[8]
Soil magnetism

Even at low concentrations in a soil, iron oxides have a high pigmenting power and determine the color of many soils. Thus soil color, as determined by the type and distribution of iron oxides within a profile, is helpful in explaining soil genesis and is also an important criterion for naming and classifying soils.

Schwertmann, V. and Taylor, R. 1977

8.1 Introduction

Although the magnetic properties of soils are seldom if ever quoted in standard texts and few articles on soil magnetism have looked beyond low field susceptibility measurements, a number of authors have pointed to ways in which magnetic measurements can be used in pedology and related fields. Following Le Borgne (1955), several Western and Russian authors have studied the mechanisms whereby magnetic susceptibility (4.4) is often 'enhanced' in surface layers. Lukshin *et al.* (1968) and Vadyunina and Babanin (1972) have shown how susceptibility enhancement is related to major soil formations in the USSR and can be used to give some general insight into the processes affecting iron minerals during pedogenesis, as well as into specific effects such as gleying. The relationships between enhancement mechanisms and lithology (Mullins & Tite 1973), climate (Tite & Linington 1975) and fire (Le Borgne 1960), have received particular attention often through both field observation and experimental study, while recent articles have dealt more directly with the geochemistry of the iron transformations which lead to ferrimagnetic (Section 2.2.4) oxide formation (e.g. Taylor & Schwertmann 1974). Most of the work dealing with instrumentation for soil magnetic measurement has been addressed more or less directly to the use of susceptibility measurements in archaeological prospecting and survey work (e.g. Scollar 1965). The most useful and comprehensive summary of this range of work is the review article by Mullins (1977). In addition, Poutiers' monograph (1975) illustrates the use of mineral magnetic measurements, in loess and palaeosol studies. More recently, Maher (1984, 1986) has begun to explore the mineral magnetic properties of both contemporary and fossil soils with a view to relating them to soil forming processes.

The problems involved in producing a single interpretation consistent with both magnetic and geochemical measurements, brought into focus for marine sediments by Henshaw and Merrill (1980), are probably even less tractable in soils than in marine sediments, and there is a dearth of authoritative work in this critical area. Nevertheless, some characterisation of the magnetic properties of soils is of vital importance to most of the subsequent chapters, since it is within the regolith that the iron released in the weathering of bedrock is transformed to chemically stable magnetic oxides which may then persist in the soil, in the suspended load of rivers, in atmospheric dusts and in the historical record preserved in sediment, peat and ice cores.

8.2 Magnetic properties of soil minerals

The magnetic properties of a bulk soil sample reflect the varied magnetic behaviour of the range of soil minerals present. Studies dealing only with low field susceptibility have often given the impression that ferrimagnetic (Section 2.2.4) minerals alone determine bulk magnetic properties. Although this is often true, there are nevertheless many situations in which it is misleading. Thus at the outset, we need to consider briefly the magnetic behaviour of major soil constituents (cf. Chs 2 & 4). The diamagnetic (Section 2.2.1) components of the soil include quartz, orthoclase, calcium carbonate, organic matter and water. In most soils, these components can be regarded merely as a dilutant. Only in extreme cases, for example pure silica sands, pure limestones and ombrotrophic peats, will the diamagnetic component be magnetically significant. In these cases it will need to be recognised as an important component of any susceptibility measurement. Many soil minerals, both primary and secondary, are paramagnetic (Section 2.2.2) and in soils which are iron rich but poor in ferrimagnetic minerals, paramagnetism will make an important contribution to total susceptibility. Table 3.4 lists the magnetic susceptibility of some common diamagnetic and paramagnetic soil minerals. The relatively high magnetic susceptibility of iron-rich clay minerals is noteworthy.

Several canted antiferromagnetic (Section 2.2.4) minerals are present in the soil. Of these, goethite (Section 3.4) is the most abundant in well drained soils formed under temperate conditions and haematite (Section 3.2.2) is predominant in relatively drier and more highly oxidised situations. Most soils contain one or the other (Oades & Townsend 1963). Schwertmann and Taylor (1977) suggest that goethite is the more generally distributed and least climatically restricted of the iron oxides and hydroxides in the soil. They confirm that, even in those environments sufficiently oxidising for haematite formation, goethite will often also be present. Lepidocrocite (Section 3.4) is more restricted in its occurrence and is largely confined to gleyed soils where it occurs as bright orange mottles and coatings lining the walls of root channels.

Of the ferrimagnetic oxides (Section 3.2.1) only magnetite and maghaemite are generally important in the soil, though titanomagnetites and pyrrhotite may be significant on some lithologies. Magnetite will occur both as a primary mineral, derived from igneous and especially basic igneous rocks (Section 3.6.1) and as a secondary mineral formed within the soil by the mechanisms outlined in Section 8.4 below. Maghaemite is a secondary soil mineral formed in a similar way. Though widespread in temperate soils, it tends to be more abundant in highly weathered soils formed under tropical and subtropical conditions (Schwertmann & Taylor 1977). It can occur finely dispersed or as concretions.

8.3 Weathering and magnetic properties

Iron in igneous bedrock is largely present in the reduced state as Fe^{2+} within the silicates. Hydrolytic and oxidative weathering reactions release this as Fe^{3+} which, as a result of its extremely low solubility, is mostly precipitated as an oxide or hydroxide. However, oxygen-deficient conditions may subsequently reduce the Fe^{3+} to Fe^{2+}. As a result, the oxide becomes more soluble and the iron may then eventually migrate to zones of oxidation where it will be reprecipitated. Thus iron oxides can undergo repeated changes in which they are alternately precipitated in oxidising conditions and are chelated or in solution as Fe^{2+}, the overall conditions under which these reactions take place being set by soil pH, climate, soil moisture and organic matter content. In consequence, it is not possible to make simple generalisations about the position of iron oxides in weathering sequences. Some of the major trends in soil oxide formation are outlined below.

Where soils are developed from igneous rocks containing predominantly Fe^{2+} in magnetite and/or within the silicates, weathering is dominated by the hydrolytic and oxidative reactions already noted, and the resulting oxides will be mainly haematite and/or goethite. Haematite is largely restricted to those soils formed under conditions of high temperatures, good aeration, rapid decomposition of organic matter, and, frequently, relatively high pH (Schwertmann & Taylor 1977). Subsequent transformation can take place in the soil surface layers in the presence of organic matter (see 8.4 below).

Where soils are developed on a haematite-rich bedrock (e.g. Triassic sandstones) long periods of pedogenesis under cooler and moister régimes will lead to goethite or more locally, lepidocrocite formation. This occurs through dissolution of the haematite by reduction or chelation and subsequent reprecipitation when or where conditions are more oxidising. Many soils form on sedimentary or metamorphic parent materials in which haematite, magnetite and the primary Fe^{2+}-rich silicates make relatively little or no contribution to the total iron content. In these cases the iron may be present in a wide variety of forms. Such iron will often be finely disseminated and associated with the clay minerals or present as a cementing agent between coarser particles. Generally these forms of iron are finely divided, easily accessible and hence relatively readily mobilised by chelation or reduction. The mechanisms of magnetic enhancement considered in Section 8.4 below will, in these circumstances, operate on many forms of iron depending not only on lithology and major climatic type, but on all the other factors of soil formation which are so sensitively reflected in the soil iron system.

8.4 The magnetic enhancement of surface soils

Le Borgne (1955) was able to show, and many subsequent studies have confirmed, that the magnetic susceptibility of topsoil is often higher than that of the underlying material. Le Borgne ascribed this to the formation of secondary ferrimagnetic oxides within the clay-size fraction of the soil. The processes contributing to this may be considered under the general heading of magnetic 'enhancement'. Common to all the processes is the conversion of iron from non-ferrimagnetic to ferrimagnetic forms. Although this can occur as a natural process of chemical weathering, it is convenient to consider it separately.

Many authors have illustrated magnetic enhancement over a wide range, of lithologies and climatic régimes. It appears to be a characteristic of many soil

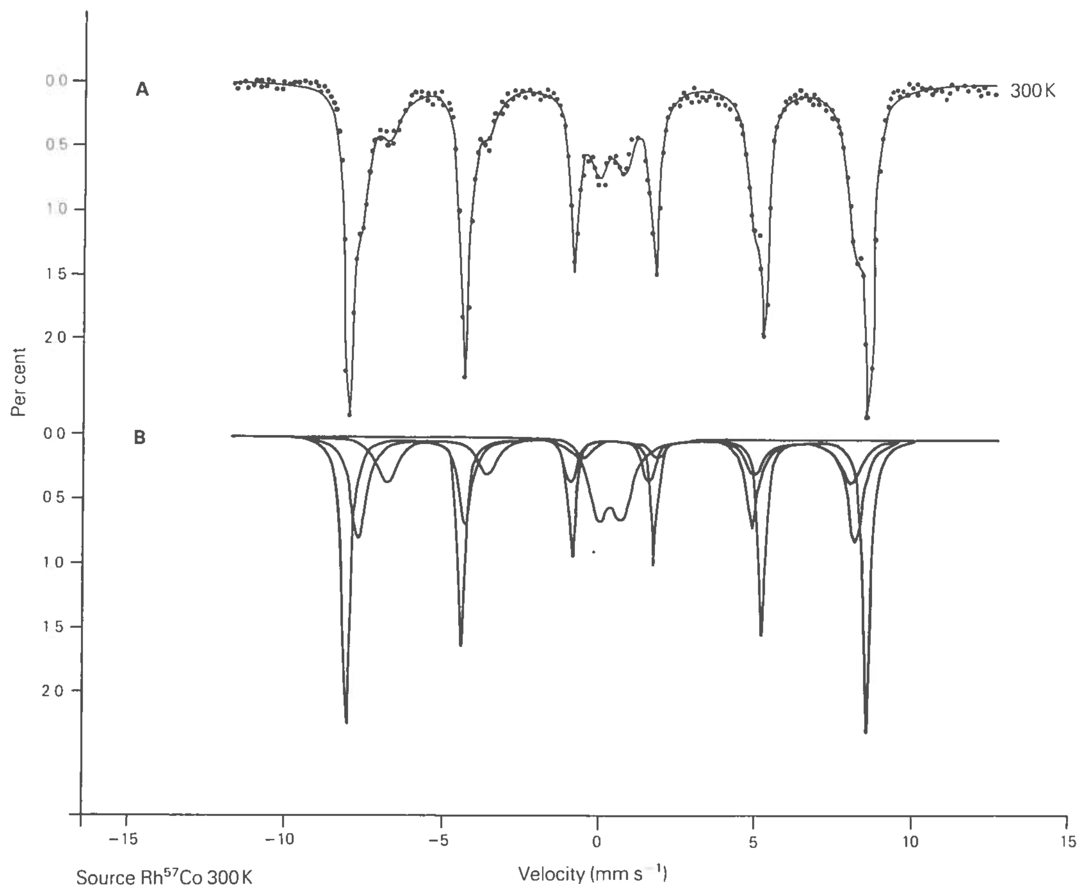


Figure 8.1 Mossbauer spectra at room temperatures of a sample of burnt soil from Caldy Hill, Merseyside, England. Plot A shows a total least squares fit to all the data and plot B subsidiary fits for individual components (see Longworth *et al.* 1979).

types under temperate conditions, although the reflection of enhancement in bulk susceptibility measurements may not always be apparent, as for example on strongly ferrimagnetic bedrocks such as basalts. It is inhibited or reversed by waterlogging and podsolisation and it may be difficult to detect in soils with low iron concentrations in the topsoil. The evidence of enhancement may be removed by truncation of the soil profile. Climates of extreme aridity or cold are also inimical to enhancement.

Mullins (1977) identifies four ways in which maghaemite, which he takes to be the product of enhancement, can be formed in the soil. The first of these maghaemite formation mechanisms, the low temperature oxidation of magnetite, is not strictly an enhancement process since no significant increase of susceptibility is likely from this alone.

Mullins' second mechanism, burning, is generally accepted as a major factor in magnetic enhancement. A wide range of observations and experimental studies show that above *c.* 200 °C, in the presence of organic matter, some conversion of non-ferrimagnetic iron minerals to ferrimagnetic minerals will occur. Le Borgne envisaged a two-stage process in which first, under reducing conditions, finely divided oxides and hydroxides are converted to magnetite, which is then subsequently oxidised to maghaemite on cooling under the less reducing conditions which may follow after the combustion of the soil organic matter. In practice, the processes and the final product are much more variable. Although maghaemite is undoubtedly produced by burning (Longworth & Tite 1977) non-stoichiometric magnetite may also be formed. For example Longworth *et al.* (1979), using Curie temperature determinations and Mossbauer spectra were able to show that at two burnt sites in Britain, Caldy Hill and Llyn Bychan, the resulting ferrimagnetic oxide was non-stoichiometric and probably impure magnetite, best approximated by the formula $Fe_{2.9}O_4$ (cf. Fig. 8.1 and also Ozdemir & Banerjee 1982).

It is likely that the fire-induced magnetic oxides formed within the soil will vary from site to site, approximating more closely to maghaemite or to magnetite depending on site conditions and the nature of the fire experienced. The finely divided nature of these oxides, their non-stoichiometric form and the frequency of isomorphous substitution within the crystal lattices makes identification complex and time consuming. Detailed studies of artificially burnt materials (Oldfield *et al.* 1981a) suggest that even in a single sample a range of oxides will often be present at each stage. Visually, burnt topsoil may range in colour from black through shades of grey and pink to salmon pink or bright orange. This visual gradation is often accompanied by an increase in the level of enhancement, together with a shift from 'soft' multidomain (Section 2.4.3) 'magnetite' to higher concentrations of viscous (Section 2.5) and superparamagnetic (Section 2.4.5) 'magnetite' alongside a growing haematite component.

The third process quoted by Mullins is the dehydration of lepidocrocite (γ FeOOH) to maghaemite. This takes place between 275 and 410 °C and, since lepidocrocite is limited to poorly drained soils, the mechanism is likely to be restricted to local situations in which gleyed soils are drained or subject to high temperatures.

Mullins' final mechanism is probably the most generally important. He envisages the formation of microcrystalline maghaemite or magnetite from weakly magnetic iron oxides and hydroxides via the reduction–oxidation cycles which occur under normal pedogenic conditions. The processes involved in this type of enhancement are complex and poorly understood. Organic matter is required as a substrate for the heterotrophic microorganisms which provide the reducing conditions and chelating agencies needed to bring into solution the iron formerly present in non-ferrimagnetic oxides and hydroxides. The extent to which subsequent recrystallisation as ferrimagnetic oxides is a purely chemical process or one which may be dependent on microbial action is still open to doubt. One possibility is that soil bacteria, analogous to the magnetotactic (Section 15.2) types shown by Blakemore (1975) to grow small chains of stable single-domain magnetite crystals within their cells, are responsible for some of the enhancement observed as a normal part of pedogenesis.

Measurements by Mullins (1974) and by Mullins and Tite (1973) largely carried out on cultivated soils developed on sedimentary deposits suggest that the secondary ferrimagnetic crystals so formed are a mixture of superparamagnetic, viscous and stable single-domain (Sections 2.4.4–6) types in roughly constant proportions, with the viscous component generally comprising between 5 and 10%.

In many situations, especially in areas of past or present cultivation and in fire-stressed ecosystems, it is difficult to tell to what extent surface enhancement is a reflection of burning or of the 'pedogenic' mechanism. However, the relative importance of the latter may be indicated by the high enhancement of many old forest soils and by the evenness of the enhancement level over wide areas of comparable lithology. No systematic attempt has been made to use magnetic measurements themselves as a basis for distinguishing different types of enhancement though this is clearly possible under favourable circumstances.

At sites close to major urban and industrial centres, surface soils may have a higher susceptibility as a result of fallout from the atmosphere of magnetic spherules derived from fossil-fuel combustion. In the industrial areas of northern England, the susceptibility values for recent ombrotrophic peats are within the same range as strongly enhanced forest soils in rural areas. This atmospheric component has not been recognised in the literature on soil magnetism, but it must be taken into account in site selection for studies of true enhancement processes and products, and in any evaluation of soil magnetic properties close to major sources of spherules (cf. Ch. 11).

8.5 Particle size relationships

The ferrimagnetic crystals in soils can be seen, from the above account, to derive from both primary and secondary ('enhanced') iron minerals. The latter are most often of stable single-domain size or less and associated with the clay fraction, whereas the former are, depending on the particular lithology, usually associated with sand and coarse silt-size fractions (cf. Ch. 10). The presence of both primary and secondary ferrimagnetic minerals will often give rise to a bimodal distribution of specific susceptibility with respect to

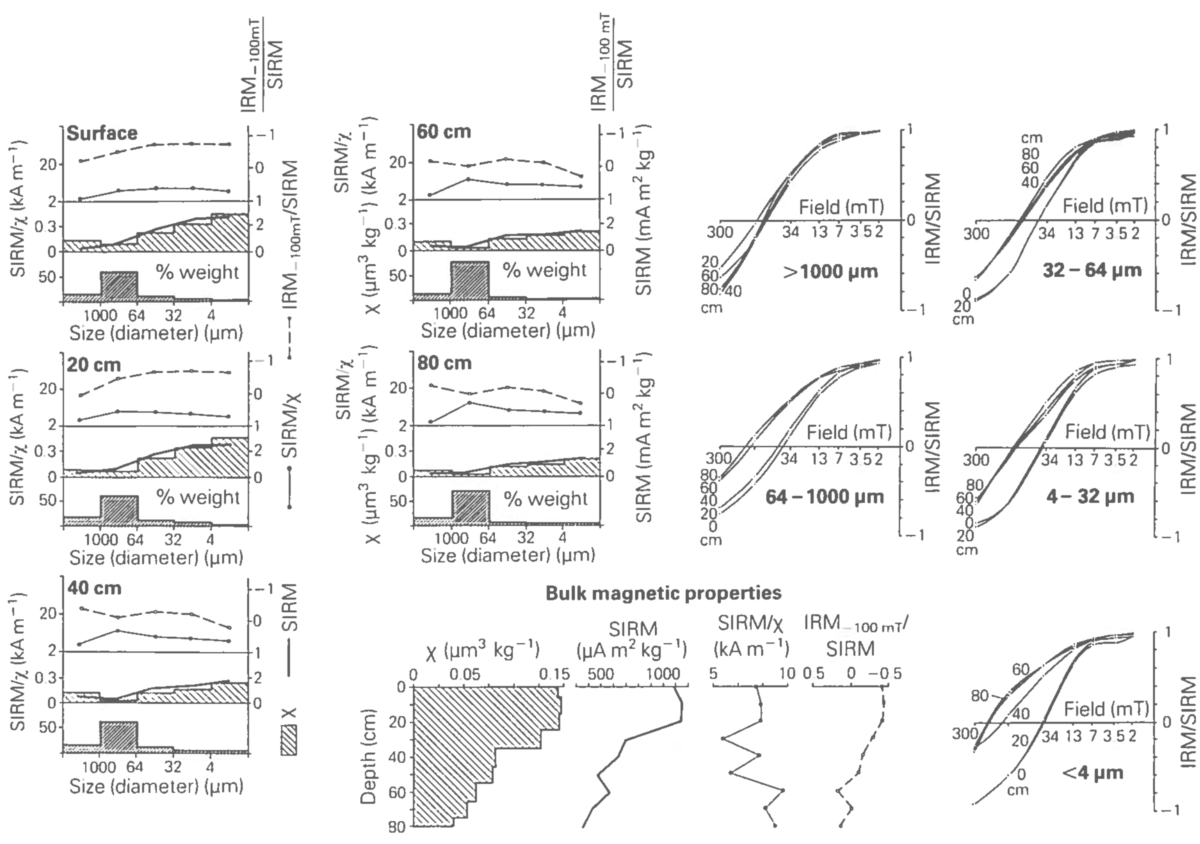


Figure 8.2 Newton Mere – Soil Pit B. Mineral magnetic parameters for bulk and particle size fractioned samples from a cultivated brown earth soil developed on haematite-rich glacial drift (Smith, unpub.). Above and to the left of the plot of bulk parameters, each diagram shows the variations in χ, SIRM, SIRM/χ and IRM_{-100mT}/SIRM against particle size. To the right, coercivity of SIRM curves are plotted for each particle size range and sample depth (see text).

particle size. In soils which are rich in non-ferrimagnetic forms of iron, this bimodal distribution will be superimposed on the effects of paramagnetic iron compounds and antiferromagnetic oxides (commonly including goethite) which may be associated with a wide range of particle sizes. These non-ferrimagnetic iron minerals will also include forms which are often more easily soluble than the ferrimagnetic minerals and which, along with adsorbed and dissolved iron, will be among the more readily chemically mobilised components of both soil and sediment systems.

Figure 8.2 shows an example of the relationship between magnetic properties and particle size for samples taken from a soil pit dug within the catchment of Newton Mere in central England (Smith pers. comm.). The soil is a cultivated and well drained sandy loam developed on glacial drift derived almost entirely from surrounding Triassic sandstones and red marls all rich in haematite. Igneous and metamorphic erratics occur sparsely in the drift. The primary magnetic components are therefore largely antiferromagnetic with ferrimagnetic forms much less abundant. The bulk soil magnetic properties show marked enhancement especially within the top 30 cm, and atmospheric fallout may be partly responsible for this (cf. Chs 10 & 11). The ratio of saturation remanent magnetisation to susceptibility, SIRM/χ (see Section 4.6) peaks in the upper and lower parts of the profile. Above 30 cm, in the enhanced layers, the high SIRM/χ values are associated with high χ and strongly negative $IRM_{-100\,mT}$/SIRM (see Section 4.6.4) values and may be ascribed to the relatively high proportion of stable single-domain grains associated with the secondary ferrimagnetic component. Below 60 cm maximum SIRM/χ is associated with minimum χ and less strongly negative $IRM_{-100\,mT}$/SIRM indicating that at this depth below the enhanced layer, the ratio has increased as a reflection of the greater relative importance of the primary haematite, abundant in the parent material.

The magnetic measurements on the size fractions may be summarised as follows:

(a) At all depths, χ values are weakly bimodal with the peak in the coarsest material always much less important than that in the fines. The peak in the clay fraction is most strongly developed in the topmost samples within the enhanced layer.

(b) SIRM/χ peaks in the 63 µm–1 mm range in all but the surface sample. In all samples the coarsest fraction has minimum SIRM/χ values and the clay fractions have lower SIRM/χ than do the silts and fine sands.

(c) $IRM_{-100\,mT}$/SIRM values and remanent coercivities $(B_0)_{CR}$ vary little down profile in the coarsest size fraction. Above 20 cm, within the enhanced layer, $IRM_{-100\,mT}$/SIRM values become more strongly negative with increasing particle size whereas below this, the reverse applies. The peak SIRM/χ in the 63 µm–1 mm range corresponds in each case with a less strongly negative $IRM_{-100\,mT}$/SIRM value and higher values of $(B_0)_{CR}$ (see 4.6.3).

These variations with particle size and depth may be tentatively interpreted in terms of four magnetic components within the soil system as follows. The *primary ferrimagnetic* component is restricted largely to the coarsest fraction where it occurs as erratics in the drift. Its presence to some degree at all depths gives rise to the slight increase in χ in material coarser than 1 mm and to the fairly constant $(B_0)_{CR}$ and $IRM_{-100\,mT}$/SIRM values observed in the same fractions. The SIRM/χ minimum in the coarsest fraction of each sample reflects a proportionally large multidomain contribution. The greater relative importance of the *antiferromagnetic* component (fine-grained haematite) is responsible for less strongly negative $IRM_{-100\,mT}$/SIRM values and higher $(B_0)_{CR}$ with depth and, below the enhanced layer, with decreasing particle size. It also gives rise to maximum SIRM/χ in the 63 µm–1 mm range from 20–80 cm, but as particle size decrease below 63 µm within these samples, the *paramagnetic* component, becomes increasingly important producing a decline in SIRM/χ but having no effect on $(B_0)_{CR}$ and $IRM_{-100\,mT}$/SIRM. The *secondary ferrimagnetic* component dominates bulk soil and SIRM within the enhanced layer and is responsible for the peaks in the clay fraction at all depths down profile and probably reflect lessivage in the sandy soil. The picture is therefore a highly ordered one within which the magnetic mineral assemblages shows the effect of soil forming processes on the parent material.

Although the bulk soil measurements give a less detailed picture than do those performed on particle size fractions they clearly reflect the main characteristics attributable to the nature of the parent material and the relative homogeneity of the cultivated and enhanced layer. The nature of bulk soil magnetic properties under different pedogenic régimes and on different lithologies is the subject of the next section.

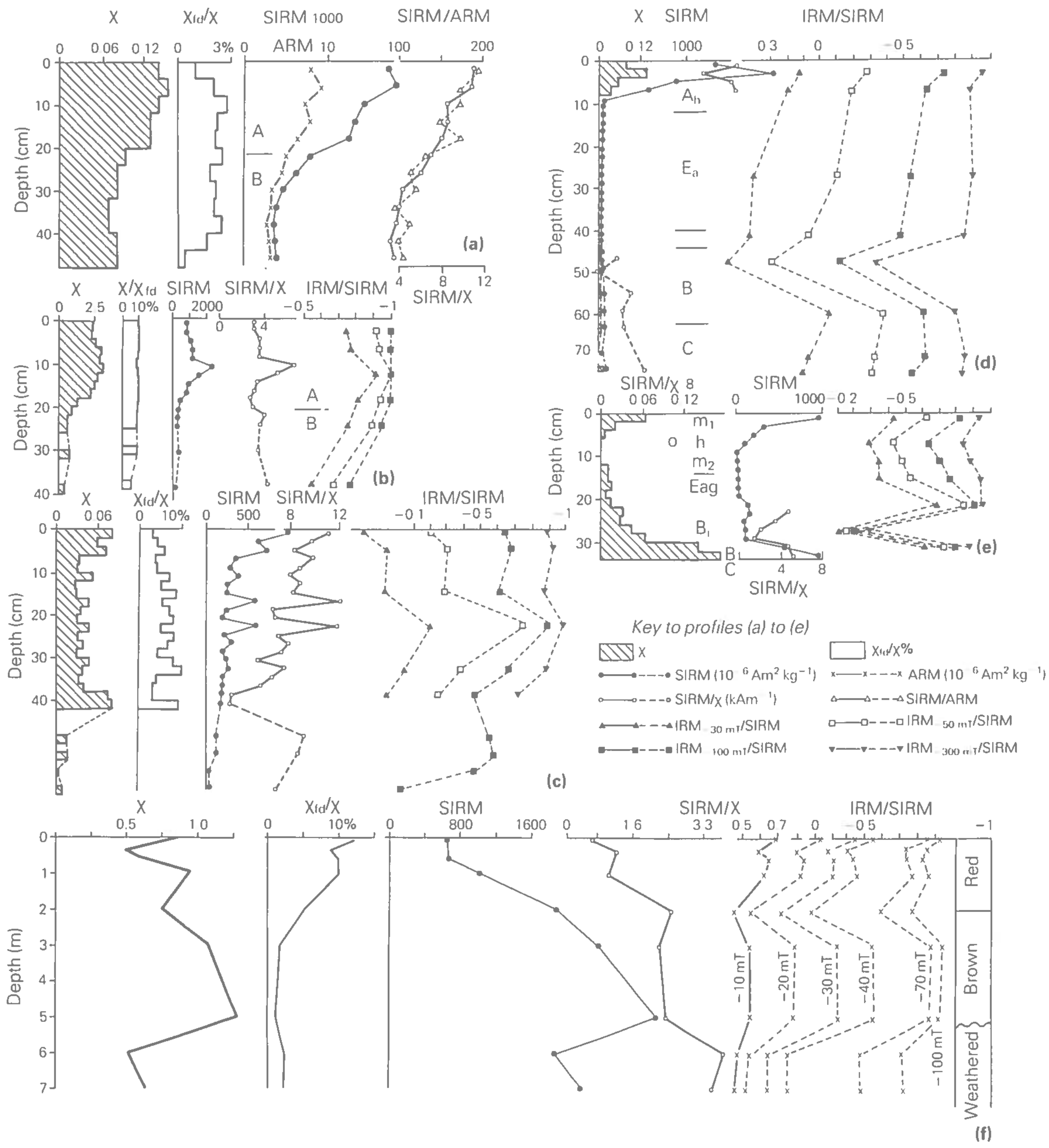


Figure 8.3 Magnetic measurements from some representative soil profiles (see text). (a) Hardwick Wood – brown earth under mature deciduous forest (Maher 1983); (b) Exmoor – unreclaimed brown earth under heathland (Yates 1983); (c) New Forest–brown earth under heathland (Yates 1983); (d) New Forest – podsol under heathland (Yates 1983); (e) Exmoor – stagnopodsol under heathland (Yates 1983); (f) North Queensland – deeply weathered tropical soil on basalt.

8.6 Some representative soil profiles

Figure 8.3 shows the magnetic properties of a series of soil profiles chosen to illustrate some of the ways in which lithology, weathering régimes and pedogenic processes combine to control the magnetic properties of soils. The profiles chosen comprise two podsols developed on tertiary Barton Sands and on middle-Devonian slates, three brown earths developed on the first two lithologies and also on cretaceous clay, and a deeply weathered humid tropical soil developed on basalt. The parent lithologies thus vary from weakly paramagnetic to strongly ferrimagnetic and a single tropical soil is included for comparison with soils developed under cool temperate conditions. The paired podsol and brown earth profiles allow comparison between weakly mixed but strongly eluviated profiles and relatively well mixed profiles which are not so strongly eluviated.

The podsol profiles (d and e), irrespective of underlying parent material, have the following features in common:

(a) Peaks in χ and SIRM indicate shallow layers of low enhancement at or near the soil surface, within the F and H layers between the fresh undecomposed litter and the bleached underlying mineral soil of the eluviated A horizon. Where measured, SIRM/χ and $IRM_{-100\,mT}$/SIRM values are within the range typical of secondary 'magnetite'. Any or all the enhancement mechanisms, including atmospheric deposition, may be significant (Yates 1983).

(b) Significant mineral magnetic changes coincide with the zone of iron enrichment in the illuviated B horizon. The combination of relatively low SIRM/χ, but extremely hard $IRM_{-100\,mT}$/SIRM values, especially in the Exmoor iron pan, indicates a magnetic assemblage dominated by paramagnetic forms of iron with some antiferromagnetic crystals present.

(c) In the bleached eluviated mineral soil, χ and SIRM reach minimum values and χ is often too low to measure. As in the gleyed profiles (8.7 and Fig. 8.5) some dissolution of ferrimagnetic oxides is implied. The $IRM_{-100\,mT}$/SIRM values resemble those in the overlying organic soil, suggesting that clay translocation may be responsible for the few magnetic minerals present.

(d) Below the B horizon the magnetic properties resemble those of the underlying parent material.

The brown earths (a, b and c) all show χ and SIRM peaks in the physically mixed A horizon where decomposing organic matter and mineral soil are in intimate contact. SIRM/χ, and the back-IRM parameters (IRM/SIRM) vary from profile to profile though they remain within the range of values compatible with dominance by stable single-domain magnetite. Where the frequency-dependent (cf. quadrature) susceptibility ratio, χ_{fd}/χ (see Section 6.3.4), has been measured it is seen to be a significant percentage of total susceptibility throughout each profile down to depths of at least, 40 cm, especially in the well drained New Forest (c) and Exmoor (b) examples, presumably as a result of the thorough mixing of the A horizons by worms. Also, in these two profiles, there are considerable variations in SIRM/χ and IRM/SIRM with depth. The horizons of maximum SIRM and 'softest' IRM/SIRM corresponding with zones of greater clay content. In the Hardwick Wood profile (a), which is developed on heavy clay, anhysteretic remanent magnetisation, ARM (4.4.2), SIRM, and SIRM/χ gently decline with depth in a manner consistent with a gradual reduction in the relative importance of the stable single-domain magnetite component (cf. Ozdemir & Banerjee 1982). The 'secondary' viscous grains at the stable single domain/superparamagnetic border which are responsible for the frequency-dependent 'quadrature' component measured here will be comparable to those grains around 20 nm identified by their higher viscous remanent magnetisation (VRM) in the upper part of the cultivated Barnes soil profile from Minnesota shown in Figure 8.4.

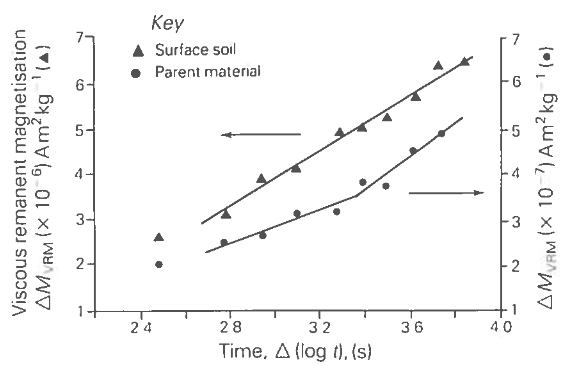


Figure 8.4 Growth of viscous remanence over time in a surface sample and a sample from the parent material of the Barnes soil formation in Minnesota (Ozdemir & Banerjee 1982). The relatively high viscous remanence in the surface soil is attributable to fine grains ~ 0.02 μm.

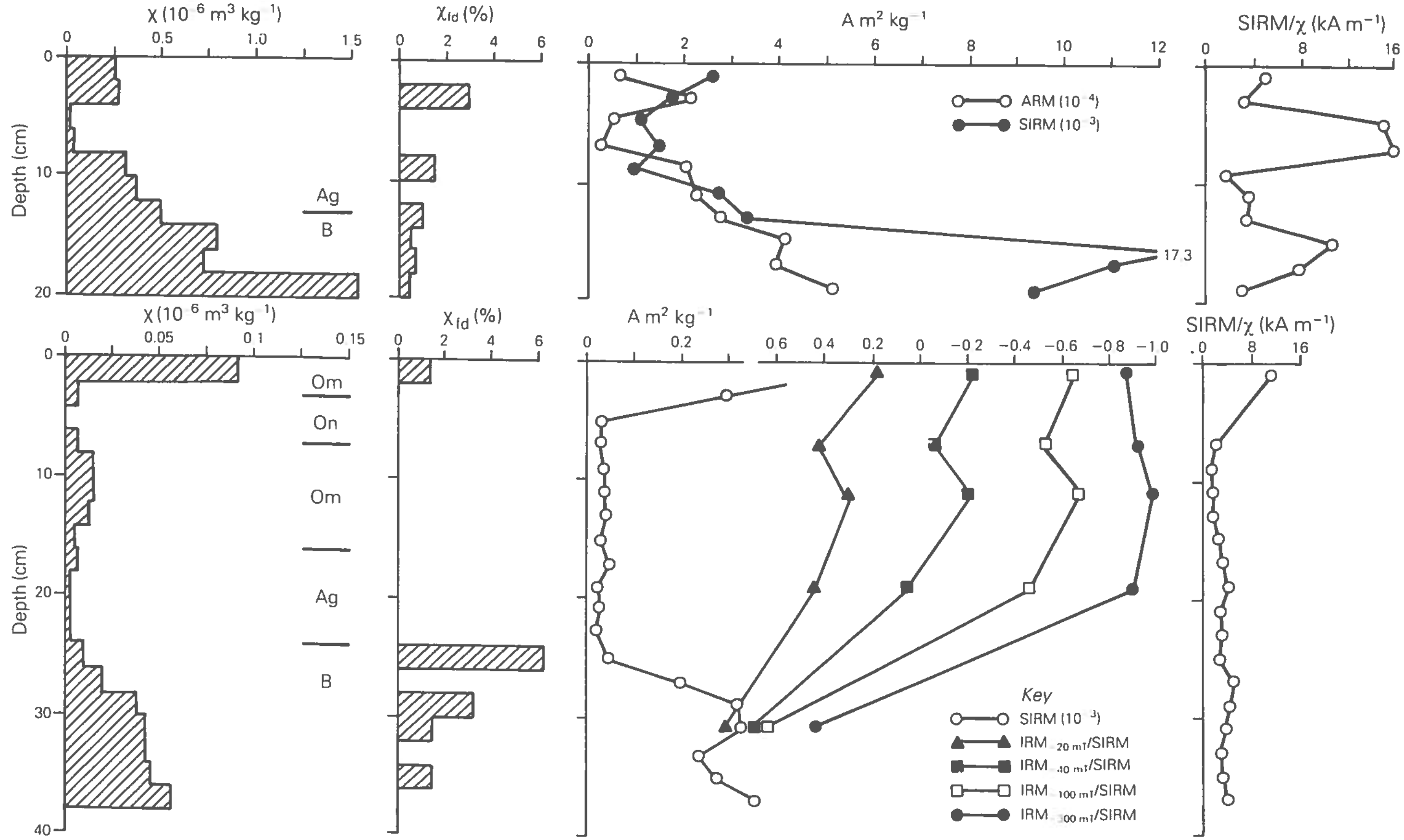


Figure 8.5 Magnetic measurements for two gleyed soil profiles from the Ardnamurchan peninsula, above, in West Scotland (Maher 1983) and, below, from Exmoor (Yates 1983). Note the minimum χ, χ_{fd}/χ and SIRM values in the horizons of most intensive gleying (see text).

The final soil type to be considered is a deeply weathered basalt based regolith from tropical Queensland (Fig. 8.3f) (Isbell *et al.* 1976). Here, χ and SIRM peak around 5 m, at the upper contact of the weathered basalt (cf. Dearing 1979), and neither parameter shows any clear evidence for 'enhancement' near the surface. However, χ_{fd}/χ rises to peak values of around 10% in the top metre of bright-red soil. SIRM/χ and the IRM/SIRM parameters are closely related, with peak ratios corresponding to 'harder' remanence in the weathered zone below 5 cm and at the base of the red soil layer *c.* 2 m. These would appear to be zones of relatively higher haematite and/or goethite concentration. The uppermost samples with maximum χ_{fd}/χ have relatively soft remanence probably as a result of the greater proportion of ferrimagnetic grains.

8.7 The effects of gleying on magnetic properties

Several authors have observed that gleyed soils have anomalously low susceptibility values. Figure 8.5 illustrates this effect on two gleys developed on basalt (a) and slate (b) respectively. Under the prevailing reducing conditions within the gleyed horizons, both the secondary and primary ferrimagnetic forms are readily dissolved and remain in solution or are leached from the profile. The low χ_{fd}/χ values and the somewhat higher SIRM/χ and ARM/χ values characteristic of the gleyed horizons suggest that, as might be expected, the finest superparamagnetic and viscous crystals are the most readily dissolved, and this is confirmed by Mossbauer measurements (Maher, pers. comm.). At first sight, the data from

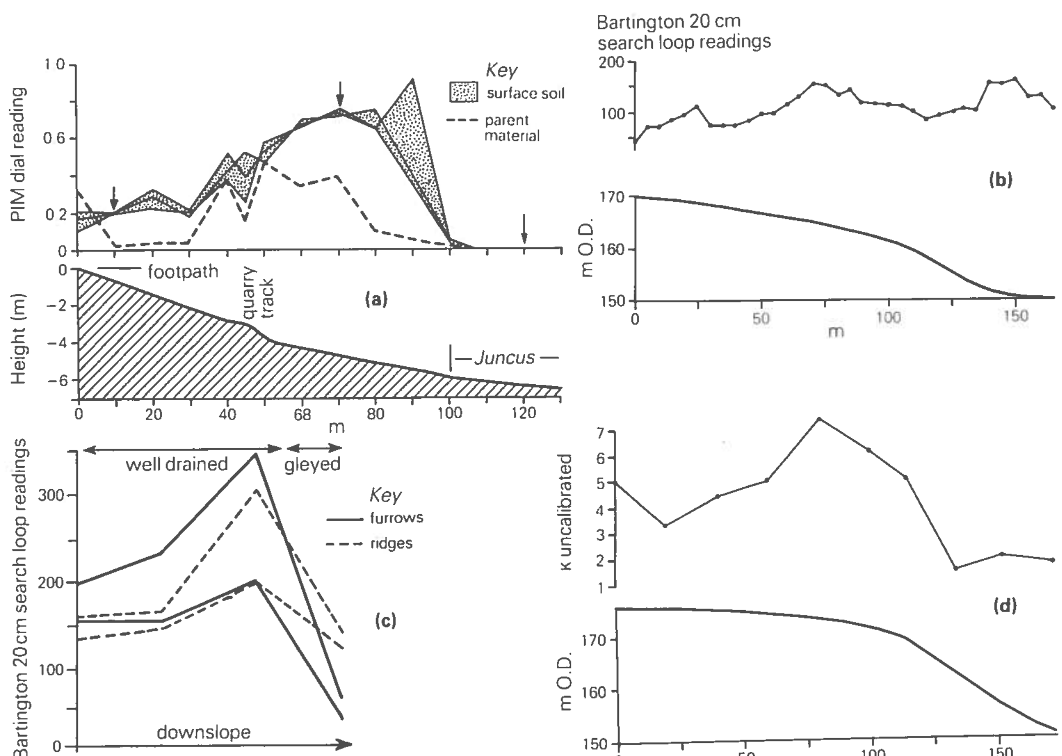


Figure 8.6 Magnetic 'catenas'. (a) Surface and bedrock pulsed induction meter (PIM) readings downslope on Ordovician slates in North Wales (see Turner 1980 and text); (b) Bartington 20 cm search loop surface readings on a Jurassic limestone slope in Oxfordshire (Sutton 1982); (c) Bartington 20 cm diameter search loop surface readings on a sloping area of former 'lazy bed' cultivation in West Scotland (Maher 1981). The effects of the slope, the lazy bed microtopography and gleying are discussed in the text; (d) Bartington 7 cm core scan loop readings on shallow drainpipe soil cores taken down a steep Jurassic limestone slope in Oxfordshire (Sutton 1982).

gleyed profiles may appear to conflict with all the evidence for the persistence of the ferrimagnetic oxides in many stream, lake and marine sediments (Chs 9, 10 & 12). Within gleyed soil however, a broad spectrum of bacteria can produce reducing conditions by using up dissolved oxygen. Dissolution of magnetic oxides may then occur as a simple chemical reaction. Iron-reducing bacteria may play a special rôle since *Clostridium* species have been shown to degrade crystalline iron oxides effectively and reduce them to non-crystalline forms (Ottow & Glathe 1971).

8.8 Soil magnetism and slope processes

Figure 8.6 plots four soil-magnetic catenas showing the relationship between susceptibility, slope processes and drainage. Transect (a) shows the envelope of values for three pulsed induction meter (6.7.3) surface readings at levelled locations down the slope of a pasture field developed on Ordovician slates in North Wales. For comparison, readings for subsoil were taken at the base of a shallow soil pit dug at each point. The subsoil readings are independent of slope and of the mostly higher surface readings, and they peak only in relation to the trackway which crosses the transect. The surface readings show a progressive downslope increase consistent with a steady enrichment in surface soil fines towards the slope foot. At the point where waterlogging gives rise to gleyed soils colonized by *Juncus* species, the surface readings fall to around zero. In (b), similar progressive downslope enrichment is shown by the Bartington susceptibility meter search loop readings plotted for the transect of a shallow soil pasture under pasture developed over Jurassic limestone in Oxfordshire.

Transect (c) subtly illustrates both the downslope enhancement trend and the effects of gleying on lazy beds, a kind of ridge and furrow cultivation associated with 'crofting' in parts of Ireland and the Scottish Highlands. The site is on the Ardnamurchan peninsula and the parent material is basalt. In the non-gleyed part of the transect, susceptibility readings from both the furrow and ridge sites show downslope enrichment, though the trend is more marked in the envelope of values for the furrow readings. This is consistent with the downslope movement of largely primary silt-sized 'magnetite' from ridge to furrow on the scale of the lazy beds themselves, as well as down the whole slope. Within the gleyed part of the transect, the surface readings for the relatively better drained ridges are higher than those for the waterlogged furrows.

Transect (d), on the Oxfordshire Jurassic limestone, as well as illustrating the gleying effect at the slope foot, shows peak susceptibility readings at the slope crest and depletion of surface material on the steepest parts of the slope. In this transect the readings were derived from volume susceptibility scans made on shallow plastic drainpipe cores.

A more detailed evaluation of the use of mineral magnetic properties to trace soil movement on slopes has recently been published by Dearing *et al.* (1986).

8.9 The persistence of magnetic oxides in the soil

The pedologist is familiar with the sensitivity of iron compounds to changes in soil-forming conditions, as demonstrated by the changes in soil colour which occur as a result of the presence or absence of different iron minerals. At first sight, it would therefore seem unlikely that the magnetic oxides in the soil could be sufficiently stable and persistent to be of value in the recognition of earlier *in situ* events or processes such as burning or more oxidative weathering régimes. It would also seem unlikely that the magnetic oxides once released from the soil, should retain their characteristics during transport and subsequent deposition. Nevertheless, the evidence available is strongly in favour of a degree of persistence of magnetic oxides both in the soils and sediments.

The magnetic characteristics of the late Holocene buried soil from the Howgill Fells in North West England, described in Harvey *et al.* (1982) suggest that little if any mineral magnetic change has taken place during the millenium or so of burial. For the most part magnetic prospecting at archaeological sites depends on the persistence and detection of secondary ferrimagnetic oxides in burnt areas and ditch fills. On a longer timescale, Poutiers' (1975) magnetic susceptibility profiles from Pleistocene sections in terrestrial sediments from the Cote d'Azur, South East France, often show a clear correspondence between peak susceptibility and the occurrence of deep-red, allegedly interglacial palaeosols.

Within the soil, persistence depends largely on the post-formation weathering and pedogenic régimes to which the oxides are subjected. Even where conditions have changed dramatically as a result of climatic fluctuations, iron oxides from earlier régimes may persist for very long periods. As Schwertmann and Taylor (1977) note, 'transformation of initially kinetically favored metastable phases to more stable ones may be extremely slow'. Hence in Britain, we may still see the expression of 'tropical' weathering in the highly oxidised regoliths locally developed on basalt. Consistent with this is Dearing's (1979) suggestion that around L. Frisa the bright orange subsoil, rich in antiferromagnetic grains, is at least in part attributable to the persistence of weathered material of preglacial origin.

The resistance to weathering of the secondary magnetic oxides formed through fire and normal pedogenic processes (8.4 above) appears to be similar to that of the comparable primary oxides (e.g. magnetites and titanomagnetites) derived from bedrock, though both are readily broken down under gleyed conditions. In the long term, there would also be a tendency under sufficiently oxidative conditions, for all these oxides to transform to goethite or haematite. This type of long-term weathering transformation sets some limit, albeit ill-defined, on the timescales over which the weathering régimes recorded in the magnetic properties of sediment profiles can be realistically reconstructed from reference to contemporary catchment soils alone.

From the above and the range of data available so far, we may conclude that persistence of ferrimagnetic and antiferromagnetic oxide assemblages, once formed, can be accepted provided the soil has not been gleyed and the pedogenic régime has not altered too drastically. The long-term survival of these oxides in drainage systems and depositional environments is the subject of later chapters.

8.10 Soil magnetism and archaeology

The most familiar application of soil magnetism to archaeology is in prospecting and site survey (see Section 6.7). The equipment available for these purposes includes both passive and active instruments. In the first category are the proton magnetometers and gradiometers. Aitken (1974) and Mullins (1974) both give full accounts of the operation of the instruments and many authors have published studies illustrating their value. Figure 8.7, taken from Scollar (1971), shows the results of a magnetometer survey at a Roman site in the Rhineland. Active instruments are rather more varied and include the pulsed induction meter or PIM (Colani & Aitken 1966), the soil conductivity meter or SCM (Mullins 1974), the Bartington system with both search loop and probe sensor attachments and various modifications of metal detectors and pipe finders. In general, these instruments tend to be more strongly affected by 'soil noise' and are less likely than the passive instruments to detect deep features. Pulsed Induction instruments detect both the eddy currents of metallic objects and the viscous decay of magnetisation in fine crystals. The fine magnetic viscous grains at the stable single-domain – superparamagnetic transition, also give rise to the frequency-dependent (cf. quadrature) susceptibility (χ_{fd}) component (Mullins & Tite 1973). The SCM as Mullins (1974) explains, does actually measure soil susceptibility directly as does the Bartington system which, with the addition of probe sensors for profile and borehole logging, greatly

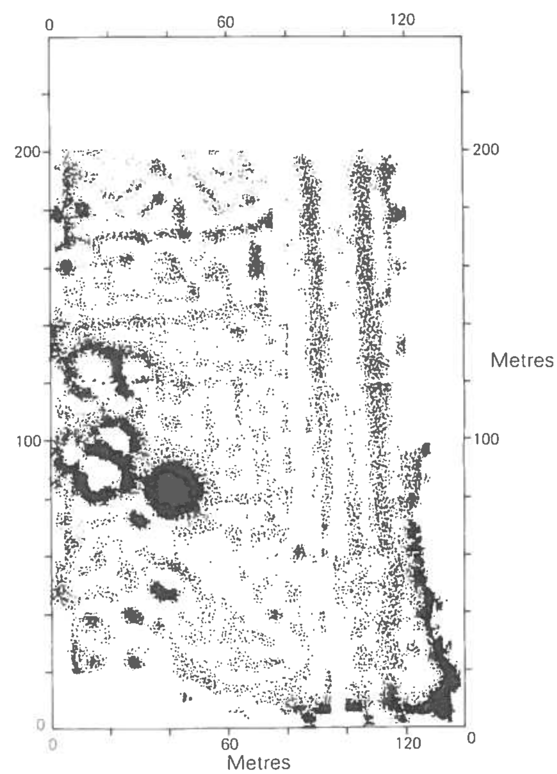


Figure 8.7 The results of a proton magnetometer survey of part of the Colonia Ulpia Triana in the Rhineland. The surveyed area is approximately 140 × 200m. The circles on the left are bomb craters. Above these are outlines of buildings and to the right are traces of two large ditches (redrawn from Scollar 1971).

increases the scope and versatility of the equipment available. The most detailed comparative evaluation of the effectiveness of proton gradiometer, PIM and SCM surveys is given in Mullins (1974) using data from Iron Age/Roman sites in southern and eastern England.

As well as using field instruments for magnetic surveys and prospecting, archaeologists have also made use of mineral magnetic measurements carried out on samples in the laboratory using various types of a.c. susceptibility bridge (e.g. Scollar 1965) and magnetometer. Krawiecki's (1982) study at Maiden Castle an Iron Age hill fort near Bickerton, Cheshire provides an interesting specific illustration of laboratory measurements (Oldfield *et al.* 1984). Charred wood occurs within the ramparts of the Maiden Castle site and visual inspection fails to reveal whether previously burnt wood was emplaced during the course of construction or the wood was burnt *in situ* during or after construction, perhaps in an attempt at vitrifying the adjacent sandy fill. It follows from studies of the effects of fire on the magnetic properties of rocks and soils that *in situ* burning would tend to enhance the magnetic susceptibility and SIRM of mineral soil in contact with the wood, by converting the natural assemblage of haematite-dominated magnetic minerals in the Triassic sands to 'magnetite'. Figure 8.8 plots χ, SIRM, SIRM/χ and $IRM_{-100\ mT}$/SIRM for a vertical section through the rampart at a point where a charred log and layers of blackened sand are present. Clearly the sand adjacent to the log, and in the lower blackened layer, has been magnetically enhanced by one to two orders of magnitude.

Figure 8.9 is a summary plot of the same four magnetic parameters for samples taken from this and three other sections as well as for laboratory-heated sands taken from nearby at the site. Proximity to the charred wood invariably has the effect of increasing χ and SIRM, decreasing SIRM/χ and 'softening' the

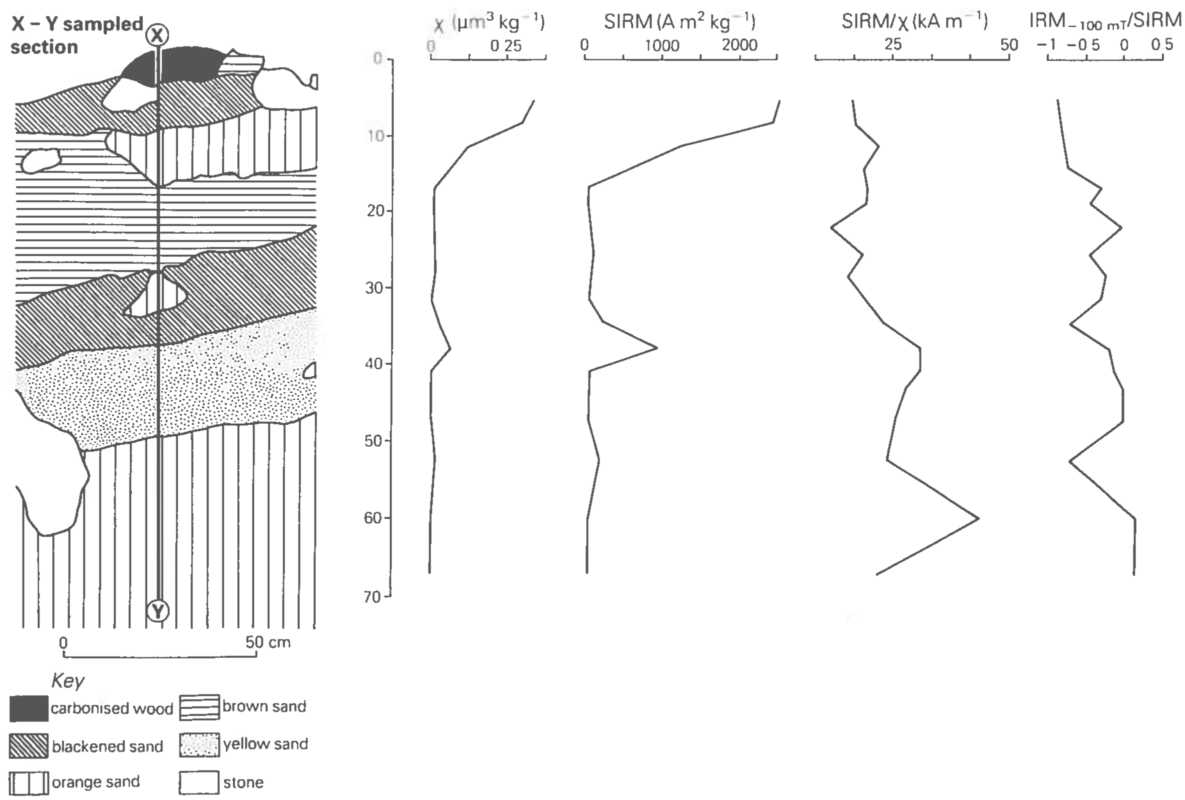


Figure 8.8 Stratigraphic and mineral magnetic profile through the outer rampart of Maiden Castle, near Bickerton, Cheshire (Krawiecki 1982).

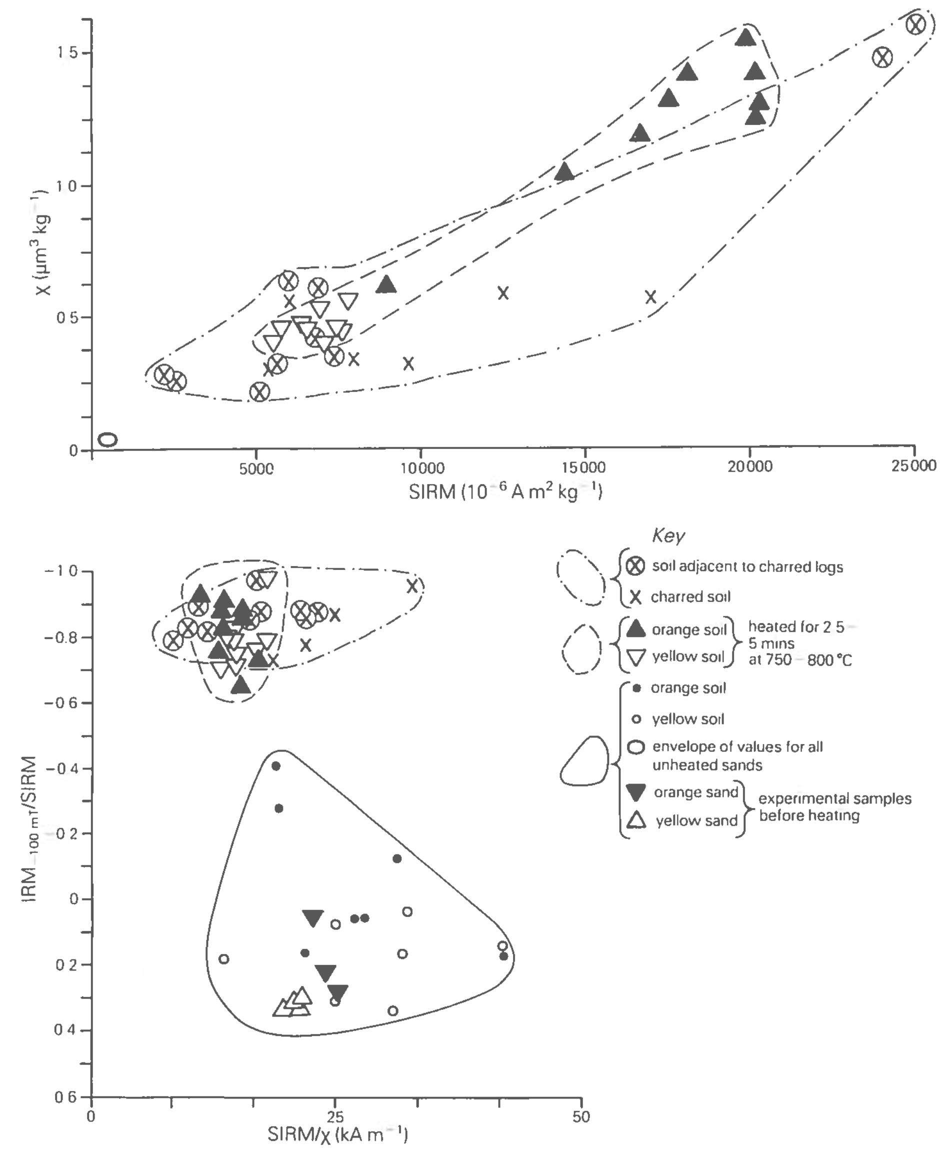


Figure 8.9 Maiden Castle hill fort, Bickerton, Cheshire. χ versus SIRM and SIRM/χ versus $IRM_{-100\,mT}$/SIRM for burnt and unburnt samples (Krawiecki 1982). Mineral magnetic parameters for samples burnt *in situ* during the construction of the prehistoric ramparts are compared with those for unheated sands and for experimentally heated sands (see text).

$IRM_{-100\,mT}$/SIRM values, all changes consistent with enhancement by fire. After many heating and cooling trials during which the parameters identified as significant in Oldfield *et al.* (1981a) were varied, closely comparable magnetic enhancement was achieved on both the yellow and orange sands abundant at the site, by heating and cooling material in a reducing environment at a peak temperature of 750–800 °C for 2.5–5 min. Subsequently, the spatial occurrence of the fire-enhanced material in exposed sections was plotted in the field using the Bartington susceptibility meter with both probe and loop sensors (Fig. 8.10).

The combination of portable magnetometer, pulse

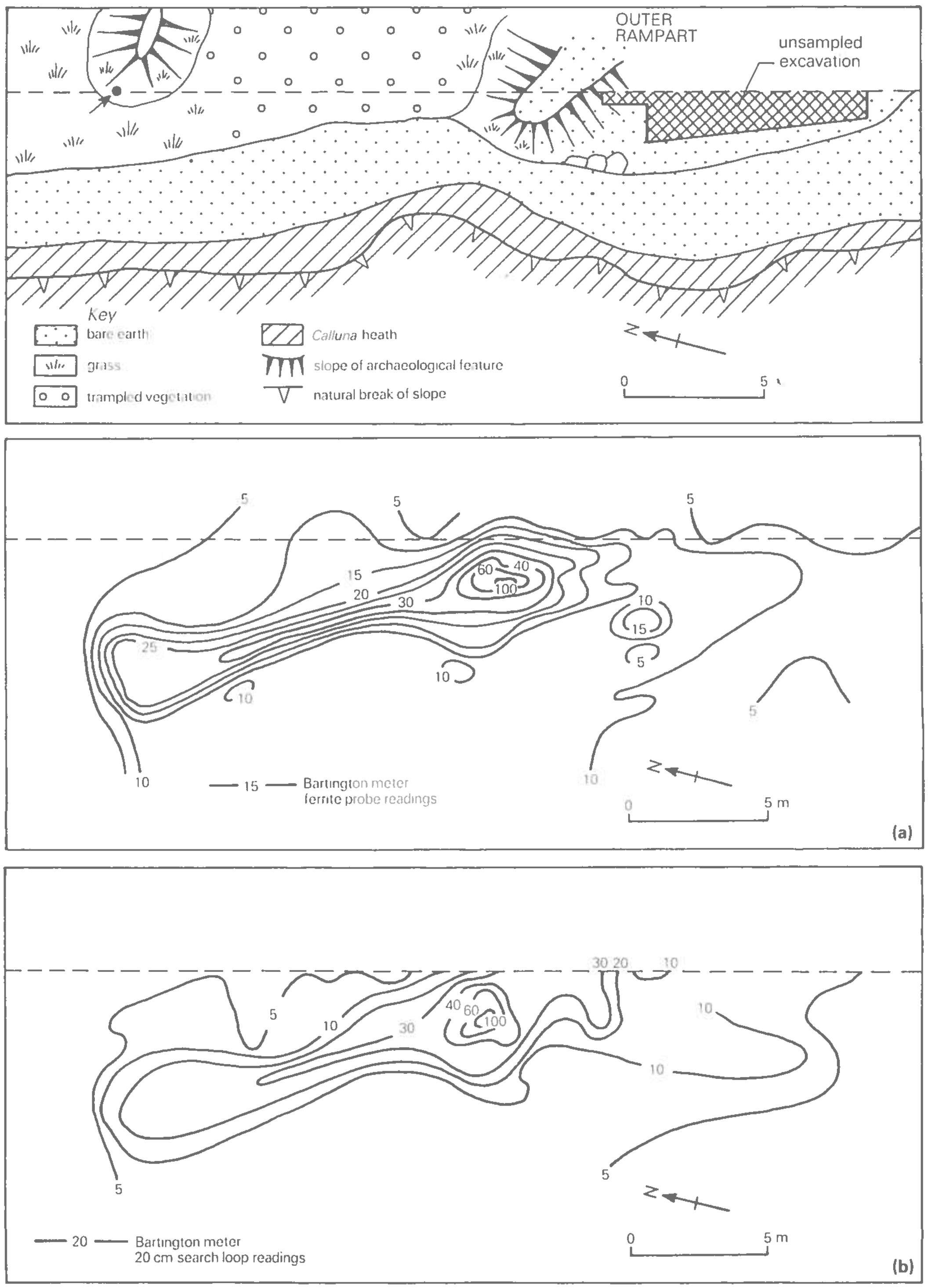


Figure 8.10 Surface susceptibility readings over part of the area of burnt timbers and adjacent magnetically enhanced sand in the Maiden Castle hill fort embankment. Contours are based on both ferrite probe (a) and 20 cm loop (b) readings using the Bartington instruments system.

magnetiser and susceptibility systems opens up new prospects in the application of mineral magnetic measurements to archaeology. Plan and section logging, detailed magnetostratigraphic description, and downhole susceptibility logging all become possible as on-site prospecting, survey and descriptive techniques. Magnetic measurements can also be used not only to locate burnt material but also to help to characterise its thermal history. It seems likely that these new opportunities herald a revival and a broadening of interest in the application of mineral magnetic measurements to archaeological contexts and problems.

8.11 Conclusions

Despite the difficulties inherent in attempting to identify finely divided iron oxides in the soil by means of either mineral magnetic or standard geochemical measurements, the categories of magnetic behaviour recognisable as a result of mineral magnetic characterisation are clearly related to soil-forming processes in a direct and coherent way. Ordered reflections of pedogenesis are apparent in variations between contrasted 'type' profiles on similar lithologies, in variations related to slope processes and poor drainage, and on a fine scale within individual soil profiles on a particle size specific basis. In consequence, the potential value of mineral magnetic measurements to the soil scientist greatly exceeds that which is apparent from the vast majority of published studies concentrating on magnetic susceptibility alone. Both as a descriptive tool in routine survey and profile description, and as an analytical technique in studies of soil-forming processes, magnetic measurements are ideally suited to complement and precede established methods. The more so since they are capable of detecting changes in magnetic mineralogy and grain size at concentration orders of magnitude below the detection limits of conventional methods. The conservation of magnetic properties and their diagnostic value also makes them of great interest in fossil soil and archaeological studies where their potential range of applications has not been fully realised. These same characteristics lie at the root of many of the most interesting applications of magnetic measurements in fluvial, lacustrine and marine systems and these are the subject of subsequent chapters. In addition, Dearing *et al.* (1985) present a general review of the role of soil magnetism in geomorphology.

[9]

Magnetic minerals and fluvial processes

. . . he sat on the bank, while the river still chattered on to him, a babbling procession of the best stories in the world, sent from the heart of the earth to be told at last to the insatiable sea.

Kenneth Graham
The Wind in the Willows

9.1 Introduction

This chapter is concerned with particles in transit once they have reached a defined water course. Prior to the period of movement within a river channel, the particles will have been either released from the land surface and delivered to the channel by rainsplash, sheet erosion, rill and gully erosion or mass movement, or else removed from the channel banks or stream bed through the erosive effect of the moving water and its entrained load. Sediment within the channel is normally considered as either suspended sediment or bedload, though as flow conditions vary through space and time the distinction is more one of practical convenience than of consistent differentiation.

Many aspects of stream sediment transport are of interest to scientists in a variety of disciplines. For example channel morphology is closely related to sediment type and to rates of sediment movement, especially where the river bed includes persistent constructional features such as gravel shoals and point bars. Identifying the source of sediments is a vital aspect of erosion studies in contexts where both surface denudation and channel change are evident. Where the fine sediments in stream channels can be ascribed to soil surfaces there are often important implications in terms of soil aggregate stability in the eroded areas, and particle-associated pollution in the water bodies down river. The dynamics of sediment transport have major engineering implications where channel change reduces the effectiveness or viability of nearby structures. These engineering implications arise because the catchment, bed and banks of the river provide the mechanical load for transport. Changes in transported load often give rise to practical problems as a result of the new erosion and deposition régimes which they generate. Estimates of sediment transport are often based on hydraulic equations which assume capacity load, though this is rarely achieved in reality. There is therefore a need for better information about sediment sources and the amount of material each contributes.

In the present account, suspended sediment is examined largely from the point of view of source identification (Section 9.2) and bedload is considered experimentally with a view to improving our understanding of its transport and storage dynamics within the river channel (Section 9.3). The special case of artificial urban drainage systems is also considered in this chapter (Section 9.4) largely in relation to heavy metal concentrations and sources. Sections 9.2 and 9.3 form a link between Chapter 8 on Soil Magnetism and the succeeding chapters dealing with sediment deposited in lakes (Ch. 10) and in the sea (Ch. 12). This particular treatment inevitably implies some loss of the integrated perspective which drainage basin studies can provide (e.g. Gregory & Walling 1973, O'Sullivan 1979). To some extent this is redressed in the lake sediment based studies discussed in Chapter 10, and more specifically in Chapter 16 which is entirely concerned with a tidal river and estuarine system and the source–sediment linkages within it.

9.2 Suspended sediment sources

In most rivers the suspended sediment load constitutes the dominant mode of particulate material loss from the catchment. This is especially so where the nature of the bedrock and the weathering processes combine to supply large quantities of fine material to the channel. Macroscopic characteristics of the sediments will often give no clue as to the main source of such fine material. Geomorphological evidence in the form of active streamside erosion scars, developing gullies or truncated soil profiles may often give a clear indication of specific contributing sources (e.g. Mosley 1980), but the significance of these sources, and their relative contribution at different times may remain obscure without direct evidence from the sediment itself.

From Chapter 8, it can be seen that at least one aspect of this problem, namely the identification of topsoil erosion, is potentially tractable using mineral magnetic measurements. The processes of weathering and especially magnetic enhancement frequently give rise to mineral magnetic assemblages in the upper layers of the soil readily distinguishable from those in the underlying parent material. Where the main problem in suspended sediment source identification is one of distinguishing between surface-derived material from the catchment slopes, and subsurface material eroded from the channel and banks, then the magnetic changes associated with soil formation in Chapter 8 may be expected to aid differentiation. This particular problem has implications not only for the geormorphologist studying denudation rates, channel form and dynamics or downstream sedimentation, but also for the environmental chemist and agriculturalists interested in water pollutants, for example limiting nutrients or persistent pesticide residues, which may often move from soil surface into rivers in sediment-associated form.

9.2.1 *Suspended sediments in the Jackmoor Brook*

The first attempt to identify suspended sediment sources from their mineral magnetic characteristics was carried out in the Jackmoor Brook, near Exeter in South West England. The Jackmoor Brook basin has an area of 9.3 km^2 and ranges in altitude from 21.5 to 235 m. Gentle ($<4°$) slopes predominate and the soils range from well drained to poorly drained and gleyed brown earths developed on Permian red-bed desert sandstones, breccias and conglomerates rich in haematite. Mixed arable farming predominates in the area with cultivated crops and grass leys covering most of the catchment. Less than 4% of the catchment is wooded. Particulate transport within the stream is mostly as suspended sediment. Relatively high concentrations (up to 3.5 g l^{-1}) occur in storm events and the annual suspended sediment yield from the catchment is estimated as around 85 t km^{-2}. There is little floodplain development and the channel, though only rarely incised by more than 1 m, reaches bedrock in most places. Obvious actively eroding sites, whether in the channel or on the catchment surface, are rare. The basin was chosen for developing and evaluating magnetic methods of sediment source tracing for several quite independent reasons. Within the catchment, there are unresolved questions relating to sediment source. In particular the relative importance of surface soil and channel contributions is hard to establish by other methods. The well developed monitoring and sampling programme already established within the catchment provides a comprehensive hydrological framework for the study. The catchment lithology and soil types are very favourable for magnetic differentiation. Brown earth soils have developed on bedrock consistently rich in haematite. Moreover, the area lies south of the maximum limit of Pleistocene glaciation and thus lacks transported erratics. The context is ideal for testing the magnetic methodology, since *a priori* one would expect the sediment yielded from such surface soils to be relatively rich in secondary ferrimagnetic grains in contrast to channel and bankside material with a preponderance of antiferromagnetic grains derived from the bedrock. (Ch. 8).

The initial magnetic studies at Jackmoor Brook predated development of an effective portable susceptibility measuring system, and the characterisation of potential sediment sources within the catchment was achieved by sampling soil pits, and by collecting material from the plough layer of tilled soils

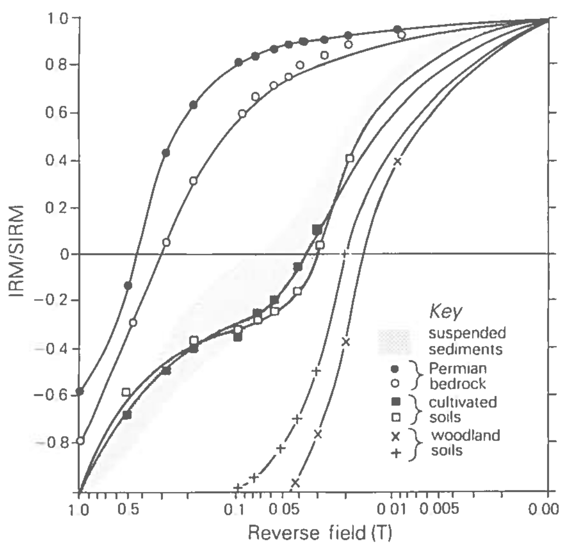


Figure 9.1 Coercivity of SIRM curves for soil, and bedrock/bankside samples from the Jackmoor Brook compared with the envelope of values for bulk suspended sediment samples from Oldfield *et al.* 1979).

and from the sites where freshy undercut exposures indicated recent erosion within the main stream channel. The first suspended sediment samples measured were obtained by centrifuging large quantities (~20 l) of stream water collected during storm events.

The results summarised in Table 9.1 from Walling *et al.* (1979) show the characteristic magnetic enhancement of surface soils developed under woodland and temporary pasture within the catchment. Figure 9.1 plots back-IRM curves for a selection of the catchment samples and the four bulk suspended sediment samples. The predicted contrast between bedrock and topsoil is confirmed, especially in the case of the deciduous woodland soils which are less vertically mixed and have been less exposed to rain-splash and rill erosion than the cultivated surfaces. Streamside samples compare closely with parent material save at the top of river banks, within exposed surface soils. The back-IRM curves of Figure 9.1 and the very high $(B_0)_{CR}$ values confirm that the magnetic properties of samples from below the depths of active soil development are dominated by canted antiferromagnetic grains.

Gleyed soils show low susceptibility and also low coercivity of remanence values whereas the well drained cultivated soils show, for all parameters, values intermediate between those for the bedrock and the unmixed woodland topsoil. In all respects, the cultivated soils and the suspended sediment samples are directly comparable. We may therefore infer from the magnetic measurements that the dominant sources of suspended sediments are the cultivated soils of the catchment and that the mineral magnetic assemblage within these soils reflects both vertical mixing by cultivation, and some loss of surface material through rainsplash and rill erosion.

The initial mineral magnetic study opened up the possibility that distinction could also be made between the balance of sources from flood to flood and between different stages within a flood event. In order to explore this possibility further, measurements were made on filter paper residues. The suspended sediment load was sampled at the outflow gauging station using an automatic pump sampler which, during flood events, abstracted 500 ml of water at hourly intervals. The magnetic properties of the suspended sediment filtered from samples can be plotted alongside the continuous records of discharge and suspended sediment concentration (turbidity) made at the gauging station (Fig. 9.2).

Adopting the methods outlined in Walling *et al.* (1979) consistent and repeatable SIRM, $(B_0)_{CR}$ and $IRM_{-100\,mT}/SIRM$ values were obtained on samples with dry weights as low as 0.02 g thus permitting over 90% of the filter paper residues to be magnetically characterised with confidence. Susceptibility was measurable on only a small proportion of these low

Table 9.1 Summary of selected magnetic properties of bulk suspended sediment samples and potential sediment sources from the Jackmoor Brook catchment.

Material	χ ($\mu m^3 kg^{-1}$)	SIRM (mAm^2kg^{-1})	SIRM/χ (kAm^{-1})	$(Bo)_{CR}$ (mT)	$\frac{-IRM_{-100\,mT}}{SIRM}$
woodland topsoil	>2.5	>10	≈4	<35	1
cultivated topsoil	0.2–2	1–10	5–7	24–41	0.28–0.8
poorly drained and gleyed soils	0.06–0.4	0.5–3.5	≈10	≈30	≈0.4
parent material	<0.1	1–2	>10	200–400	−0.8– −0.6
suspended sediment	0.25–0.75	2.5–9	≈10	37–60	0.06–0.4

mass samples. Figure 9.2 summarises the results obtained. Two general points emerge:

(a) The mean values and total range for all parameters strongly reinforce the conclusion previously reached that the dominant sources of suspended particles in the Jackmoor Brook are the cultivated soils of the catchment.
(b) There are both similarities and contrasts between the magnetic trends in each flood event and these are interpretable in terms of a coherent process model of sediment supply.

In floods 1 and 4 maximum SIRM values follow the peaks in discharge and suspended sediment concentration. Flood 1 was the first of the winter and followed a prolonged dry period. Flood 4 is marked by a very sharp rise in discharge to high levels. Thus in both cases channel scour may be inferred and would be expected to reach a maximum during the rising stage of the hydrograph. The effect of this has been to contribute a relatively greater proportion of bedrock-derived material up to the point of channel source depletion. Floods 2 and 3 are marked by gentler discharge rises during a period soon after the channel source depletion associated with the first event. In both cases any delay between peak discharge and sediment yield, and peak SIRM, is less apparent. Moreover, most of the SIRM values for floods 2 and 3 range from 4 to 6.5 mA m^2 kg^{-1} whereas for floods 1 and 4 the values lie between 3 and 5.5. There is therefore some indication that during the two middle flood events there is less contribution from bankside sources and a more exclusively surface-derived suspended sediment load. The tendency for the surface sources to dominate from peak discharge onwards in all floods is consistent with a situation where maximum surface yields coincide with maximum rainfall intensity and rainsplash effectiveness, and maximum surface runoff rates.

The fifth flood event portrayed was the product of snowmelt rather than rainfall. The low SIRM values are consistent with a lack of rainfall energy reducing mobilisation by splash erosion. This factor along with the persistence of freezing conditions in the soil has resulted in a relatively low contribution from the cultivated soils. Thus channel sources become relatively more significant contributors to the rather modest suspended sediment concentrations recorded.

Subsequent studies by Peart (unpubl.) have tended to confirm the above inferences whilst at the same time documenting a wide variety of mineral magnetic response to flood events and identifying gleyed soil areas close to stream channels as significant sediment sources during the early stage of some floods. His evaluation of the relative consistency of source-sediment linkages, derived from mineral magnetic measurements as well as other chemical parameters such as phosphate or carbon concentrations, suggest that only the mineral magnetic properties are conservative within the system.

9.2.2 *Other studies of suspended sediment sources*

Although the Jackmoor Brook site is developed on an ideally favourable lithology for the type of sediment source differentiation illustrated above, it follows from Chapter 8 that in many other contexts, magnetic differences between bedrock and the topsoil will be identifiable. Brief reference is made to two other case studies chosen to illustrate problems and possibilities elsewhere.

The Great Eggleshope Beck catchment which is instrumented by the Freshwater Biological Association covers 11.68 km^2 in the North Pennines of Britain (Carling & Reader, 1982). The channel lies within an area of colluvium head and till largely derived from upper carboniferous millstone grits which together with carboniferous limestones form the bedrock to the catchment. Shallow, acid brown earths, podsols and peaty gleys are the main soil types and these support extensive areas of rough pasture and moorland, parts of which are periodically burnt. Mineralisation upstream of the study site has led to earlier periods of mining activity which has resulted in areas of mineral spoil covering parts of the valley floor. The spoil heaps are gullied and in parts, the main channel is eroding them. In the present study (Chorlton 1981), sediment-source comparisons have been attempted largely on the basis of SIRM measurements made on bedrock, channel material, spoll and topsoil as well as on suspended sediments from the periods of maximum concentration during two flood events. The values for the suspended sediments are within the range characteristic of bedrock and channelside material and generally much lower than those of either the surface soils of the catchment or the areas of mining spoil. Similar inferences may be drawn from the results summarised by Wise (1979) for the Wadhurst Park catchment in Kent. Here, a largely pasture-covered catchment developed for the most part on Ashdown Sands yielded suspended sediments

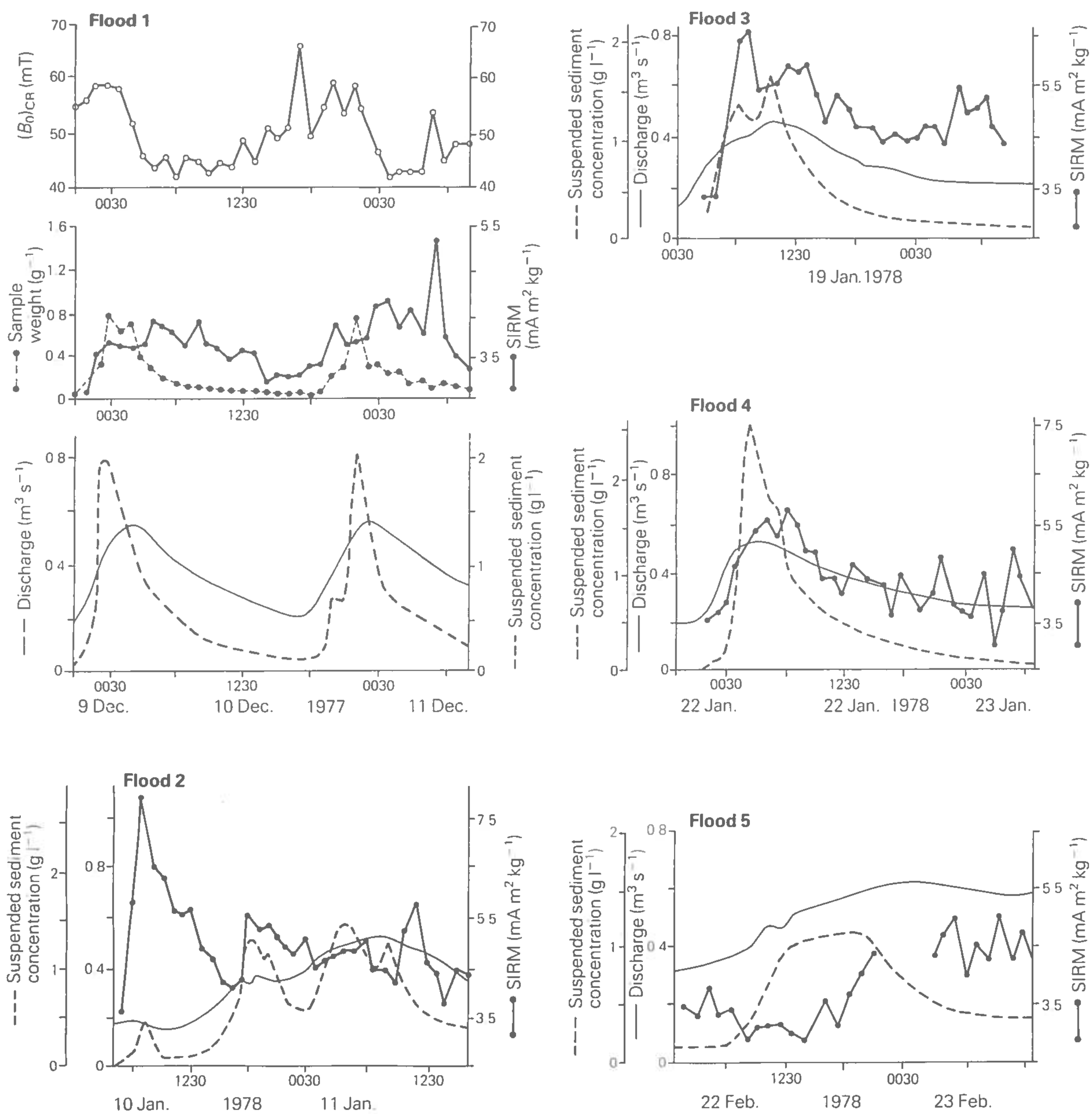


Figure 9.2 Mineral magnetic and hydrological parameters for five flood events in the Jackmoor Brook catchment (From Walling *et al.* 1979). See text for interpretation.

comparable magnetically to the exposures of eroding subsoil adjacent to the stream channel.

9.2.3 *Prospects and problems*

So far, we have tended to concentrate on uniform, relatively iron-rich sedimentary lithologies. The prospects for this type of approach will decline in iron-poor environments and in the situations where magnetic enhancement of topsoil is retarded or inhibited (see Section 8.4). Also, although frequency-dependent susceptibility measurements should allow differentiation between topsoil and bedrock, where the latter is rich in primary ferrimagnetic minerals, this parameter will rarely be measurable on low volume filter paper residues. Thus it will be difficult to achieve the same temporal resolution without the use of larger integrated sampling devices. In catchments of mixed lithology the added complexity may either increase or reduce opportunities depending on whether or not the variations are readily characterisable by magnetic parameters and on whether the spatial distribution of magnetically distinguishable lithological units relates coherently to the problems of source identification posed by the catchment. Glaciated catchments with varied and irregularly distributed drifts and abundant erratics are probably the least suitable for this type of study although individual till sheets and drifts of uniform provenance can be distinguished and characterised magnetically (Sugden & Clapperton 1980; Walden & Smith, pers comm.)

Rather different problems are posed by stream channels incised in and currently eroding older alluvium. Where this alluvium has been derived from eroding surface soil, then provided the eroding sites have not been gleyed, the magnetic properties are likely to compare closely with contemporary surface soils. Mineral magnetic study of this type of system must include very detailed particle size specific characterisation of the whole range of actively eroding exposures with a view to determining the range of variation present and any indications of post-depositional transformation. Sandland's (1983) and Arkell's (1984) data from the middle reaches of the Severn in an area where the river is actively eroding older alluvium suggest that there, the problem is potentially tractable.

In the studies outlined above little or no attention has been paid to the effects that changing particle size : magnetic grain size relationships will have on the magnetic parameters used to establish sedimentological linkages; yet discharge variations will often lead to changes in the particle size distribution of the suspended load. Where this gives rise to shifts in the proportion of grains in different magnetic domain states, we may expect changes in magnetic parameters even where no *mineralogical* variations are present. At the same time, in natural samples the mineral and domain size variations will rarely if ever be independent. For example, secondary ferrimagnetic iron oxides in the soil will always tend to be stable single domain or smaller, while equally fine-grained haematite or goethite crystals will often be associated with cemented sands. Probably the safest procedure available for avoiding either spurious or coincidental source–sediment linkages and for reducing the likelihood of invalid mineral magnetic inferences is to look in detail at the magnetic properties of particle size specific fractions for both the potential sources and the trapped sediments (cf. Ch. 16).

In catchments with substantially lower suspended sediment yields than the Jackmoor Brook, the small mass of the filter paper residues will eventually limit the effectiveness of the method. This problem can be compounded by the presence of ferrimagnetic impurities in both the glass-fibre filters commonly used and the standard 10 ml sample pots. It has been found that 25 mm diameter Teflon filter discs without sample holders can be measured and that in practice this approach provides at least an order of magnitude better sensitivity than that described in Oldfield *et al.* (1979 c).

Finally, it is apparent that in their present form, the mineral magnetic methods are qualitative rather than quantitative. Oldfield *et al.* (1979c) attempted to make the bulk sediment characterisation at Jackmoor Brook more quantitative, but only in terms of estimating crudely the bedrock : unmixed topsoil ratio which could produce the range of magnetic parameters common to both the cultivated soils and the sediments. Quantitative estimates of the relative importance of specific sources and source types for particular episodes may however sometimes be feasible (Stott 1986). Future studies concentrating on this aspect of the technique and also on combining magnetic measurements with radiometric tracing (cf. Campbell *et al.* 1982) will be especially valuable.

9.3 Magnetic tagging and tracing of stream bedload

Just as the naturallly evolved magnetic properties of soils provide a basis for sediment-source identification, artificially induced magnetic characteristics can be used to provide material for use in tracing experiments. As we have seen in Chapter 8, fire can lead to a strongly enhanced magnetic signal in surface soils. In practice, most reasonably iron-rich natural materials can be magnetically enhanced by heat treatment in the laboratory, though the initial idea for magnetic tagging and tracing came from monitoring the after effects of a major forest fire. The Llyn Bychan forest fire of 1976 (Rummery 1981, 1983) in North Wales gave rise to magnetically enhanced material which persisted in the soils and the lake sediments and found its way to the Afon Abrach, the river which drains both the lake and the intensively burnt area down stream of the lake outfall. After the fire, a series of magnetic measurements were made on sieved material from successive downstream shoals beginning in the burnt area and continuing for some 2 km. In the case of the coarser clasts the downstream magnetic variation involved an order of magnitude decline. By contrast, the finest materials showed exceptionally high SIRM values close to the fire and a three order of magnitude decline downstream. These results were interpreted as reflecting the selective loss of magnetically enhanced fines from the burnt area and the gradual dilution of this material at increasing distances down stream. This observation opened up the possibility of using not only naturally but artificially enhanced material as a bedload tracer in river channels.

9.3.1 The Plynlimon case study

The Plynlimon area of central Wales was chosen for the initial testing of magnetically enhanced tracers for several reasons. One of the major concerns of the Institute of Hydrology's catchment research at Plynlimon is the large volume of bedload generated in the upper reaches of the Severn by the rapid recent erosion of forest drainage ditches. By the time the first magnetic trials began, a major programme of hydrological and sedimentological monitoring had been established by the Institute (Newson 1980) and this provided an essential framework for the trials. More recently, the work was extended downstream into the piedmont zone in response to concern expressed by the Ministry of Agriculture Fisheries and Foods about the effects that the increased gravel yields, coupled with the water regulation policies adopted in headwater reservoirs, might be having on channel stability and possible land loss in cultivated areas.

The main reasons for using bedload tracer studies as part of the research strategy devised in response to the academic and practical problems posed by the Upper Severn are set out in Arkell (1984). Most conventional tagging and tracing techniques are limited to a particular particle size range. Pebble painting or plugging with radioisotopes are suitable only for large clasts, whereas fluorescence is more applicable to sands. Existing techniques also pose serious problems of signal persistence and particle recovery. Problems are further compounded in the study area by the very wide size range of the bedload and the preponderance in many reaches of fine gravel which is difficult to tag conventionally. Fortunately, the bedrock is a shale uniformly rich in finely disseminated paramagnetic iron giving both a consistently low susceptibility and saturation remanence in its unheated state, and a high potential for enhancement by heat treatment.

The work so far has involved developing:

(a) suitable heating procedures for enhancing the magnetic susceptibility of large quantities of gravel,
(b) instruments and techniques for magnetic measurements both in the river channels and on abstracted material in the laboratory and
(c) field trial strategies on a range of spatial and temporal scales designed to contribute both to the evaluation of the technique and to the understanding of the substantive problems of bedload transport in the area.

The heating trials leading up to adoption of a practical bulk 'toasting' method for the Plynlimon material are described and their mineralogical effects interpreted in Oldfield *et al.* (1981a).

Instrumentation was initially limited to a Littlemore susceptibility bridge for laboratory measurements of bulk samples. Subsequently, commercially available portable metal detectors (see 6.7) were used for location of enhanced tracer material on and down stream from 'seeded' shoals. A pulsed induction meter, a Whites Savo TR induction balance coil and an Arado VF90 acoustic loop were all capable of detecting enhanced material in the field, but not of giving more than a very crude qualitative indication of strong presence only. A 20 cm diameter search loop and both hand-held and ground-search versions of ferrite probes were finally constructed by Bartington Instruments specially for the Plynlimon bedload monitoring project.

Field trials began in two of the overdeepened drainage ditches within the afforested upland part of the Severn catchment. The ditches are essentially field flumes and together with the bedload traps at their mouths, they provide a simple and confined channel within which to test techniques for emplacement, location in transit and downstream recovery. Gravel was taken from shoals up stream from the bedload traps and replaced in the same particle size proportions by weight, with previously trapped material which had been heat treated in a large muffle furnace. These initial traces were characterised by high tracer recovery rates, and the results greatly improved insight into the rôles of storage and supply within the systems.

Encouraged by the results from these field experiments (see Arkell *et al.* 1982) and by improvements in 'toasting' techniques, the methodology was extended to three sites in the natural river channels. These were in the river Severn at Morfodion, the Llwyd, one of its tributaries, at Dolydd, and the Cefn Brwyn in the upper reaches of the Wye system. At Morfodion, the Severn is approximately 30 m wide with a 500 m flood plain. The Morfodion site provided a location for which loss from a seeded area was much more readily measurable than subsequent downstream movement. The heat-treated, magnetically enhanced gravel was placed in a trench cut normal to flow through a shoal which projected down stream into the river from the true left bank. The Dolydd trace on the Llwyd was set up beginning beneath a road bridge spanning the whole river channel. The site provided an opportunity to monitor not only loss but movement through storage locations down stream. At the Cefn Brwyn site on the Wye, the seeded site was immediately down stream of the Institute of Hydrology compound crump

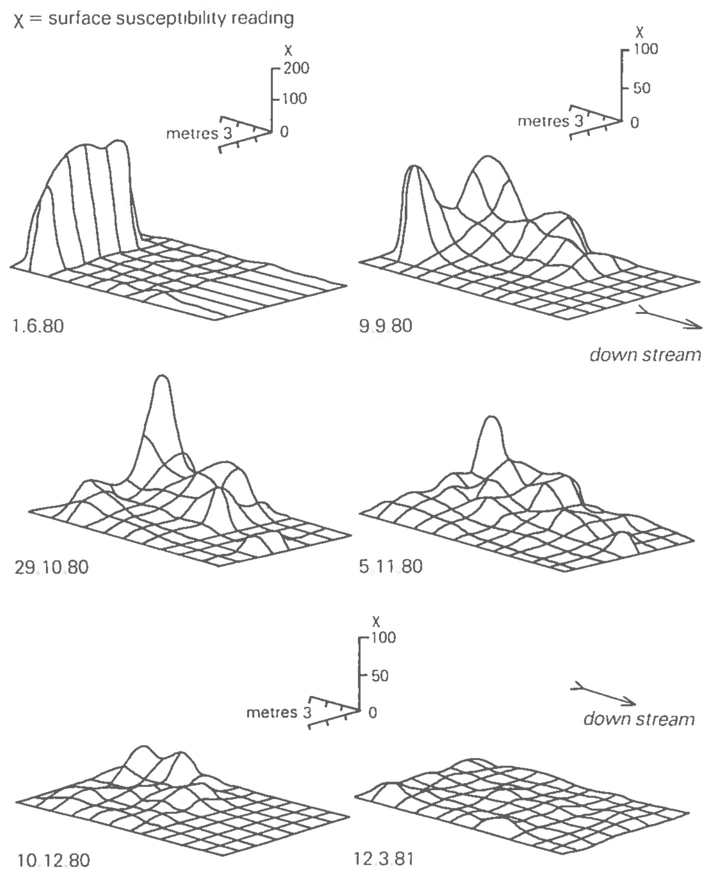
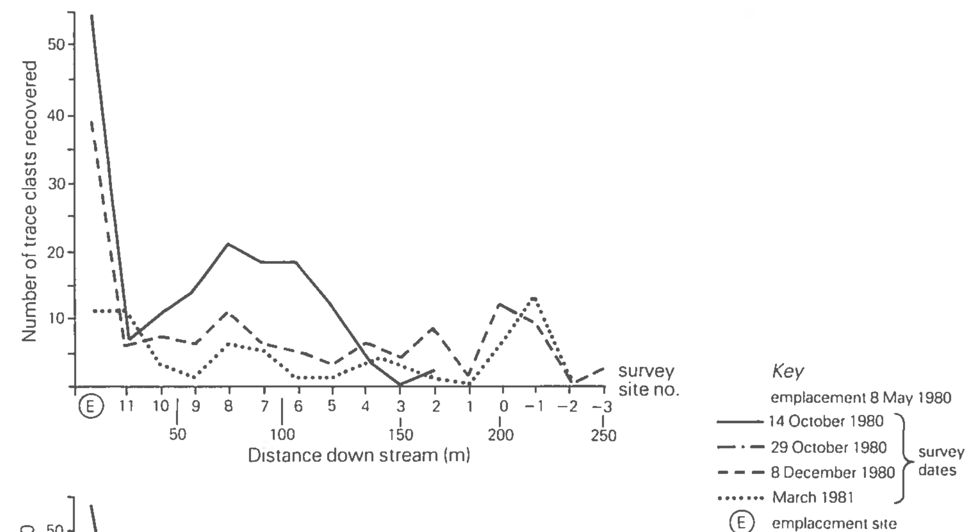


Figure 9.3 Bartington 20 cm search loop surface readings from the magnetically 'seeded' shoal at Morfodion on the River Severn. The initial isoplot of surface susceptibility readings records the effect of the magnetically enhanced gravel immediately after emplacement. Subsequent isoplots record its downstream dispersal and partial burial (see Arkell *et al.* 1982).



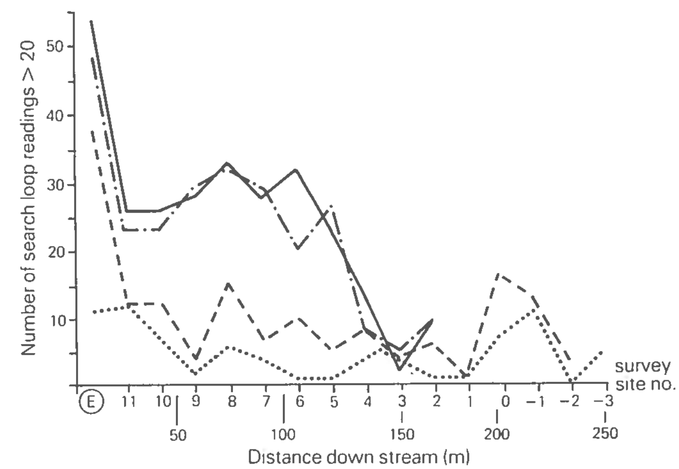


Figure 9.4 Downstream magnetic tracer recovery of the Cefn Brwyn site on the River Wye. Successive surveys gave a changing temporal and spatial pattern of recovery for positively identified tracer clasts (above) and a comparable pattern for surface search loop readings (below).

weir, allowing loss and subsequent downstream movement to be monitored without the additional complication usually found in natural channels of bedload addition from up stream. Emplacement procedures varied from site to site in response to the nature of the channel and the local bedforms, and alternative schemes of sampling and magnetic susceptibility measurement were used to tie in with different scales of topographic monitoring (Arkell *et al.* 1982).

Figure 9.3 shows some of the results obtained for the Morfodion shoal from the time of emplacement in June 1980 through to March 1981. Downstream movement of the tracer on the shoal is associated with small topographical changes. The results show that the topography on the latest survey date has been produced in part by removal of tracer along the northern edge of the shoal and its replacement by gravel from up stream which has partially recreated the original form. Figure 9.4 is a plot of tracer movement down stream from the emplacement site at Cefn Brwyn as detected both by surface susceptibility 'search loop' readings and by the recovery and indentification of tracer clasts. The comparability of the results yielded by the two methods on each survey date reflects in part the use of the search loop to locate individual clasts for subsequent laboratory confirmation as tracer. Using the hand-held probe individual tracer particles down to 3 mm diameter can be identified. The main hydrological implications of the results obtained from all the traces so far is the overriding importance of channel storage on sediment transport even within the small forest ditch channels (Arkell *et al.* 1982, Arkell 1984).

9.3.2 *The prospects for magnetic tracing*

Further development of the magnetic tracing methods used at Plynlimon and their adaptation to river sediment tracing on a wide range of lithologies will be constrained by several factors, some environmental and some technical. The main ones are outlined briefly below:

(a) *Lithology.* Optimum conditions are presented by bedrock types uniformly rich in weakly magnetic forms of iron. On iron-poor lithologies the introduction and tracing of exotic enhanced material will be feasible. On strongly magnetic or magnetically heterogenous lithologies, magnetic tracing is likely to prove impossible.

(b) *Channel size, bedload flux density and shoal geometry.* The larger the channel, the greater the flux density of moving bedload through the monitored reach and the greater the probability of deep burial of enhanced material in shoals, the greater will be the logistic problems posed in downstream detection whether through field or laboratory measurements. These problems find expression both in the 'toasting' where larger volumes have so far posed problems of environmental control during heating, and in the 'post-seeding' field situation where any increase in scale of operation will tend to reduce the probability of recovering tracer material.

(c) *Heat treatment.* The optimum heat treatment of the Plynlimon material is strongly conditioned by the self-reducing nature of the sulphur-rich shales at high temperatures and by the finely disseminated nature of the iron present. Thus the experience gained so far is unlikely to be directly applicable elsewhere and each rock type will require a different combination of the main variables. Nevertheless, some general problems have emerged. Resistence of rocks to thermal stress strongly affects the possibilities of optimum magnetic enhancement in large size classes where, as in the Plynlimon studies, insertion at high temperature and a consequently rapid rate of heating were used. Moreover, heat treatment of bulky samples in large crucibles means that at any one stage in the treatment, the thermal history of material in different parts of the crucible (top *v.* bottom, side *v.* centre) will be very different. The effects of this on the shales used in the Plynlimon study are exhaustively illustrated and crudely modelled in Oldfield *et al.* (1981a). In theory, the phase-equilibrium approach should dispose of this problem though in practice it has not yet proved successful for large volumes of gravel. If the treatment of bulk samples can be combined with manipulation of the heating atmosphere, then reducing atmospheres (e.g. nitrogen or carbon dioxide at high temperature) should greatly increase the efficiency of conversion of all iron present to magnetite provided temperature and partial oxygen pressure can be held for long enough within the equilibrium phase.

(d) *Magnetic sensor performance.* All magnetic sensors are sensitive to variations in the geometry of the material to be measured. Thus the field search loop used in the present study is unable to detect small quantities of magnetised material *in situ* and buried beneath a thick armour layer; moreover, a small 'toasted' pebble close to the sensor rim will increase the signal by as much as a larger pebble in the centre of the sensor or some way outside its perimeter. The main response to this type of difficulty has been to develop strong, stable and sensitive probe sensors for insertion between the cobbles of an armour layer. An alternative response would be to use pipe detectors and thereby radically change the coil/sample geometry.

9.4 Magnetic measurements of stormwater-suspended solids

Heavy metal toxicity can pose serious problems in urban stormwater drainage. Many authorities regard non-point surface sources such as roads as significant primary contributors to high heavy metal loadings. Where the contribution is in a particulate, chemically relatively immobile form the heavy metals will pass through the system little modified. Where the heavy metals are in a chemically mobile form, adsorption and precipitation mechanisms in the below-ground phase of the system lead to enrichment in the suspended and benthic particulates present. Thus the heavy metals are mostly found in either a particulate or an eventually particle-associated form. In studies of heavy metal fluxes and concentrations in storm water it is therefore important to identify particle sources with a view to establishing which parts of the system are important either as heavy metal contributors or as contributors of particles with which heavy metal species become associated during transit. An initial appraisal of the possible rôle of mineral magnetic measurements in this field has been made in the separate stormwater system of a 3.5 km^2 catchment in Hendon, North West London.

Samples from two storms of low to medium rainfall intensity were collected on 29 November 1979 (storm 1) and 28 January 1980 (storm 2). An automatic water sampler situated at the sewer outfall, triggered by a float switch on the rising limb of the hydrograph, obtained samples every six minutes throughout the storm events. Suspended solids were isolated by filtration through 0.45 μm Millipore filter papers which were subsequently used for the SIRM measurements. Heavy metal determinations of the suspended solids were carried out by digestion of the filter papers in a nitric acid–perchloric acid mixture followed by evaporation to dryness and dissolution of the residue in 2% hydrochloric acid prior to atomic absorption spectrophotometry. Figure 9.5 plots SIRM variations against total suspended solids, and SIRM versus Pb, Zn and Cu concentrations for each flood. Generally, strong linear correlations between SIRM and heavy metals are indicated in all three cases for both flood events. Urban catchments are rich in magnetic mineral sources which are as yet poorly evaluated in terms of their type, location or spatial and temporal contributions to stormwater runoff. Atmospheric fallout and automobile emissions are known to be rich in magnetic particulates (Oldfield *et al.* 1978, Oldfield *et al.* 1979c, Hunt *et al.* 1983, Linton *et al.* 1980 & Ch. 11). Both these sources may also be expected to contribute heavy metals. Rust and attrition of vehicles, gutters, pipes and other iron and steel surfaces may be expected to yield magnetic particles to road surfaces and drainage channels. In addition, authigenic formation of magnetic oxides or sulphides in pipe and gully sediments receiving a dissolved iron input may also be important. However, some tentative conclusions on sediment and metal sources can be postulated from a study of the magnetic patterns.

SIRM values, which are here interpreted as concentration-related parameters, are reciprocally related to sediment concentrations with an exact match of sediment peaks and magnetic troughs in the first storm. The correlation between metal and SIRM values has been investigated not only in general terms but also by comparing their flow-weighted ratio through time (Revitt *et al.* 1981). Close agreements in the time distribution of these ratios is found especially for the metals plotted in Figure 9.5. In storm 2 the flow peak lags nearly one hour behind the sediment peak. However, the SIRM values follow the pattern of the storm hydrograph with the peak discharge coinciding with the maximum SIRM values of 16×10^{-3} A m^2 kg^{-1} declining to a minimum of 7.2×10^{-6} A m^2 kg^{-1} on the recessional limb. The leading prime sediment peak can be explained (Ellis 1979) as an early flushing of pipe deposits lodged in the sewer system from previous low flow events. It would appear that these leading sewer sediments on the rising limb of the hydrograph possess magnetic properties different from those of the suspended sediments associated with the late flows and it is tempting to ascribe the more magnetic nature of the later sediments to scouring and transport of toxic particulate from the street surface. In storm 1 there is a general temporal coincidence of peak flow with maximum suspended solids and SIRM values although there are two subsidiary magnetic peaks associated with the rising limb of the storm hydrograph. If by analogy with storm 2, relatively low SIRM values can be interpreted as an indication of proportionally greater sediment contributions from below-ground sources, then these leading peaks may reflect early inputs from contributing surface areas, such as road gutters, located relatively close to the sewer outfall.

In terms of metal loadings and sources, the magnetic properties would therefore indicate that for storm 1 both below- and above-ground sources are contributing to outfall toxicity but at different times during the storm. In storm 2, the increase of the metal concentration well into the recessional limb of the hydrograph would point to the predominance of above-ground sources in this event. At present, the work is insufficiently developed to allow identification of magnetic characteristics and further magnetic typing of potential sources is required. The parallelism between metal levels and SIRM values would suggest nevertheless that magnetic parameters might be useful as a rapid and non-destructive surrogate method for monitoring metal patterns during storm flow events as well as for helping to identify heavy metal sources within the urban stormwater drainage system (Beckwith *et al.* 1984; 1986).

9.5 Conclusions

The three areas of application illustrated above by no means cover the whole range of potential con-

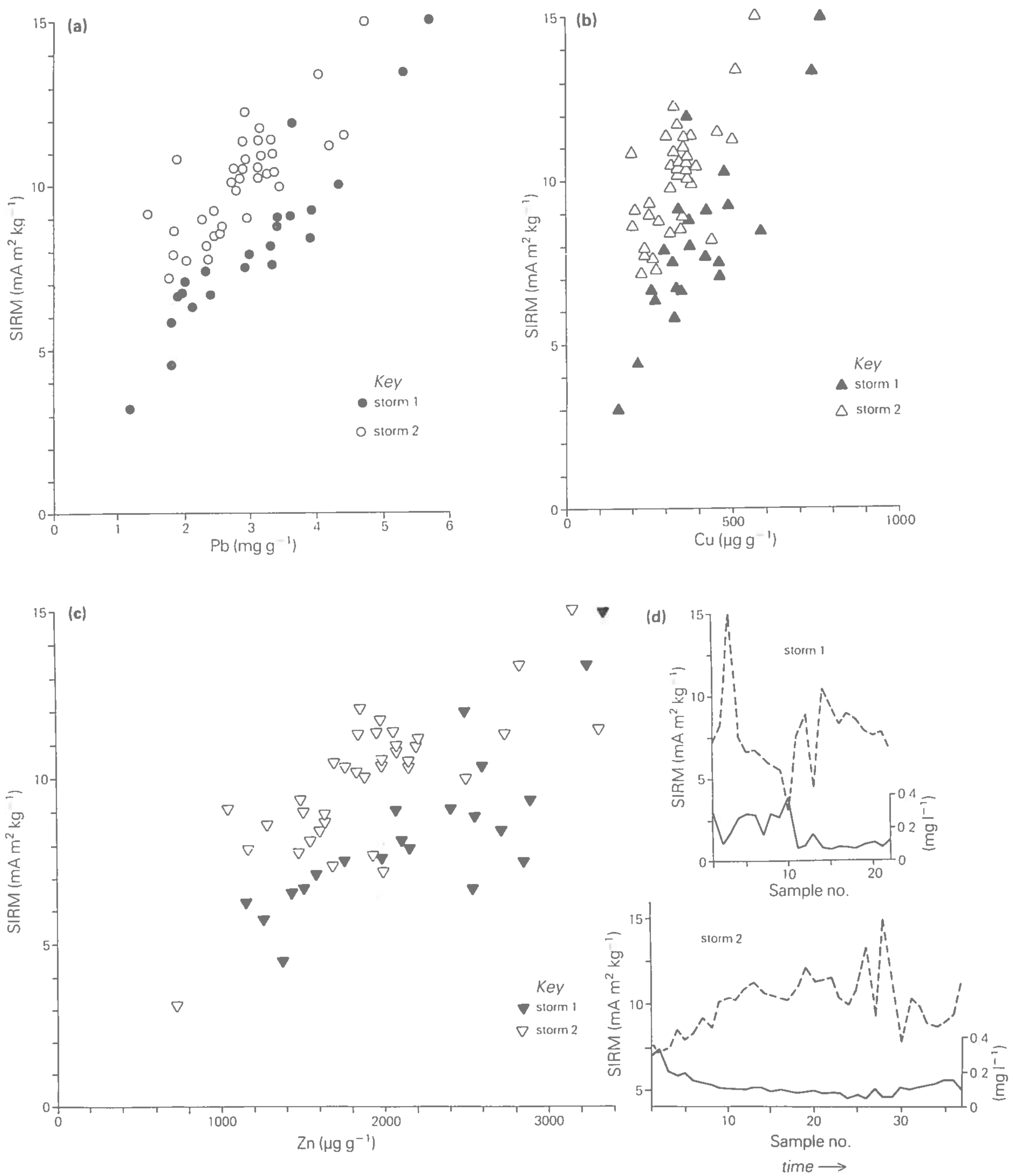


Figure 9.5 SIRM versus heavy metal concentration (a, b and c) and total suspended solids (d) for two high flow episodes in the Hendon stormwater catchment (see text).

tributions which mineral magnetic measurements may make to studies of fluvial systems. There is, in addition, scope for mineral magnetic studies of sediment transport in a much wider range of morphogenetic régimes, on a much larger spatial scale with a focus on lithological differentiation rather than on topsoil/parent material contrasts, and on a much longer temporal scale where within valley sediment storage is a significant element in the long-term evolution of the geomorphic system. An important area of future methodological development will be the association of mineral magnetic study with complementary mineralogical radiometric and geochemical analysis. Mineral magnetic parameters that can be used to identify sediment sources may provide a basis for surrogate particulate pollution monitoring in rural as well as urban and industrial environments. The rôle of mineral magnetic measurements in integrated catchment studies is illustrated more fully in Chapter 16.