[16]

The Rhode River, Chesapeake Bay, an integrated catchment study

Let the downpour roil and toil!
  The worst it can do to me
  Is carry some garden soil
  A little nearer the sea.

Robert Frost
In time of cloudburst

16.1 Physical setting

The Rhode River is a tidal estuary on the western shore of Chesapeake Bay (Fig. 16.1) some 10 km south of Annapolis, Maryland. The surface waters of the estuary comprise some 485 ha and the total catchment is 3332 ha. The tidal range is low (<1 m) and the estuary is shallow with no strongly developed deep channels and a maximum water depth of about 4 m at its mouth. The open water is bordered for the most part by gentle wooded slopes though there are extensive salt marshes along the southern shoreline and, more locally, actively eroding cliff sections exposed to wave action at the present day. In particular, the islands in the middle of the 'River' are scarred by conspicuous cliffs. Relief overall is low with no part of the catchment above 180 m. The underlying bedrock comprises a variety of sedimentary types. Very restricted exposure of Marlboro Clay are overlaid by the sandy, glauconitic, Eocene, Nanjemoy formation, the sandy and diatomaceous sediments of the Miocene Calvert formation and the alluvium of the Talbot formation. The Nanjemoy and Talbot formations are the only important lithologies in the lower parts of the catchment and around the water's edge. Of the actively eroding cliffs, only one is in the Talbot alluvium, the rest are in Nanjemoy sands. Most of the higher ground in the catchment is developed on Calvert sediments or the locally overlying Sunderland terrace deposits. The well drained parts of the catchment are deeply weathered and soils are mostly eluviated sandy loams. More locally, gleyed soils occur in streamside locations, and the main drainage system is flanked in its lower reaches by an extensive swamp.

The climate is humid through most of the year with a mean annual average precipitation of 1120 mm (Brush *et al.* 1980). There is a tendency to sudden heavy rain storms in spring and summer as well as occasional severe hurricanes. No significant transport of material coarser than 3 mm occurs in the catchment, most of which lacks particles larger than this. Only very locally are stream channels incised and active channel erosion is very limited. Character-

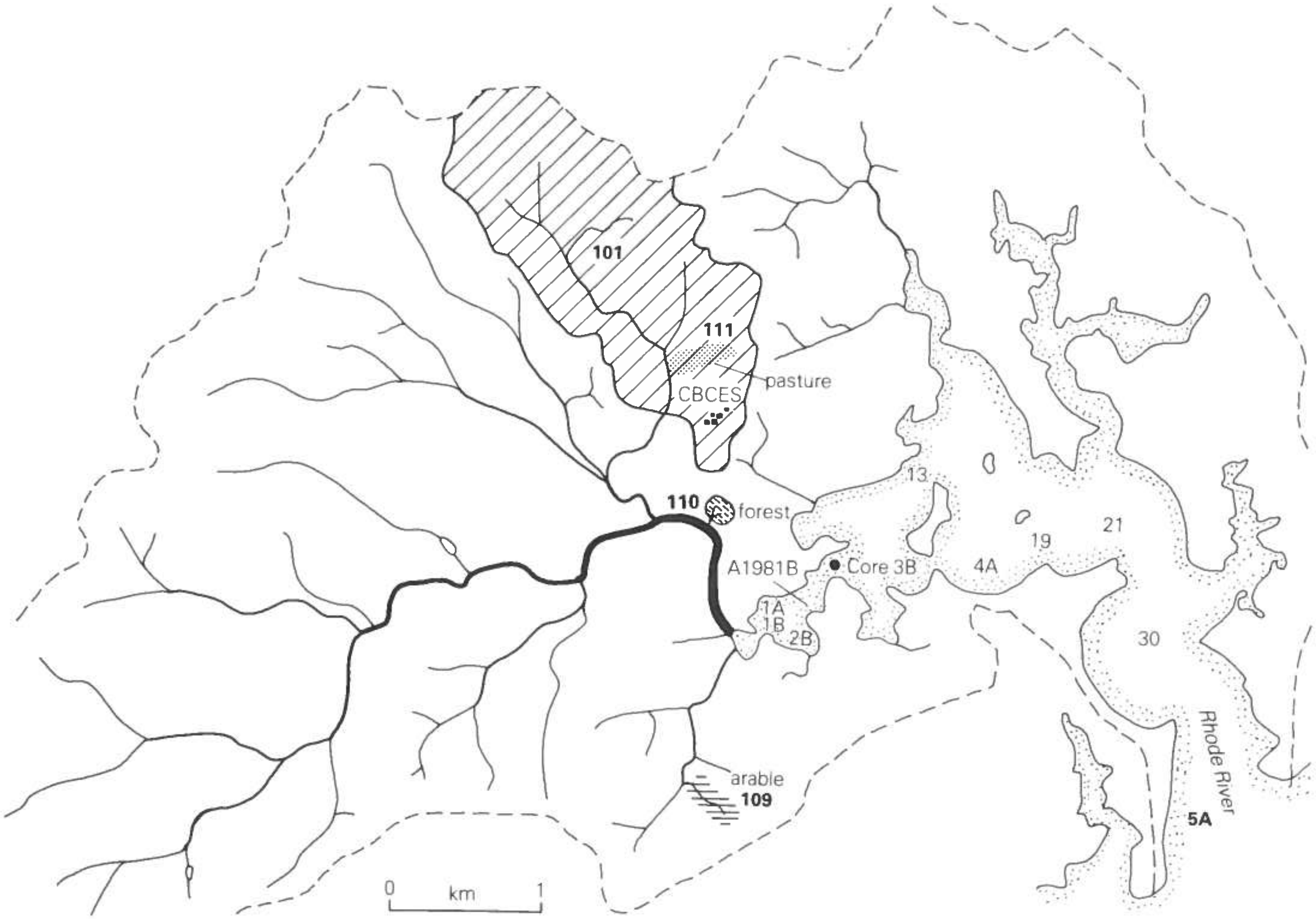

Figure 16.1 Map of the Rhode River catchment. Subcatchments 101 (large, mixed land use), 109 (arable) 110 (forest) and 111 (pasture) are located, as are the main coring sites in the estuary. Two of the islands shown are the sites of the magnetic reference profiles on eroding cliff sections (Fig. 16.4).

istically, at low flow, streams dwindle to a narrow thread of water within a residual sandy-bedded channel between banks of graded and subhorizontally bedded sands, silts and clays laid down during the receding levels of preceding floods. It is apparent from the channel morphology that large volumes of fine sediment are both stored and moved within the system.

As part of the Rhode River ecosystem monitoring programme operated by the Smithsonian Institution, several stream gauging stations are maintained, four of which are located on Figure 16.1. Three of these are at the outfall of small predominantly single land-use catchments – number 109 (cultivated crops – corn and tobacco), 110 (mixed hardwood forest) and 111 (pasture); the fourth 101, is a large mixed land-use catchment which includes 111. Further details of geology and land use and of the hydrological/sedimentological monitoring programme are given in Correll (1977). The main overall aim of the monitoring programme is to assess the contribution of non-point pollution sources to the waters of the Bay by making a detailed study of the relationship between land use and water and sediment quality in a small rural watershed.

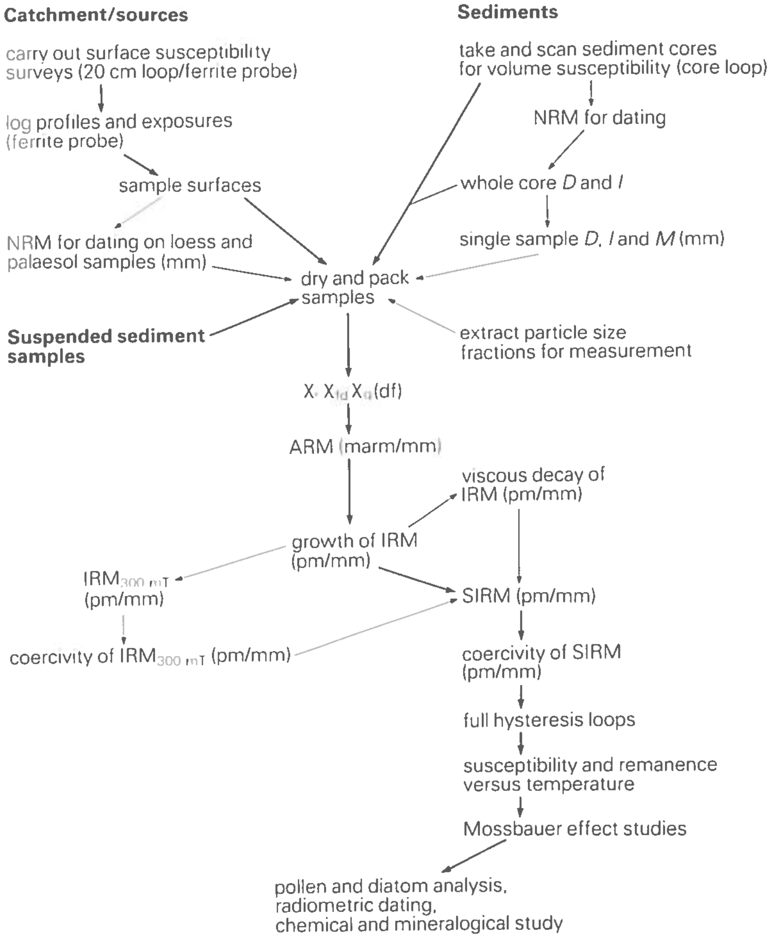

Figure 16.2 A flow diagram of measurements used to characterise the magnetic mineralogy of the Rhode River sediments and sources, to measure the record of palaeomagnetic secular variations in the sediments and to identify samples for subsequent more detailed study. pm = pulse magnetiser; mm = magnetometer; em = electromagnet; D.F. = dual frequency magnetic susceptibility sensor.

16.2 Sediment sources

At the outset there are three potential major sediment sources for the estuary:

(a) The conspicuous eroding cliffs provide large volumes of predominantly Nanjemoy bedrock and associated deeply weathered subsoil at least close to the cliffs themselves. This is the local expression of a much more widespread coastal erosion problem round Chesapeake Bay (Slaughter *et al.* 1976).

(b) The terrestrial surfaces of the catchment are extensively cultivated. Pierce and Dulong (1977) using data from the suspended sediment sampling programme for the mixed land-use catchment 101, calculate a loss of 511 kg ha^{-1} a^{-1} for 1975. This implies that erosion rates for the catchment may range from 5 to 16 cm/1000 years depending on the extent to which the total output is ascribed to the cultivated parts of the catchment.

(c) It is quite possible that there is a significant flux of sediment into the Rhode River from the open bay. Donoghue (1981) proposes that this may contribute as much as 17% of the current sediment budget. Clearly all these sources and others less significant at present, will have

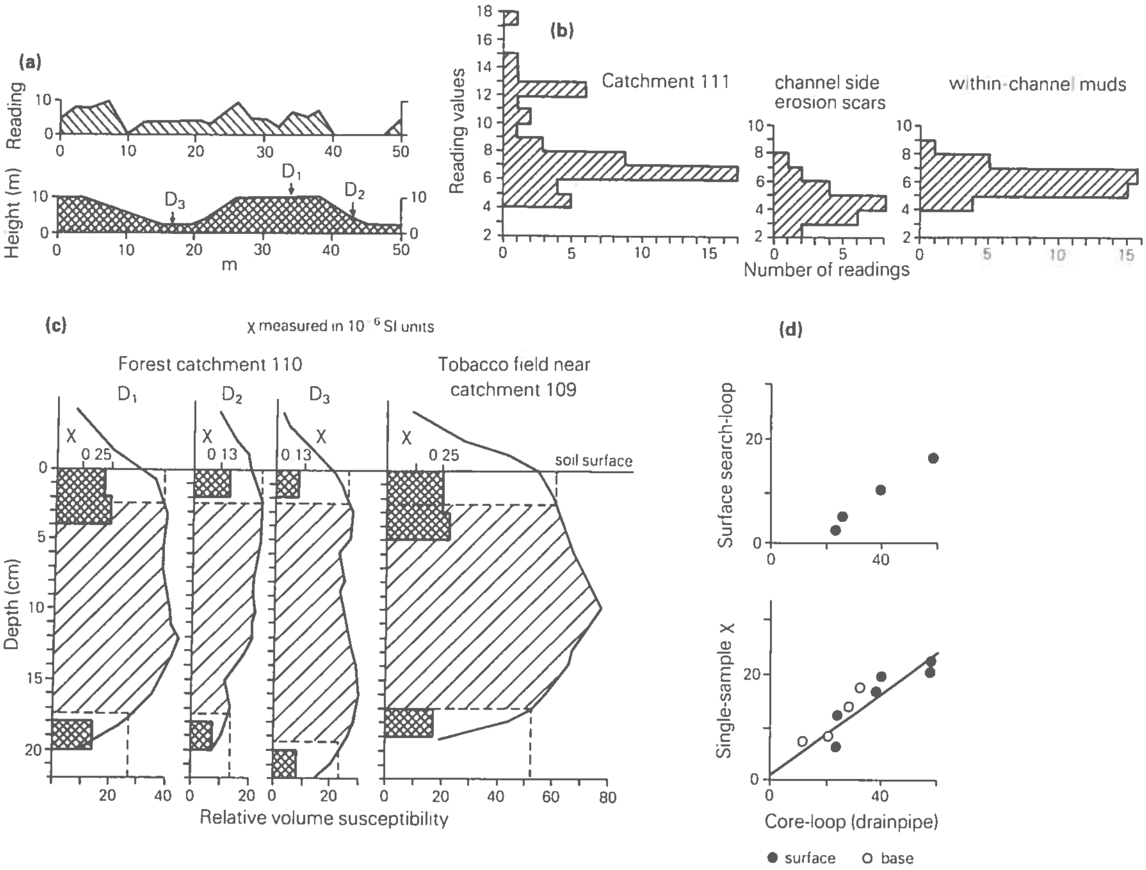

Figure 16.3 Magnetic survey and initial characterisation of the Rhode River catchment: (a) surface 20 cm search-loop readings in relation to topography in the forest catchment (110); (b) frequency plots of surface 20 cm search-loop readings for the pasture catchment (111) (note the bimodal distribution resulting from high values on Calvert soils in the upper part of the catchment), stream channels side minor erosion features (note the low values) and within-channel sediments; (c) drainpipe cores of surface soils providing core-loop scans of volume susceptibility,and single samples from top and base for individual measurements; (d) plots of the drainpipe core-loop readings at the ends of the scans (see c) versus surface search-loop readings and single-sample measurements.

responded to both physiographic and anthropogenic changes over the past few centuries. Notable among these are the isostatic sea-level rise estimated by Donoghue at over 2.7 mm per year for the last millenium, the land-use changes that have occurred subsequent to the first colonial settlements in the area some 300 years ago, and the recent dramatic increase in powerboating and associated developments along the shores of the 'river'.

16.3 Study aims

The Rhode River magnetic study was started in 1980 with a number of methodological and substantive aims. In terms of methodology, the application of the newly developed environmental magnetic techniques to an estuarine context was a significant extension from previous experience based on lacustrine systems which are for the most part more 'closed', subject to lower energy levels and sedimentologically less complex. Moreover, unlike the previous study localities used in developing and evaluating mineral magnetic techniques, the Rhode River area was chosen with no prior knowledge of its lithology and hence in ignorance of its primary magnetic mineralogy. Within this new environment two further methodological challenges were identified as especially important. The first of these was to develop and evaluate a comprehensive magnetic approach to catchment studies through every stage from field survey to detailed source and sediment characterisation. The second was to overcome the possibility of coincidental or invalid sediment source identification, by attempting a detailed magnetic characterisation of

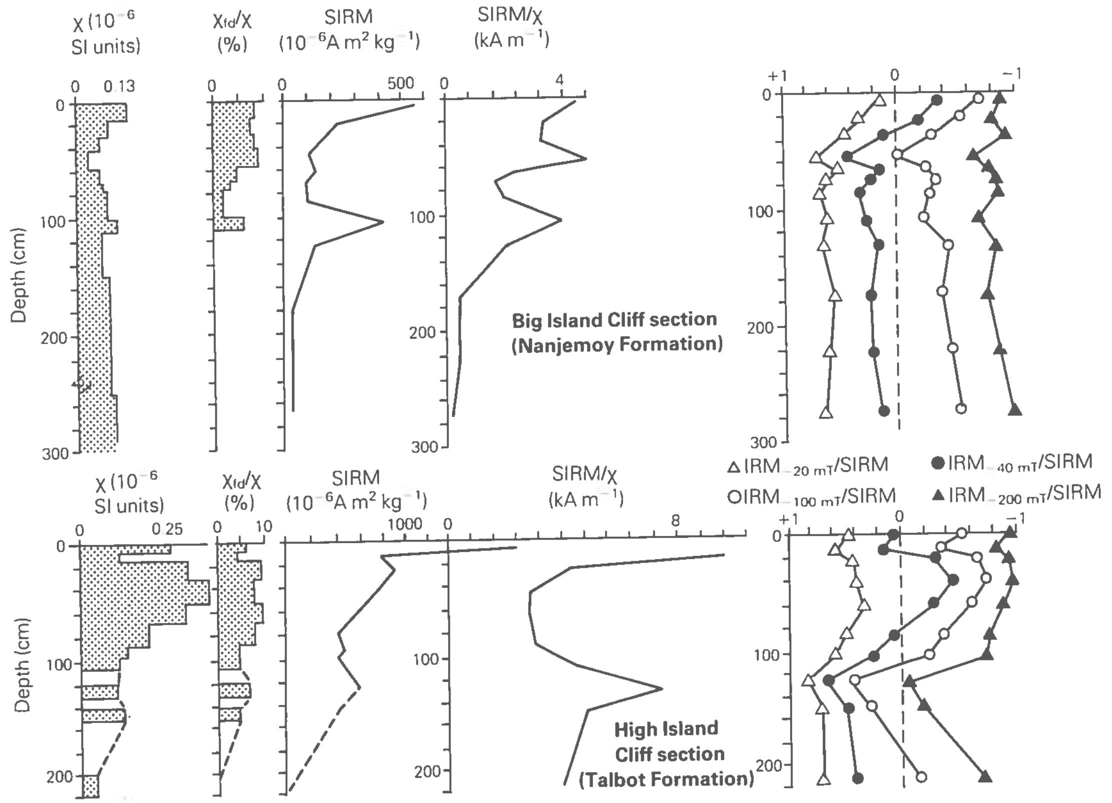

Figure 16.4 Mineral magnetic characterisation of the reference profiles from eroding cliff sections on Big Island and High Island (Fig. 16.1). The two parameters which most consistently identify the upper part of the profiles are χ_{fd}/χ (%) and SIRM. In both profiles there are lower peaks of χ_{fd}/χ and SIRM as well as higher ('harder') IRM/SIRM in the strongly illuviated zone. Note also the very low SIRM values in the basal samples. In the Nanjemoy section which is representative of most of those in the estuary, this SIRM minimum is associated with a steep viscous loss of SIRM and very low SIRM/χ ratios.

material in all phases of the system, using, in so far as possible, mutually independent magnetic parameters measured on a particle size related basis (Olfdield *et al.* 1985c).

The substantive aims were:

(a) to reconstruct spatial and temporal variations in sedimentation since pre-colonial times in terms of rates and sources;
(b) to characterise magnetically particulate flux within the system at the present day;
(c) to establish the implications of (a) and (b) in terms of erosion rates and of their relation to land-use changes and other human activities.

16.4 Methods

As a result of experience gained in the first two field seasons (1980 and 1981) and of improved instrument design taking place *pari passu*, the methodology outlined in Figure 16.2 was gradually developed and applied. It can now be advanced as a general scheme for subsequent catchment-based magnetic studies. The initial survey stage in the catchment involved extensive surface measurements using both the 20 cm 'search loop' and the ferrite probe attachments of the portable Bartington susceptibility equipment. Figure 16.3 shows plots of some of these results. Soil 'drainpipe scans' and single-sample measurements at selected sites followed, and from the extensive field survey stage involving many hundreds of readings, representative sites were chosen for more detailed study.

At the beginning of the project, estuarine cores from 1 to 2.5 m in length were already available for study (Donoghue 1981) and others were taken subsequently. Samples from several cores had already been used for ^{14}C, ^{210}Pb and ^{137}Cs assay. All cores were scanned for volume susceptibility variations using successive versions of the Bartington whole core measuring equipment. Examples of whole core traces are shown in Oldfield (1983a). Subsequently cores were subsampled for single-sample measurement.

Pilot sediment samples from cores taken in 1981 confirmed that at least for parts of the record, the NRM signal was strong, stable, repeatable and compatible with recent geomagnetic inclination values. Subsequent NRM measurements were carried out on subsamples from two cores at the mouth of the estuary using the methods outlined in Chapter 14.

During the course of the study, samples were taken for mineral magnetic characterisation from deep reference soil profiles in Nanjemoy, Calvert and Talbot formation exposures; a variety of field surface flow features in the aftermath of heavy storms; stream channels and the banks of fine contemporary alluvial sediment on either side; areas of water ponding behind the weirs built at each gauging station; the suspended sediment samples taken at each gauging station during flood events as part of the routine monitoring programme; the suspended sediments of the open estuary; and surface sediments within the Rhode River and beyond its mouth. Particle size measurements were carried out on a variety of soil and sediment samples within the system. Standard magnetic characterisation for virtually all samples comprised measurement of χ, χ_{fd}, SIRM, $IRM_{-20\,mT}$/SIRM, $IRM_{-40\,mT}$/SIRM, $IRM_{-100\,mt}$/SIRM and $IRM_{-300\,mT}$/

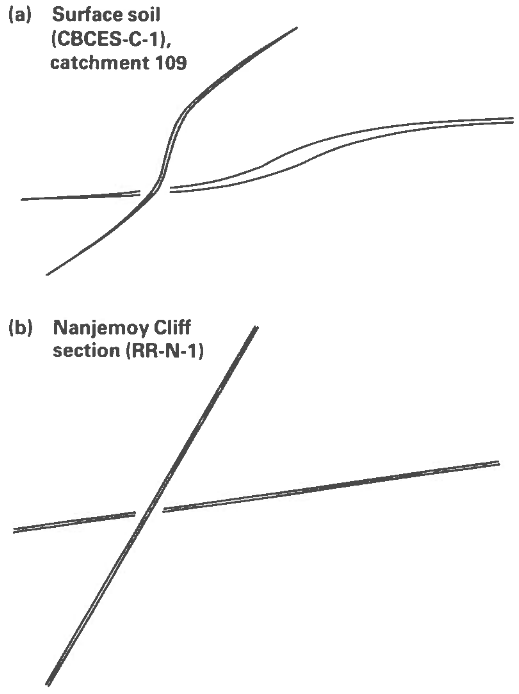

Figure 16.5 Hysteresis loop plots for a representative surface soil and an unweathered Nanjemoy cliff section sample. Full plots up to ±00 T are superimposed on expanded plots of the central part of each loop. The basal Nanjemoy sample is almost exclusively paramagnetic. The surface soil has both a paramagnetic and a ferrimagnetic component identifiable in the plot.

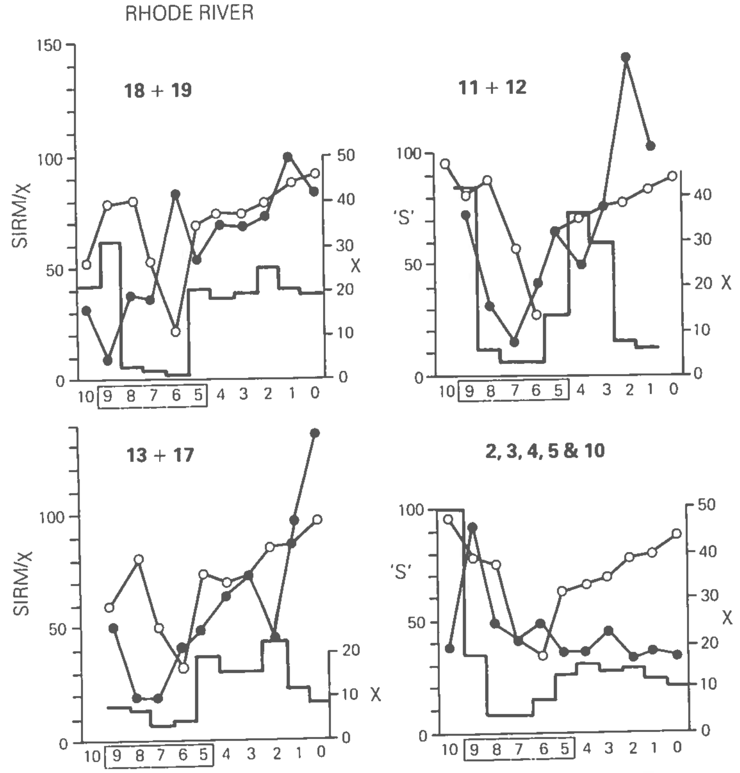

Figure 16.6 χ, SIRM, SIRM/χ and IRM$_{-100mT}$/SIRM measured on particle size fractions for a range of catchment samples. The 'surface samples' are taken from residual 'sediments' retained on the arable catchment (109) after heavy rainfall. Each graph plots the mean values of between 2 and 4 samples. Each sample was divided into size fractions down to 4 phi by dry sieving then further subdivided by the pipette method. Thus each of the phi sizes 5 to 9 include the finer sizes as well. IRM$_{-100mT}$/SIRM values show a similar trend in all samples with a peak of 'hardness' in the fine sands. SIRM/χ increases towards the fines except in the case of the channel muds (see text).

SIRM. Full coercivity of SIRM profiles were produced for 24 samples using 12 to 14 reverse fields. For selected samples, ARM was measured, hysteresis loops were plotted and Mössbauer spectra determined at 300 K, 77 K and 4.2 K. Pollen diagrams were constructed for Cores 3B and 1982A.

16.5 The magnetic mineralogy of the Rhode River catchment

In attempting to characterise the magnetic mineralogy of the potential sources in the catchment, particular attention has been paid to Nanjemoy bedrock exposures, to reference soil profiles (Fig. 16.4) in both Nanjemoy and Talbot formations and to the surface soils developed on all the catchment lithologies. This reflects the need to characterise especially material derived from cliff recession and from surface soil erosion.

As a result of the range of measurements summarised above, the following four distinctive magnetic components can be identified in the system:

(a) A *primary ferrimagnetic component* present in the unweathered Nanjemoy sands below the conspicuous zones of ferrugination found at all well

Table 16.1 Range of mineral magnetic parameters for potential sediment sources from the Rhode River catchment.

Potential sources	χ (10^{-6} m^{3}kg^{-1})	χ_{fd}/χ (%)	SIRM (10^{-6} Am^{2}kg^{-1})	SIRM/χ (kAm^{-1})	$\frac{IRM_{-100\,mT}}{SIRM}$
surface soils	0.1–0.8	6–15	500–6000	3–8	−0.30 to −0.95
weathered/illuviated substrates	<0.1	0–3	<700		+0.50 to −0.40
unweathered substrates	0.08–0.2	0–1	<150	<0.8	−0.10 to −0.85

drained sites. Very low or zero χ_{fd} values (Fig. 16.4) coupled with low $(B_0)_{CR}$ and rapid viscous loss of isothermal suggest that this material is predominantly multidomain.

(b) A *secondary antiferromagnetic component* especially significant in iron-enriched illuviated subsoil horizons (Fig. 16.4 & 6). In extreme cases up to 95% of the SIRM remains unsaturated in a reverse field of 0.3 T and $(B_0)_{CR}$ exceeds 0.2 T. This component could be either haematite, goethite, or both.

(c) A *secondary ferrimagnetic component* present in all non-gleyed surface soils. This gives rise to near-surface peaks in χ, χ_{fd}/χ, SIRM and SIRM/χ (Fig. 16.4). All the mineral magnetic characteristics indicate a stable single-domain fine viscous and superparamagnetic assemblage, typical of surface enhancement whether by fire or 'fermentation'. Magnetite, maghaemite or both may be represented.

(d) A high *paramagnetic component* abundant in all but the eluviated A horizons of freely drained soils. Mössbauer spectra and hysteresis loop plots (Fig. 16.5) suggest that paramagnetic forms of iron are probably dominant in all phases of the system. In the Nanjemoy sections this gives rise to very low SIRM/χ values.

Components (a) and (d) dominate the magnetic characteristics of bulk samples in the extensive unweathered Nanjemoy cliff sections. At higher levels in the regolith components (b) and (d) dominate, although residual primary ferrimagnetic crystals are still present. In surface soils component (c) dominates the magnetic characteristics though, especially where soils are mixed by ploughing, all four components will be present. Measurements of particle size splits of these mixed soils shows that component (c) dominates in the finest clay fractions, component (b) and (d), the medium to fine sands, and component (a) the coarser sands (Fig. 16.6). Components (a), (b) and (c) may be regarded as conservative components on the time-scales of interest to us in the present account (cf. Ch.

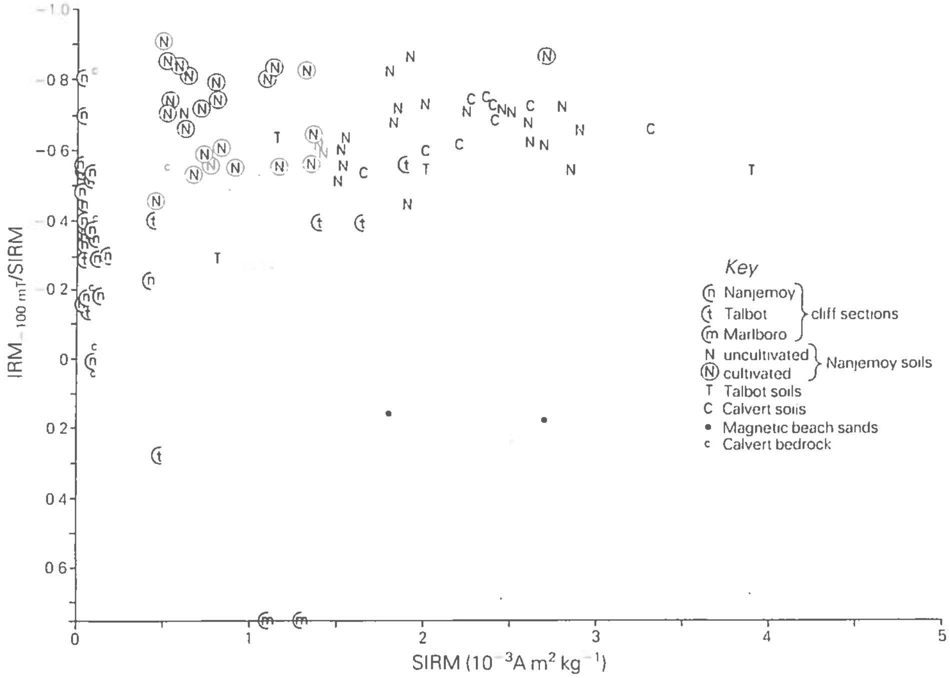

Figure 16.7 SIRM versus IRM$_{-100mT}$/SIRM for potential sediment source types within the Rhode River catchment. 90% of the cliff section and bedrock samples have SIRM values less than 500 × 10^{-6}Am^{2}kg^{-1}, though the IRM$_{-100mT}$/SIRM values range from −0.8 to +0.3 The values for the soil samples as a whole are much more varied in terms of SIRM (~500 to 4000 × 10^{-6}Am^{2}kg^{-1}) but the IRM$_{-100mT}$/SIRM range is narrower (−0.3 to −0.9). Note the contrast in SIRM between cultivated and uncultivated Nanjemoy soil samples.

8). The paramagnetic component includes readily soluble iron which is likely to change phase during erosion, transport and subsequent deposition. The change in SIRM/χ versus particle size between soils and channel sediments (Fig. 16.6) confirms visual impressions that during removal from the field surfaces and temporary deposition in the channel zone the soluble iron is dissociated from the sand fraction to become associated with finer clay and silt-sized particles. For this reason SIRM/χ has not been used here as a key parameter in source characterisation. Table 16.1 summarises the magnetic characterisation of the potential sediment sources within the Rhode River catchment and identifies those used in subsequent comparisons.

Figure 16.7 plots SIRM versus IRM$_{-100\,\mathrm{mT}}$/SIRM for all the catchment samples measured. Plotting these parameters confirms that there is very little overlap between the values for surface soils and those for the range of underlying parent materials. On a particle size basis (Fig. 16.8a) the sand and clay components of cultivated soils can also be clearly

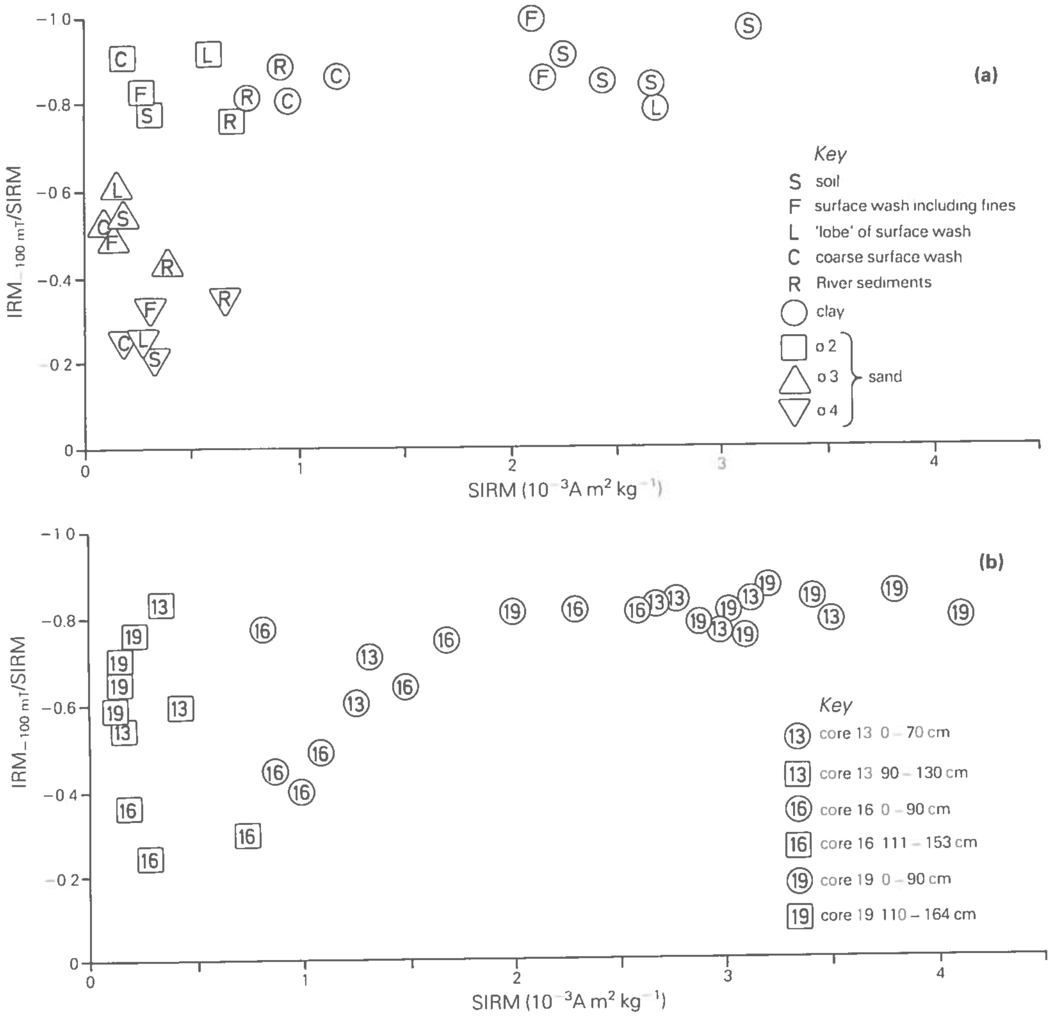

Figure 16.8 SIRM versus IRM$_{-100\,\mathrm{mT}}$/SIRM for (a) sand and clay fractions from catchment surface samples and (b) for clay fractions from estuarine sediments. The catchment surface clay fractions and the clay fractions from the upper parts of each core are comparable with bulk surface soils (Fig. 16.7). The clays from the lower part of each core have low SIRMs and are more comparable with surface *sands* and with bulk parent material samples (see text).

differentiated, the former overlapping with the parent material envelope, the latter corresponding more closely with the surface soils.

16.6 Suspended sediment samples

Figure 16.9a summarises the range of mineral magnetic values obtained from the 88 suspended sediment samples measured to date. All three estuarine samples and all but one of the 85 catchment samples have the high SIRM and low $\mathrm{IRM}_{-100\,\mathrm{mT}}$/SIRM values characteristic of surface soils. The extremely high SIRM of the estuarine sample from farthest down 'river' suggests some selective transport of relatively more ferrimagnetic fines into the open estuary. As would be expected from previously published data (Pierce & Dulong 1977), the bulk of the suspended stream sediments abstracted from the gauging stations fall within the envelope of values for *cultivated* rather than uncultivated soils in Figure 16.7.

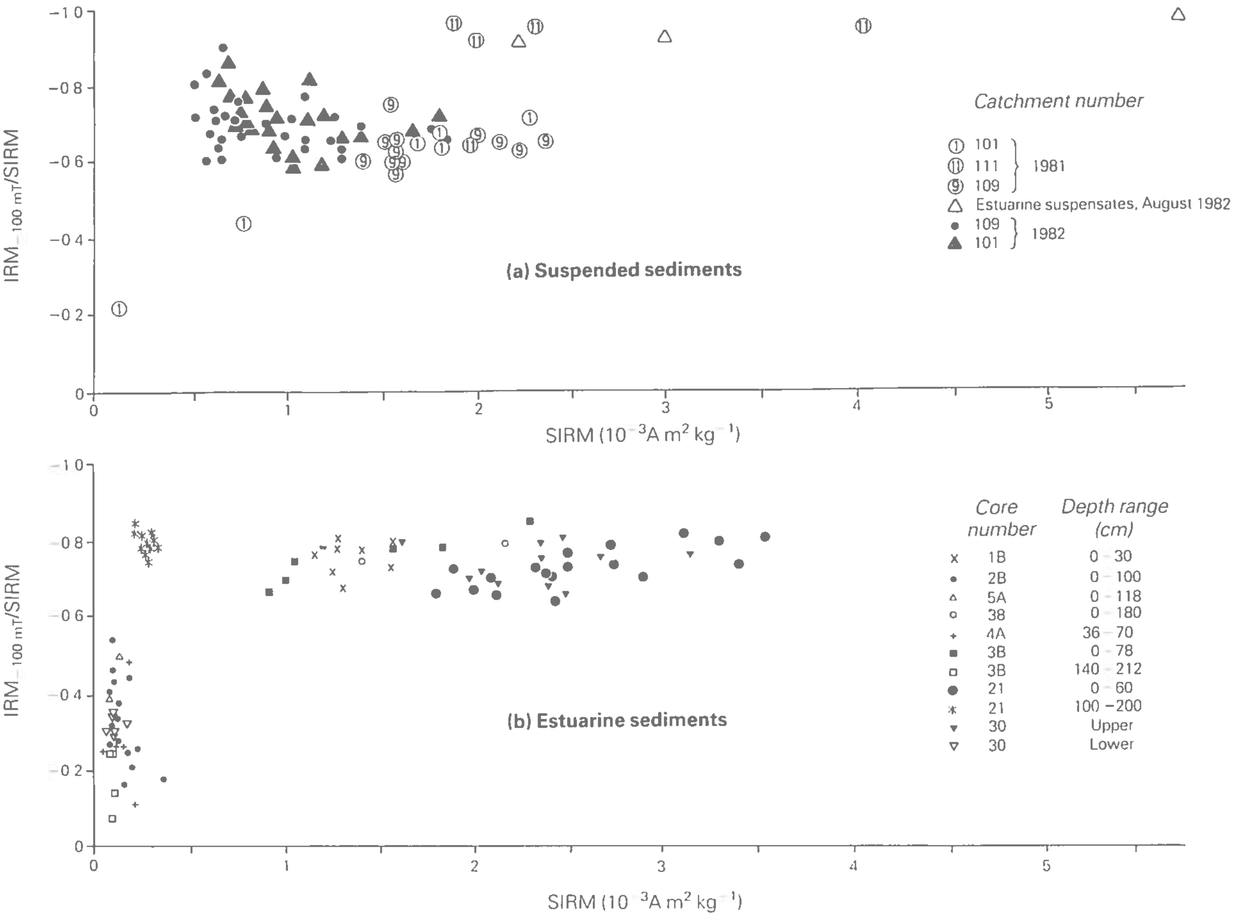

Figure 16.9 SIRM versus $\mathrm{IRM}_{-100\mathrm{mT}}$/SIRM for bulk suspended sediments and estuarine sediment. (a) The suspended sediments were taken during spring and early-summer floods by means of an automatic integrated water sampler installed by the weir at the outfall of each catchment. (b) The estuarine sediment samples all come from cores obtained by J. Donoghue. In the case of marginal cores (2B, 4A and 5A) the samples are not separately identified by depth range. The samples from the 'central' cores are grouped into upper and lower sets separated by the horizon of increasing χ and SIRM values (see text and Fig. 16.11).

16.7 Estuarine sediment cores: mineral magnetic characteristics

The sediment cores subsampled and measured so far fall into two types (Fig. 16.9b). Those close to eroding shoreline sites (e.g. 4A and 5A) are dominated by magnetic mineral assemblages comparable to those of the nearby eroding cliff sections (cf. Fig. 16.7) with low SIRM, SIRM/χ and variable IRM$_{-100\,\mathrm{mT}}$/SIRM. At these sites, save for occasional horizons of higher SIRM there seems to have been little variation in sediment source for the past few centuries at least, and sedimentation appears to have been largely dominated by the coastal exposures. Sediments in these cores tend to be relatively coarse.

Sediment cores from the central parts of the estuary, whether close to the head of any of the tributary creeks or in the open waters of the middle and lower reaches show a different mineral magnetic pattern. Although whole core scans do not correlate in detail over more than a few metres, the vast majority of cores record an increase in volume susceptibility in the upper levels (Oldfield 1983a). Single-sample measurements make it possible to subdivide the central cores into an upper part characterised by high SIRM, SIRM/χ and χ_{fd} and a lower part characterised by low SIRM, SIRM/χ and χ_{fd}. Samples from the upper part of each core have bulk magnetic parameters which correspond with those of the surface soils of the catchment and with the contemporary suspended sediments. Lower samples correspond much more closely with material derived from much deeper in the regolith. Every 'central' core from the head of the estuary to its mouth records this shift (Fig. 16.9b) and in each case it is a dramatic and irreversible feature.

On a particle size specific basis (Figs 16.8b & 16.10) we see that above the shift clays dominate the bulk magnetic characteristics and have a range of values directly comparable both with surface soil and with the clay fraction therein. The small sand fractions above the shift may be comparable to either weathered or unweathered parent material as is the case in the sand fraction of contemporary soils. The magnetic mineralogy confirms a surface soil source for most of this material. Below the shift, both the sands and clays have low SIRM values suggesting that the latter are derived from comminution of 'primary' parent material rather than from magnetically enhanced surface soil.

In summary all the evidence obtained so far is interpretable in terms of within-catchment shifts of magnetic mineral assemblages and hence, of sediment sources. The central cores record a major shift in sediment source from bedrock and subsoil-derived material to surface soil-derived material. However, the characteristics of material derived from the open bay remain unresolved at present, as does the possibility that external sources are significant in the lower reaches of the 'river'. These topics form the main focus of continuing study.

16.8 Chronology and links with land-use change

Depending on the model of ^{210}Pb dating used (Oldfield & Appleby 1984) the date at which the shift in

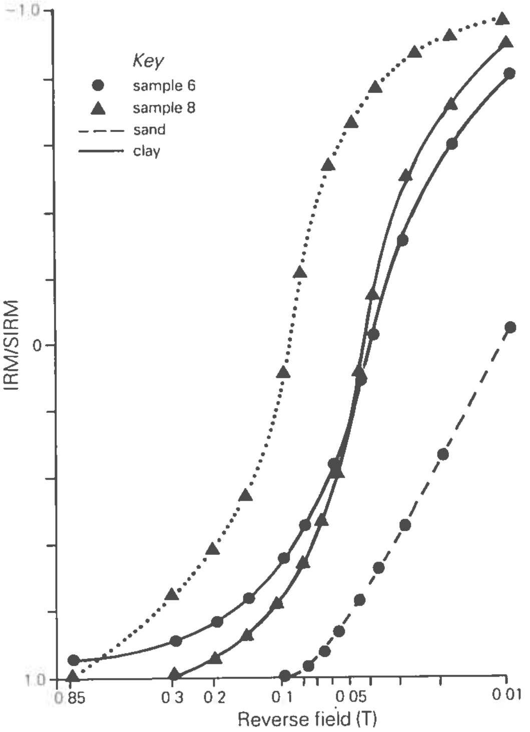

Figure 16.10 Coercivity curves for sand and clay size fractions from two sediment samples. Core 21 is located on Figure 16.1. The samples plotted here lie above 60 cm (see Fig. 16.9b). Values for the clay size samples compare with those for the soil clay fractions and the bulk surface soil samples. The sand size samples can have either very low or relatively high coercivities. They may thus be comparable with sands from either the weathered and illuviated or the unweathered sands from eroding cliff sections.

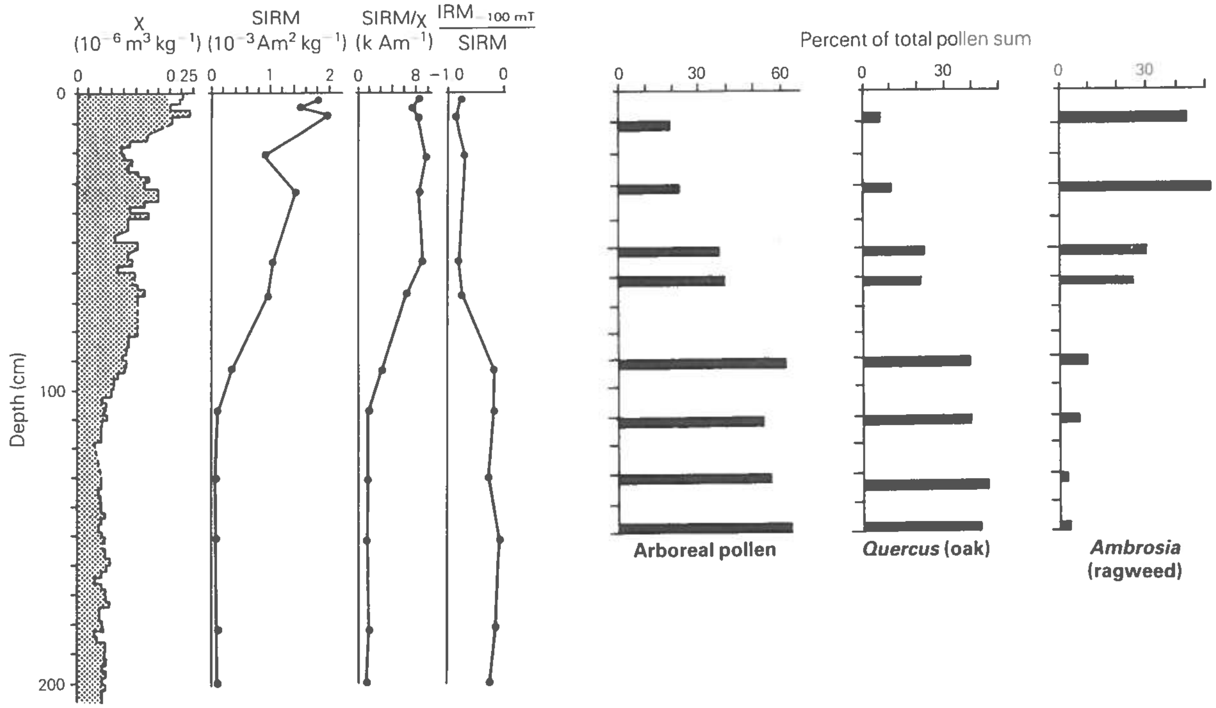

Figure 16.11 Rhode River estuarine core 3B (see Fig. 16.1). The horizon at which χ, SIRM, SIRM/χ and IRM$_{-100\mathrm{mT}}$/SIRM all change from values typical of eroding parent material to those characteristic of soils corresponds with a major change in pollen assemblage summarised here in the total arboreal pollen, *Ambrosia* and *Quercus* values (cf. Brush *et al.* 1982).

sedimentation takes place ranges from *c.*1840 to 1880 AD in cores 3B and 30. Associated pollen analysis in cores 3B and 1982B links the sedimentation shift to a dramatic change in the *Quercus* (oak) to *Ambrosia* (ragweed) ratio, a development indicative of more extensive forest clearance and cultivation (Fig. 16.11). This pollen assemblage change is dated by Brush *et al.* (1982) to *c.*1780 along the north shores of the bay and to the first half of the 19th century further south. The pollen-analytical change is interpreted as a reflection of land-use intensification and a greater concentration on corn as against tobacco cultivation. Additional chronological insights are provided by the NRM record in Cores 1982A and B from the mouth of the estuary. In both cores, the directional measurements vary widely from sample to sample above 30 cm. Below this, the intensity of NRM and the repeatability of the directional measurements are closely correlated with SIRM and hence the changes in magnetic mineralogy associated with the shift in sedimentation found in these cores around 150 cm. Above the shift, NRM intensities are relatively high and directional measurements are repeatable, below it, intensities are too close to instrumental noise level for the directional measurements to be reliable. Within the zone of repeatable measurements the main distinctive feature replicated in both cores is the increase in inclination around 100–120 cm (cf. Figs 5.5, 14.2 and 14.3 and Table 14.1). This would indicate a date of *c.*1850 AD for the 120 cm level, some 30 cm above the beginning of the main rise in χ and SIRM.

Thus from all the lines of evidence available so far it would appear that the shift in magnetic mineralogy from parent material to surface soil characteristics took place some time around 1800 AD. Since then, soil sources have dominated sedimentation through to the present day.

16.9 Summary and implications

As a result of the work completed so far, it is possible to attempt a brief appraisal of the value and limitations of the magnetic approach to the Rhode

River catchment study in the light of the methodological and substantive aims declared at the outset.

The procedures outlined in Figure 16.2 have provided a basis for within-catchment source characterisation right through from the initial extensive survey stage to the point of detailed diagnostic measurements using SIRM, $\mathrm{IRM}_{-100\,\mathrm{mT}}/\mathrm{SIRM}$ and χ_{fd} for differentiation. With the advent of the portable pulse magnetiser (6.6.2), not available until the last stage of the work, it would now be possible to complete all these stages on site with remarkable speed and economy. Sediment characterisation can be quickly completed in the same way beginning with whole core scans, each done in a matter of minutes, and continuing through to single-sample measurements, again easily carried out on site. The magnetic methods are suitable for measuring material in all phases of the system, though input from the open bay still remains to be characterised. Source–sediment linkages have emerged and can be confirmed not only by largely independent measurements on bulk samples (e.g. SIRM and χ_{fd}) but also by measurements on particle size fractions. Moreover the record of palaeomagnetic secular variation in the recent sediments provides an additional source of evidence for sedimentation rates. At the end of this full range of magnetic measurements the samples remain available for palaeoecological study, radiometric dating or mineralogical analysis.

The substantive results point to a pattern of sediment flux within the system over the past 100–150 years dominated by the export of soil-derived particulates from the land surfaces of the catchment. Results from the Potomac Estuary (Oldfield & Maher 1984) confirm that this pattern also prevails in most of the cores taken between Washington DC and the mouth of the estuary. The high ARM, SIRM and χ_{fd}/χ values associated with this material in both the Rhode River and the Potomac are found in the clay-sized particles, and the magnetic parameters here can be confidently regarded as indicators of the loss of fines from the cultivated soils. In the Rhode River, the contemporary suspended sediment record confirms that this process is continuing and the magnetic traces from many of the cores suggest that the material now coming in is itself rather more depleted in the finest fractions than was the sediment deposited during the early stages after the shift to soil sources. The evidence points to selective loss of fines over a long period leading to their progressive depletion and eventual relative paucity in contemporary soils. This process has serious implications for soil moisture retention, resistance to future erosion and the maintenance of both soil structure and fertility. The mineral magnetic approach can thus highlight not only quantitative but also important qualitative aspects of erosion for both the present day and the past.

[17]

Prospects

> **The history of science, like the history of all human ideas, is a history of irresponsible dreams, of obstinacy and of error. But science is one of the very few human activities – perhaps the only one – in which errors are systematically criticized and fairly often, in time, corrected.**
>
> Karl R. Popper
> *Conjectures and refutations*

Clearly most of the chapters from 7 onwards are concerned with relatively new applications of magnetic measurements to environmental systems, and in virtually every case, there is considerable scope for further development. Future prospects range from the further extension and refinement of established approaches (for example secular variation studies of lake sediments), through the transfer of newly developed techniques to different types of environment (for example magnetic tagging and tracing of beach sands), to the possibility of identifying a range of entirely new opportunities in fields such as medical and forensic science. This final chapter is concerned with summarising some of these prospects as they appear at the present time.

17.1 Palaeomagnetism of recent sediments

Chapters 13 and 14 deal with palaeomagnetic aspects of investigations of recent sediments and rocks. As the laboratory instrumentation and magnetic techniques used in these palaeomagnetic studies were largely developed in the 1950s and refined in the 1960s, progress in secular variation magnetostratigraphy is perhaps now more likely to arise from improved dating techniques, or through the development of a practical sediment palaeointensity method, than through further advances in instrumentation dealing with palaeomagnetic directions.

A palaeointensity method which can yield full vector information for recent sediments is sorely needed. Geomagnetic interpretations of palaeomagnetic directional data are seriously hampered by lack of intensity control. Present attempts at extracting palaeointensities from recent sediments have not yet been demonstrated to be capable of yielding repeatable between-lake intensity *and* direction logs. Palaeointensity investigations which provide only intensity data without accompanying directional data, or which yield only information on selected sections of sediment core are likely to be viewed with suspicion.

Substantial efforts have been invested in tens of thousands of NRM and partial demagnetisation measurements and in extensive geomagnetic modelling computations in palaeomagnetic investigations of Holocene lake sediments, while little attention has been directed by palaeomagnetists to the topic of dating. This seems a surprising situation considering all the possible sources of error associated with lake sediment chronologies. There are two immediate prospects for improving the dating of the palaeolimnomagnetic logs.

First, there is the recent development of the accelerator method of the detection of radiocarbon which allows minute samples to be dated. Sections of core, 20 cm long, need no longer be the prime source of radiocarbon dates. Small fractions of sediment, such as seeds or chemical extracts, can now be analysed and so provide a practical possibility for the reduction of natural contamination errors.

Secondly, annually laminated lake sediments are being discovered in increasing abundance. These potentially accurate chronological successions are being unearthed largely on account of the development of the freezer corer technique (Swain 1973, Saarnisto 1975, Huttunen & Merilainen 1978). O'Sullivan (1983) comprehensively reviews the distribution and formation of laminated lake sediments. He describes four main types of annual laminations, namely biogenic, calcareous, ferrogenic and clastic. Of these four, calcareous laminations possibly hold the greatest prospect for palaeomagnetic studies. Calcareous laminations are not suppressed by allochthonous clastic input, so the laminated sediment can hold a stable (post-) depositional remanence (Thompson & Kelts 1974). Deep flat-bottomed lakes with semi-permanent stratification and with a scarcity of oxygen in the bottom waters (which discourages mixing and inhibits benthic activity) are prime candidates for annual laminations (O'Sullivan 1983). Calcareous laminations occur in lakes with high internal carbonate loading and are formed in the summer months, during the time of high water temperatures, by precipitated $CaCO_3$. O'Sullivan (1983) concludes that the present scarcity of annually laminated lake sediments is more apparent than real, and that a search for laminated sediments, not just in lakes of the North Temperate zone, but in many parts of the Earth should prove fruitful. It has been found that certain laminations are much more clearly seen in material collected by freezing and that some biogenic laminations only become apparent after long exposure to air (Renberg 1982). This suggests that it will probably be advantageous in palaeomagnetic studies to collect freezer cores for detailed lamination counts, especially those of the surface sediments, and to take parallel piston cores for magnetic work.

Palaeomagnetic dating and correlation has relied on pattern matching by eye and subjective assessment of goodness of fit. Clark (pers. comm.) has adapted Gordon's (1973) sequence slotting method to allow it to accept data on the unit sphere. This development will permit formal dating of palaeomagnetic secular variation direction records by matchings with previously established secular variation time series using sequence slotting algorithms. Clark's approach will also allow a formal statistical testing of the discordance between the palaeomagnetic record and the master time series. Current developments of sequence slotting programmes may permit matching of several sequences simultaneously. Applications of such advances would include across lake correlations in multi-core mineral magnetic studies and between site stacking of secular variation records.

17.2 The mineral magnetic approach

The present account barely serves to introduce the full range of possible applications in soil and weathering studies. Systematic application of the techniques on appropriate spatial scales is required to evaluate the potential rôle of mineral magnetic parameters in soil characterisation. Initial results suggest that they may be valuable on all spatial scales from local survey to world-wide classification. The value of mineral magnetic parameters derives both from the close links apparent between magnetic mineral assemblages and soil forming processes, and from the relative ease with which these assemblages can be characterised and distinguished even in very low concentrations well beyond the reach of other techniques. Further exploration of the relationship between magnetic minerals and soil forming processes, using both natural and synthetic materials, will establish a rôle for magnetic measurements in, for example, both descriptive and experimental studies of rates of weathering and soil formation, of processes such as gleying, lessivage and ferrugination, and of the rôle of organic matter in the soil environment. There is also considerable scope for exploiting more fully the sensitivity of magnetic minerals to the effects of fire in the soil as well as in peats where there is every prospect of being able to use them to reconstruct site-specific fire histories. Although some indication of the potential of mineral magnetism in archaeological studies has begun to emerge not only from the studies outlined in Section 8.10, but also from recent studies of obsidian (McDougall *et al.* 1983) and iron ore artifacts (Pires-Ferreira 1976), the potential in palaeosol studies is virtually unevaluated. Mineral magnetic aspects have also, for the most part, been neglected in published magnetic studies of loess deposits.

Within the broad area of particulate flux between terrestrial and fresh-water systems the scope for extending the mineral magnetic approach on a much wider range of temporal and spatial scales is very attractive. Most of the sediment-based studies reported so far are concerned with timescales ranging from 10^2 to 10^4 years and the scope for capitalising on the conservation of magnetic properties, in order to link these to contemporary process studies through integrated long-term lake-watershed ecosystem-based projects, has not been fully realised. Nor have magnetic measurements been applied to the reconstruction of environmental variables at the level of detailed temporal resolution made possible by laminated sediments (cf. Rummery 1983). At the other extreme, mineral magnetic studies of longer-term deposition sequences in low latitude lakes will offer new insights into climatic variation and its bearing on erosion and sedimentation. In fact there are few aspects of Quaternary studies that cannot benefit from mineral magnetic measurements, and where, as in lake or in rapidly accumulating marine sediments, there is often an opportunity to obtain geochronological information from the palaeomagnetic record at the same time, the present repertoire of techniques provides a valuable new methodology.

The approach to sediment source identification and to tagging and tracing experiments, though initially developed in small river basins on carefully selected lithologies, is capable of extension not only to larger and more complex contexts (cf. Oldfield & Maher 1984) but to new environments – for example in studies of coastal sediment movement, erosion, accretion and shoreline protection. Moreover, the link between magnetic measurements and erosive processes, which was one of the first areas of possible application to emerge, is now seen to be potentially of qualitative as well as quantitative value in view of the diagnostic nature of the parameters in terms of both source type and particle size.

Mineral magnetic characterisation has not hitherto been one of the recognised research tools in sedimentology or petrology, nor has it been used as a logging technique in hard-rock exploration. Given the range of studies now completed on contemporary and recent sediments and on soft rocks, the time is ripe to extend the techniques to older materials. Results reported from Pleistocene marine sediments point to the sensitivity of the magnetic mineral assemblages to diagenetic changes. Moreover, initial trials using rapid magnetic susceptibility probe and loop readings on core samples from a deep borehole in the Trias (Robinson, pers. comm.) confirm their probable geotechnical value.

Chapter 12 outlines the challenge of reconstructing the flux of magnetic minerals to the oceans and confirms its palaeoclimatic significance. Like so many aspects of environmental science, it calls on the researcher to unite insights from contemporary process monitoring and long-term sediment-based reconstruction, and it requires a comprehensive appraisal of the linkage between environmental systems, in this case atmospheric and oceanographic. The scale of study implied clearly requires both the continued international co-ordination and collaboration that has been characteristic of much research in this field in recent years, and wider recognition of the virtues of mineral magnetic characterisation in terms of its intrinsic value and compatibility with other lines of study.

One of the threads running through several of the later chapters is the apparent link between mineral magnetic properties and particulate pollution as a result of fossil-fuel combustion and other industrial processes such as smelting and the manufacture of iron and steel. Although the main emphasis so far has been on the use of magnetic measurements in monitoring heavy metal deposition this is not the only possible application. The association of long-distance sulphur dispersal with the particulate component of atmospheric aerosols to which the soluble phases become temporarily adsorbed may indicate a rôle for magnetic measurements in studies of acid rain sources and trajectories. Equally, the recent interest in the use of fly-ash as a source of magnetite (Chaddha & Seehra 1982) makes magnetic characterisation especially important since we may expect a quantifiable relationship between susceptibility or SIRM and crystalline iron concentration in any given fly-ash. At present, the studies completed fall somewhat uneasily between reinforcing the view that magnetic/heavy metal ratios are sometimes sufficiently constant to encourage the use of magnetic measurements as a surrogate monitoring technique, and suggesting that variations in these same ratios and in mineral magnetic parameters indicative of changes in magnetic assemblages will be of value in identifying aerosol and sediment sources. To a large extent these apparently contradictory indications must be a function of spatial scale and hence of proximity to distinctive sources.

This points the way to one urgent area of future study.

Just as the ease with which magnetic minerals can be characterised and identified makes them attractive as tracers in aquatic systems, it also makes them potentially valuable in atmospheric transport and deposition experiments. This is especially so in contexts where because of the complexities of surface roughness, neither mathematical models nor empirical observations have been completely successful. For example, experiments using magnetic powders can complement and extend into much finer particle size ranges, e.g. the type of study carried out by Chamberlain (1966) using radioactively tagged *Lycopodium* spores. In addition, some empirical appraisal of the relative effectiveness of trees as aerosol filters should be possible using magnetic measurements.

In the realm of historical reconstruction, the possible use of magnetic mineral assemblages in reconstructing atmospheric deposition has barely been extended beyond the beginning of the Industrial Revolution. On longer timescales using both ombrotrophic peat and ice core samples, one may expect to see evidence emerge of significance in the reconstruction of past atmospheric circulation patterns, local and global dust-veil variations and sediment supply to the world's oceans. All these will have direct or indirect palaeoclimatic implications.

Looking beyond the scope of the present themes, further applications in medical and forensic science are not difficult to envisage. Identification of inhaled particulate types and sources should be possible from lung tissue measurements as well as characterisation of work environments in terms of aerosol loadings and types.

In relation to all the above, one of the notable limitations of the mineral magnetic approach, as outlined in the foregoing chapters, is its failure to provide a basis for expressing results in quantitative terms with regard to mineral composition and domain size assemblages.

One quantitative approach currently being pursued is the development of a procedure which compares mineral magnetic measurements on natural samples with equivalent measurements on synthetic specimens. In this approach, measurements of susceptibility and of isothermal remanences and coercivities are matched with synthetic sample results so that the magnetic characteristics of natural materials can be described as being equivalent to the properties of various concentrations of synthetic minerals. One method of applying such a procedure is to determine the magnetic properties of particular combinations of synthetic minerals by consulting tables of results from a great range of synthetic minerals and well characterised mixtures. Such a task can be greatly simplified and undertaken in a relatively straightforward manner through a minimisation algorithm.

The procedure currently under development involves a simplex minimisation technique (Nelder & Mead 1965). In the procedure the magnetic properties of synthetic minerals are expressed as continuous functions. For example, isothermal properties are represented by smooth bicubic spline surfaces (Hayes & Halliday 1974) which relate back fields and remanences. By using this type of functional approach possible mathematical problems associated with local minima can be largely avoided and rapid searches of the mineral magnetic parameter space can be performed. The simplex minimisation procedure is arranged to hunt for a best fit to the mineral magnetic measurements by varying the concentrations and grain sizes of the constituent minerals and the concentration of a (super)paramagnetic component. While it is recognised that such a formalised approach cannot cover all possible natural magnetic mixtures, because the range of natural magnetic minerals and their properties is just so large and the range of magnetic mixtures is so vast and complex, it does appear that the simplex minimisation formulation is able to handle the majority of environmental samples that we have encountered.

Problems that arose during the development of the procedure have highlighted two particular areas in which further research is needed. First, many natural samples appear to contain intermediate coercivity minerals, with remanence coercivities of around 0.1 T, which are difficult to explain. Secondly, distinguishing between paramagnetic and superparamagnetic components has not proved to be simple and additional measurements appear desirable to aid the distinction. The uses of frequency-dependent or quadrature susceptibility, low temperature susceptibility variations and saturation magnetisation measurements are being investigated in connection with this second problem, while further high-field measurements on synthetic and well characterised imperfect antiferromagnets are being carried out in relation to the first problem.

A further development being pursued is a method of calculating the errors associated with concentration and grain-size determinations. Such estimates of the ranges of likely interpretations of mineral magnetic measurements appear to be very desirable. Divergences of opinion in the interpretation of mineral magnetic data between various research groups, particularly on the importance of superparamagnetic grains, can lead to very different environmental models being proposed. Such disparities should be clarified by a quantitative approach which is capable of handling magnetic mixtures and of assessing possible plausible ranges. An important test of the minimisation formulation will be to compare mineral magnetic estimates of iron oxide concentrations with chemical, X-ray and Mössbauer determinations.

Not only is progress urgently needed in the direction of quantifying mineral magnetic properties in terms of magnetic domain states and mineralogy, but, given the size of data sets readily obtainable by mineral magnetic measurements, the time is now ripe for a much more rigorous statistical approach. This will be increasingly important in the more 'open' atmospheric (cf. Hunt 1986) and marine systems where linkages are more extended and complex and much less direct than in the more materially bounded soil and watershed systems considered in most of the studies completed so far.

Measurement of both major and minor hysteresis loop characteristics coupled with initial and anhysteretic magnetisation properties, using a slow field cycling technique combining a bipolar supplied electromagnet and a new software controlled electronic integrator, has allowed Jiles and Atherton (1984) to test a simple theory of hysteresis based on mean field approximation. Trial experiments (Jiles pers. comm.) on a weakly magnetic granite cylinder and red sandstone sample suggest that the equipment, with some small modifications, could be used to analyse the great majority of 'environmental' samples. More complete characterisation of magnetic properties using such equipment would yield many advantages, over current methods, especially in the quantification of the mineral magnets approach.

Perhaps a final and more general qualification of the mineral magnetic studies summarised in the foregoing chapters is in order. The approach has been almost exclusively empirical and observational rather than theoretical and experimental. This reflects in large part a reluctance to make heavy investments of time and resources in more closely controlled studies until apparently significant (though often initially only circumstantially supported) empirical relationships and patterns can be demonstrated. Such an approach carries with it inevitable dangers – of exaggerating the potential significance of possibly coincidental relationships, of failing to perceive and give adequate consideration to exceptions, and of avoiding the critical evaluation of assumptions for as long as favoured explanatory paradigms can be sustained. In consequence, several of the major assumptions, which have proved practical and consistent with all the reported observations so far, now require closer scrutiny under conditions which will allow them to be more securely defined and qualified. Specifically, there is a need to establish the quantitative significance of bacterial magnetite in depositional environments, to specify more fully the conditions under which authigenic and diagenetic processes are magnetically significant and to evaluate questions of magnetic mineral survival in peats and sediments where extremely acid and/or reducing conditions prevail.