-2*b/(d13*d23)+c/(d23**2))

" THE ESTIMATED VALUE OF P, THE PROPORTION OF SOURCE 1 (COMPARED WITH SOURCE 1 + SOURCE 3), APPROX STANDARD ERROR and confidence interval"
print [orient=across ; serial=no] P,seP,Plow,Phigh,gfiel ; skip=2

"ANGLE PHI IS IN RADIANS i.e. 0-90 DEGREES"

calc sp=sin(dphi) & cp=cos(dphi)
calc sb1c=sp+b1*cp
calc sb2c=sp+b2*cp
calc sb3c=sp+b3*cp
& p3=(b2-b3)*sb1c/(b1-b3)*sb2c
& Vbeta$[!1...3]=MINV$[!1...3]
& D$[!1;1]=-p3*sb3c/(b1-b3)*sb2c
& D$[!2;1]=sb1c*sb3c/(b1-b3)*sb2c
& D$[!3;1]=(b2-b1)*sb1c/(b1-b3)*sb2c
& Vp=I(D)+Vbeta*D & sevP[ii]=sqrt(Vp) & vP[ii]=p3
endfor

"ANGULATION & INTERVAL FOR P"