[10]

Mineral magnetic studies of lake sediments

A lake is the landscape's most beautiful and expressive feature. It is the earth's eye; looking into which the beholder measures the depths of his own nature

Henry David Thoreau
Walden

Lake-folk require no fiend to keep them on their toes

W. H. Auden
Lakes

10.1 Lake sediments and environmental reconstruction

In recent years, lake sediment studies have become increasingly important in many branches of environmental science. This reflects both a natural scientific curiosity in the sediment-based reconstruction of past environmental conditions, and also, especially over the last decade, a need to set studies of present day environmental processes and problems in a longer time perspective. This is often best achieved within the lake-watershed ecosystem framework (Borman & Likens 1969, Oldfield 1977, O'Sullivan 1979). Within this framework, the evaluation of human impact and the effective assessment of its present and future implications will often depend on (a) comparing present day observations and experimental results with data derived from the analysis of sediments predating anthropogenic effects (Oldfield *et al.* 1983b), (b) reconstructing in detail the history of human impact on some aspect of biosphere function, for example soil erosion (Dearing 1983), heavy metal flux (Edgington & Robbins 1976), or primary productivity (Battarbee 1978), and (c) linking present day process study and historical reconstruction so as to develop a continuum of insight into environmental processes, within which past and present states and rates can be compared (Oldfield 1977, 1983b).

Lake sediments are especially useful in historical monitoring for several reasons. Despite unresolved problems of mud–water exchange chemistry and early diagenesis, there is often a conformity of process linking past and present deposition mechanisms. Moreover, evidence both of primary productivity in aquatic communities and of material flux in the total lake-watershed ecosystem are often well preserved in the sedimentary record. Rates of sediment accumulation are usually more rapid in lakes than in marine environments. In consequence, the period of accelerating human impact on environmental processes over the last one or two centuries is usually well resolved in the upper sediments. Several new dating techniques have been developed which are applicable to recent lake sediments and allow close chronological

control of recent sediment-based analyses (see e.g. Oldfield 1981). Finally, the lake-watershed ecosystem is material-bounded in large measure and thus provides a convenient and spatially finite framework for study.

From the preceding chapters (8 & 9) it can be shown that variations in the type and concentration of magnetic minerals in lake catchments will often be related to soil and slope processes and land use changes. Moreover, the magnetic properties characteristic of different soils and lithologies are often highly conservative within the drainage net. The mineral magnetic characteristics of lake sediments are therefore likely to be related to and often indicative of specific sources and processes. The following sections explore the rôle of mineral magnetic measurements in lake sediment studies.

10.2 The origin of magnetic minerals in lake sediments

The magnetic minerals present in lake sediments are of varied types and origins. Interpreting the record of mineral magnetic variation in the sediments is therefore strongly dependent on evaluating alternative sources for a given lake and catchment, with a view to identifying the dominant types, sources and pathways represented. The conventional distinction between authigenic, diagenetic and allogenic sediment is useful in this respect. Authigenic magnetic minerals are those formed by chemical or biogenic processes *in situ* after deposition of the sediment. Diagenetic magnetic minerals are the result of the transformation of existing magnetic or non-magnetic minerals to new magnetic types (cf. 12.2). Allogenic magnetic minerals are brought into the lake from outside. They may have originated within the drainage basin of the lake or have been transported (for example by wind or by man) from more distant sources beyond the immediate catchment. Table 10.1 identifies the main types and sources of magnetic minerals found in lake sediments. Although some of the least abundant of these are authigenic, and for others, such as magnetite and haematite, it is sometimes difficult to preclude entirely an authigenic or diagenetic origin, in the majority of cases studied so far, circumstantial evidence strongly suggests an allogenic origin. The circumstantial evidence includes (a) a tendency in many lakes for magnetic mineral concentrations and fluxes to peak most sharply in more marginal sediments (Thompson *et al.* 1975) and in zones close to inputs from the catchment, (b) a strong direct link between down-profile variations in magnetic susceptibility and other palaeoecological or chemical indicators of accelerated detrital mineral input, (c) clearly established linkages between sediment and catchment source in a variety of lakes (cf. Ch. 16) and (d) confident ascription of many recent mineral magnetic variations to well documented catchment events. Thus the studies completed so far have led us to regard magnetic minerals in lake sediments as overwhelmingly allogenic except where there is positive evidence to the contrary (e.g. Hilton and Lishman 1985).

ALLOGENIC MAGNETIC MINERALS FROM WITHIN THE LAKE CATCHMENT

Lithology exerts an important control on the magnetic

Table 10.1 Magnetic minerals in lake sediments: major types and sources.

Source type	Location origin	Major pathways	Magnetic mineral types
bedrock	lake catchment	streams overland flow mass movement	magnetites; haematite; pyrrhotite MD/SD
soils	outside lake catchment	wind	impure magnetite; maghemite SD/SP goethite/haematite
volcanic ash	lake catchment	streams, etc.	magnetites
	outside lake catchment	wind	
fossil fuel combustion and industrial processes	lake catchment	streams, etc.	impure magnetite
	outside lake catchment	wind	haematite
lake sediments	authigenic/diagenetic/post-depositional/*in situ*		magnetite greigite

Table 10.2 Maximum χ values from late-glacial sediments.

Site	Locality	Bedrock	χ (10^{-8} m^3 kg^{-1})
Hawes Water	Lonsdale, northern England	limestone	0.4
Loch Garten	Speyside, Scotland	schist/granite	0.4
High Furlong	Blackpool, England	marl	0.5
Roos	Holderness, England	chalk	1.0
Hornsea Mere	Holderness, England	chalk	1.1
Mellynllyn	Northern Wales	slate	1.2
Paajarvi	Southern Finland	schist/granite	1.2
Loch Morlich	Speyside, Scotland	schist/granite	1.2
Nant Ffrananconn	North Wales	slate	1.7
Lough Fea	Northern Ireland	granite/gabbro	2.8
Kiteenjarvi	Eastern Finland	schist	4.0
Kingshouse	Rannoch, Scotland	granite	6.7
Vuokonjarvi	Eastern Finland	granite/gneiss	9.0
Ormajarvi	Southern Finland	gneiss	10
Geirionydd	North Wales	slate/rhyolite	20
Hjortsjon	Southern Sweden	granite/gneiss	20
Windermere	Northern England	slate/andesite	22
Loch Davan	Deeside, Scotland	schist/granite	50
Bjorkerods Mosse	Southern Sweden	gneiss/dolerite	100
Loch Lomond	Southern Scotland	schist/basalt	130
Geitabergsvatn	Iceland	basalt	160
Barrine	Queensland, Australia	basalt	200

mineralogy of lake sediments. This is most easily illustrated by reference to specific susceptibility values obtained from the earliest late-glacial sediments present in a variety of infilled lake basins (Table 10.2). Such sediments predate weathering and soil formation and are often poorly sorted. They therefore reflect and integrate the primary magnetic mineralogy of the freshly exposed parent material surrounding the lake basin at the close of the last glaciation. The full range of specific susceptibility values reflects the range of parent material from calcareous boulder clay to basalt, and confirms that lithology is a major variable controlling magnetic concentrations in lake sediments.

Modification of the primary iron compounds in bedrock during the course of weathering and soil formation is a major theme in Chapter 8 and also provides the basis for distinguishing magnetically between topsoil, subsoil and bedrock sediment sources in rivers (see Ch. 9). In the case of lake sediments, any part of the drainage basin regolith exposed to erosive processes is a potential sediment source and most allogenic sediments will be a mixture of soil-, subsoil- and bedrock-derived material in widely varying proportions. Magnetically therefore, we may expect allogenic lake sediments to reflect not only the primary magnetic minerals in the catchment but also the secondary magnetic minerals formed in the soil as a result of the processes summarised in Chapter 8. The evidence from catchments within which secondary magnetic minerals greatly outweigh primary magnetic minerals in terms of overall importance and erodability (e.g. the Lac d'Annecy in the French Jura), confirms the persistence of some if not all of the eroded secondary minerals in lake sediments despite widespread indications of inhibition and reversal of secondary magnetic mineral formation in gleyed (waterlogged) soil horizons. The most conclusive evidence for the persistence of allogenic catchment-derived secondary magnetic minerals in lake sediments relates to those produced by fire (Rummery *et al.* 1979). Although incontrovertible *direct* evidence for the persistence of 'biogenic' or 'chemical' soil magnetic minerals in lake sediments (see Ch. 8) is more difficult to establish, the Rhode River case study (Ch. 16) clearly confirms persistence in that environment and it seems equally likely in most lakes.

Human activity within the catchment or on the lake itself may also generate magnetic minerals which pass into the lake sediments. The particulate fraction of effluent from industrial sites (12.5) and in urban stormwater drainage (9.4) is often highly magnetic. Moreover, in the recent sediments of the Grand Lac d'Annecy (Higgitt 1984, unpubl.) a striking susceptibility peak in several cores was shown to be the result of clinker from the coal barges which plied the lake in the first half of the 20th century.

ALLOGENIC MAGNETIC MINERALS FROM OUTSIDE THE LAKE CATCHMENT

Clearly, all the types of magnetic mineral encountered in the atmosphere (Ch. 11) contribute to the sedimentary record. However, only in specific circumstances will the contribution become significant in comparison with the input from the land surfaces surrounding the lake. These circumstances may result from volcanic activity, from fossil-fuel combustion and from forest fires.

Oldfield *et al.* (1980) show the impact of at least four tephra layers from 10 000 to 300 years in age, on the magnetic susceptibility of a suite of samples from three lakes in the Highlands of Papua New Guinea. Each ash layer is relatively enriched in primary magnetite and gives rise to a distinctive susceptibility maximum, (of Hamilton *et al.* 1986). There is strong evidence from the sediments of Newton Mere (Oldfield *et al.* 1983a) in the English Midlands and the nearby Whixall Moss, for the recent deposition of magnetic minerals resulting from fossil fuel combustion and industrial processes in areas lying down wind, but outside the tiny catchment (see Ch. 11). The evidence for wind erosion and for fine soil and charcoal dispersal associated with major forest and savannah fires suggests that these agencies may contribute magnetic minerals to lake sediments down wind. High ferrimagnetic concentrations have been detected in peat cores from Bega Swamp in S. E. Australia, at two horizons with high charcoal counts (Singh *et al.* 1979), and presumably were caused by atmospheric transport of fire-enhanced topsoil.

AUTHIGENIC AND DIAGENETIC MAGNETIC MINERALS

Jones and Bowser (1978) note that Fe_2O_3, presumably goethite, has been identified by electron microprobe analysis as the major mineral constituent of the iron-rich ferromanganese nodules recovered from Romahawk Lake, Wisconsin, and that both todorokite and goethite have been identified by X-ray diffraction there and at other sites including the Green Bay arm of Lake Michigan. Dell (1971) has identified greigite (Fe_3S_4) in sediment cores from Lake Superior. It is likely that magnetic phases associated with nodules and crusts, and with sulphide formation are more frequent than the current range of mineral magnetic case studies would indicate. Hilton and Lishman (1985) have shown that the volume susceptibility peak present in the fresh near-surface sediments of Esthwaite Water, in the South of the English Lake District can be reduced by aeration of the samples. These sediments are very rich in reduced forms of iron and sulphur which, at the right combination of E_h and pH appear to give rise to a rather impermanent magnetic phase. Similar results have been reported by Smith (pers. comm.) from an artificial pond receiving drainage from sulphur-rich coal waste.

The other significant authigenic magnetic phase in lake sediments arises from the production of magnetosmes by bacteria (see Ch. 16). Blakemore's observations (1975) suggest that this process may make an important contribution to the magnetic properties of sediments in a wide variety of lakes, though there is little support for this in the mineral magnetic studies completed so far.

PARAMAGNETIC MINERALS

Goddionduon, a small upland lake in N. Wales (see 10.4), has been studied in considerable detail by Bloemendal (1982). Here the peak in χ gives rise to extremely low SIRM/χ ratios and, it corresponds with maximum Fe and Mn concentrations (Fig. 10.1) and with peak Fe/Al and Mn/Al ratios. Mossbauer spectra and hysteresis loop plots for samples from the feature are typical of paramagnetic material.

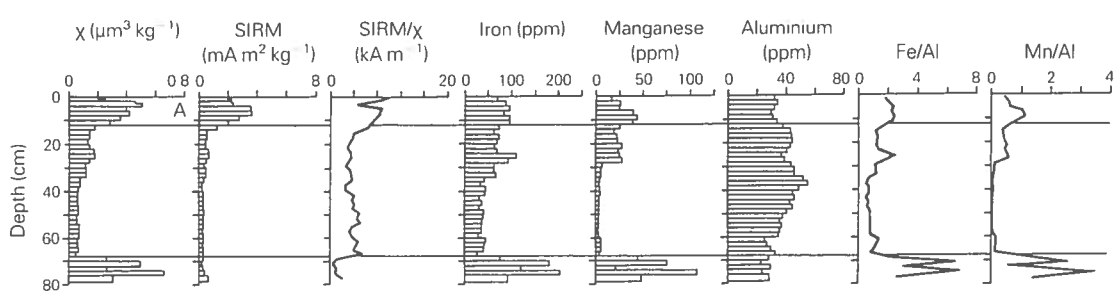

Figure 10.1 Paramagnetism in lake sediments. Mineral magnetic and chemical data from Llyn Goddionduon Core 120/-100. Susceptibility peak B (68–80 cm) coincides with minimum SIRM/χ and peak Fe, Mn, Fe/Al and Mn/Al.

Bloemendal concludes that the paramagnetic effects which dominate the magnetic properties of these samples are responsible for the very low SIRM/χ ratios. The feature coincides with an inferred lowering of lake level at the site (cf. Bengtsson & Persson 1978). At Loch Davan in north-east Scotland (Edwards 1978) and at Weir's Lough in Northern Ireland (Hirons 1983) similar χ peaks and SIRM/χ minima coincide with maximum Fe and Mn concentrations in the early Flandrian sediments. Following Mortimer (1942) and Mackereth (1966) these high concentrations are interpreted as a reflection of the acidification, leaching and podsolisation of the surrounding iron-rich soils under increasingly reducing conditions. The iron and manganese salts, once released from the catchment in solution are then deposited in the lake sediments provided conditions at the mud–water interface are sufficiently aerobic. The high susceptibility values are interpreted as a reflection of Fe and Mn accumulation as paramagnetic salts in the sediments. An increase in susceptibility and decrease in isothermal remanence observed upon cooling the Davan sediments to liquid nitrogen temperature indicates that the magnetic minerals are paramagnetic and are not superparamagnetic ferrimagnetic grains (see Section 4.7). From Bloemendal's summary and from the published chemical analysis of many European and N. American lake sediment sites it is clear that comparable features are widespread.

10.3 Sampling and measurement

Although it is possible to carry out a wide range of mineral magnetic measurements on uncontaminated sediment samples obtained by any reliable coring method, there are major advantages in using non-metallic core tubes or liners. Moreover the whole process of initial measurement can be expedited by keeping whole cores intact so that they can be scanned for volume susceptibility variation before extrusion and subsampling. Pneumatic Mackereth (1958, 1969) corers provide ideal samples not only for palaeomagnetic studies (see Section 14.2) but also for the mineral magnetic studies considered here. Alternative types of corer are considered briefly in Oldfield (1981). Irrespective of the type of corer used, and provided the core can be retained in, laid on, or

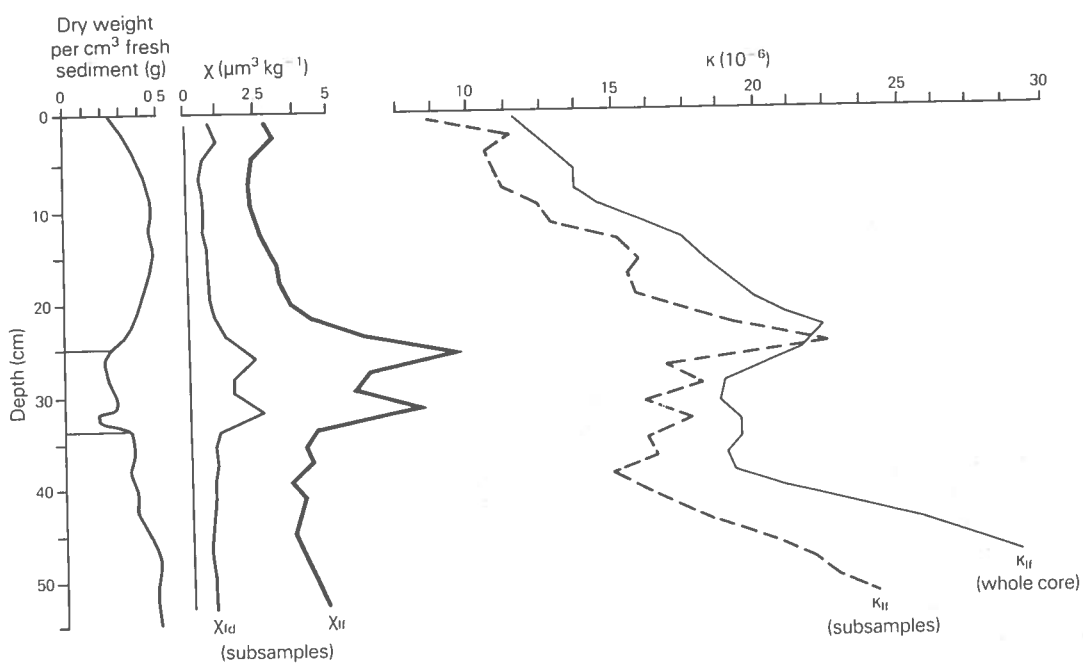

Figure 10.2 A comparison of whole core, single sample volume (κ) and single sample mass (χ) susceptibility traces for Core 16 from Lawrence Lake, Michigan. The plots show the effects of smoothing on the whole core trace and of strong variations in the dry mass/fresh wet volume ratio on the comparability of volume and mass specific measurements. The sharp rise in χ_{fd} and χ_{lf} at 34 cm is the result of early 'European' settlement round the lake and it is partly obscured in the volume-based measurements.

extruded into a rigid non-magnetic liner, whole core susceptibility scanning (Radhakrishnamurty *et al.* 1968, Molyneux & Thompson 1973) should be possible using a suitably designed sensor.

Scanning of unopened sediment cores in plastic drainpipe or perspex (plexiglass) tubes for variations in volume susceptibility (κ) provides rapid insight into down-core mineral magnetic variations. Where use of a microprocessor-controlled long core susceptibility bridge is feasible (Section 6.3.1) the rate of scan is in excess of 6 m min^{-1} with an automatic reading interval of 0.5–5 cm. Whole core scanning necessarily presents a smoothed trace of variations in magnetic susceptibility (due to instrument response) and may fail to resolve fine detail. Moreover, it is unsuitable for detecting and portraying accurately variations as the mud–water interface is approached, since the readings will be depressed both by the increase in water content which often occurs in the most recent sediments and also, very near the surface, by the fact that the sensor 'sees' both the sediment and the immediately overlying water. If after whole core scanning, a more detailed picture of variation is required, extrusion of the core and measurement of the susceptibility as well as the induced remanence characteristics of single samples on a constant volume or preferably on a dry weight specific basis, will be necessary. Figure 10.2 compares whole core and single sample susceptibility data from the same core.

10.4 Prospecting, core correlation and sediment accumulation rates

Many palaeolimnological studies are marred to some degree by the extent to which inferences rely on data from a very small number of cores and by the problems involved in correlating cores which have provided complementary but often poorly synchronised data. Both problems arise largely from practical constraints since most methods of biostratigraphic, sedimentological or chemical analysis are time consuming, sediment destructive and relatively costly. One response to this problem is to select a 'representative' or 'master' coring site and use one of several large diameter samplers now available to provide enough bulk for different types of analysis. In this case, choice of coring site is crucial and techniques which may aid site selection by speeding initial prospecting are potentially very useful. Even this approach provides an inadequate basis for fully quantitative budget studies within a lake-watershed ecosystem framework (cf. Oldfield 1977), since the latter may call for estimates of material flux or productivity for given time intervals on a whole catchment–whole lake basis. Extrapolation from a single core or a small selection, to a whole lake is complicated by spatial variations in primary sedimentation rate, as well as by mechanisms of post-depositional sediment resuspension, redistribution and focusing (Davis & Ford 1982). Mathematical models for such extrapolations lack empirical validation (Lehman 1975), and 'whole' lake estimates based on empirical studies using data from multiple cores (e.g. Davis 1976, Davis & Ford 1982) are rather scarce. Rapid methods of correlation are therefore desirable not only for aiding the comparison and synchronisation of data from several cores, but also for developing quantitative estimates of sediment flux. In addition detailed core correlations may also aid the establishment of chronologies of sedimentation both by facilitating sample aggregation for radiometric dating (Oldfield *et al.* 1978) and by providing an independent check on the internal consistency of dates derived from different cores from the same lake. Finally, magnetically distinct horizons at or near the mud–water interface resulting from catchment events such as forest fires or land use changes, provide a natural time stratigraphic marker for subsequent follow-up studies and recurrent monitoring. The studies summarised below have been chosen to illustrate some of the above applications.

The first use of magnetic susceptibility scanning as a means of multiple core correlation arose from the realisation that in Lough Neagh in Northern Ireland, single sample volume susceptibility measurements on a range of widely separated 3 m cores from Antrim Bay provided a basis for very detailed comparison (Fig. 10.3). The correlation suggested by susceptibility measurements supported the record of secular variation previously found in the same samples (Thompson 1973). Subsequent work confirmed that similar susceptibility correlations could be established using the much more rapid whole core scanning method. Moreover, these correlations were shown to hold good in widely separated depositional environments and in sets of cores with differences in mean accumulation rate of at least three times. In order to test the validity of the susceptibility-based correlations, diatom analysis was carried out on each core. As a result, it was possible to show that the main peak in susceptibility coincided with a distinctive

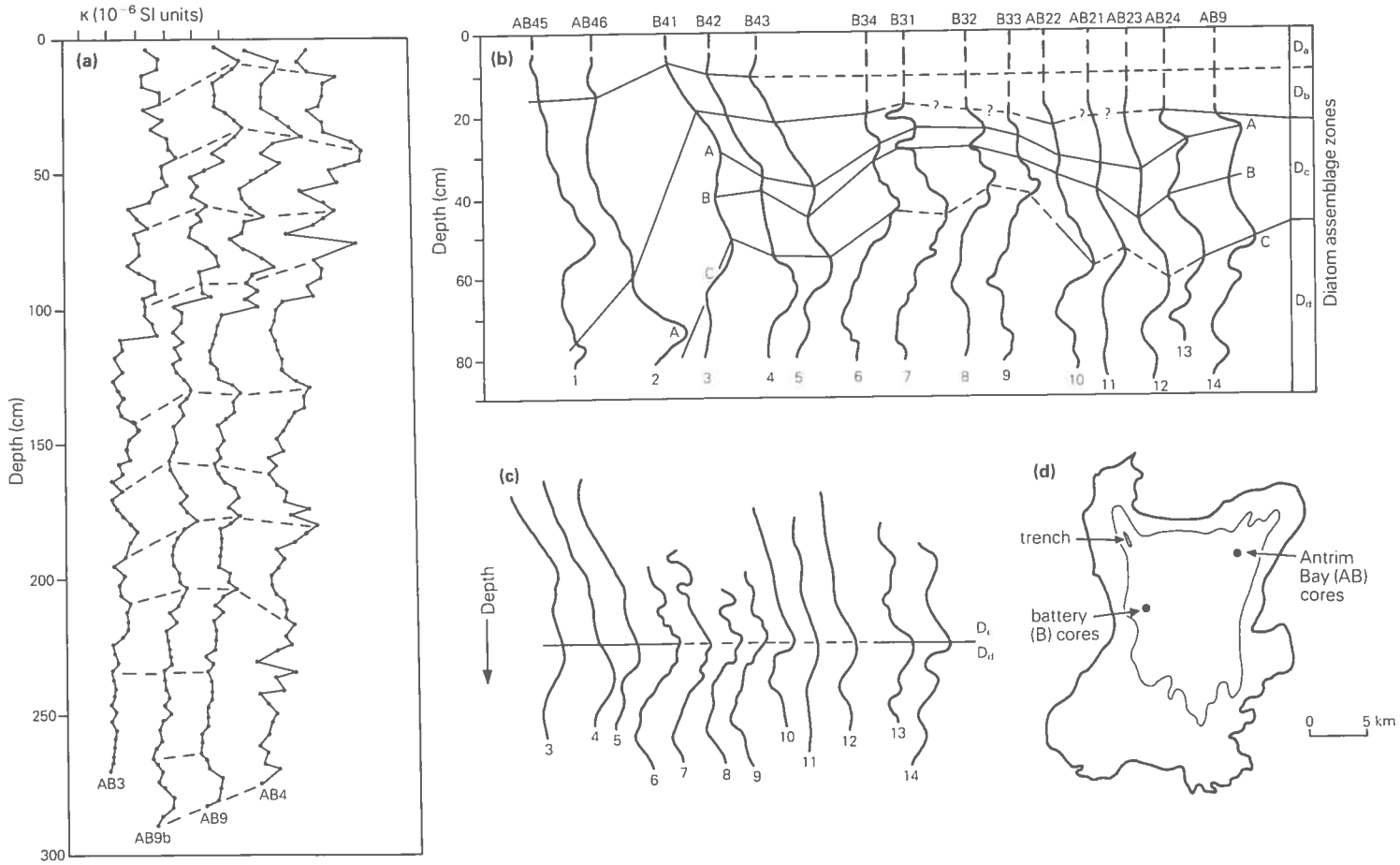

Figure 10.3 Susceptibility traces from Lough Neagh cores. Correlated single sample traces from four Antrim Bay 3 m cores are shown in (a). In (b) and (c) 14 plots from the Battery and Antrim Bay show variations in volume susceptibility measured on whole 1 m cores, compared with changes in the fossil diatom content of the sediments (Battarbee 1978). Diatom zones D_a–D_d are shown in (b) as well as several horizons of susceptibility-based correlation. In (c), the susceptibility traces are aligned by means of the D_c/D_d diatom boundary (see Thompson *et al.* 1975).

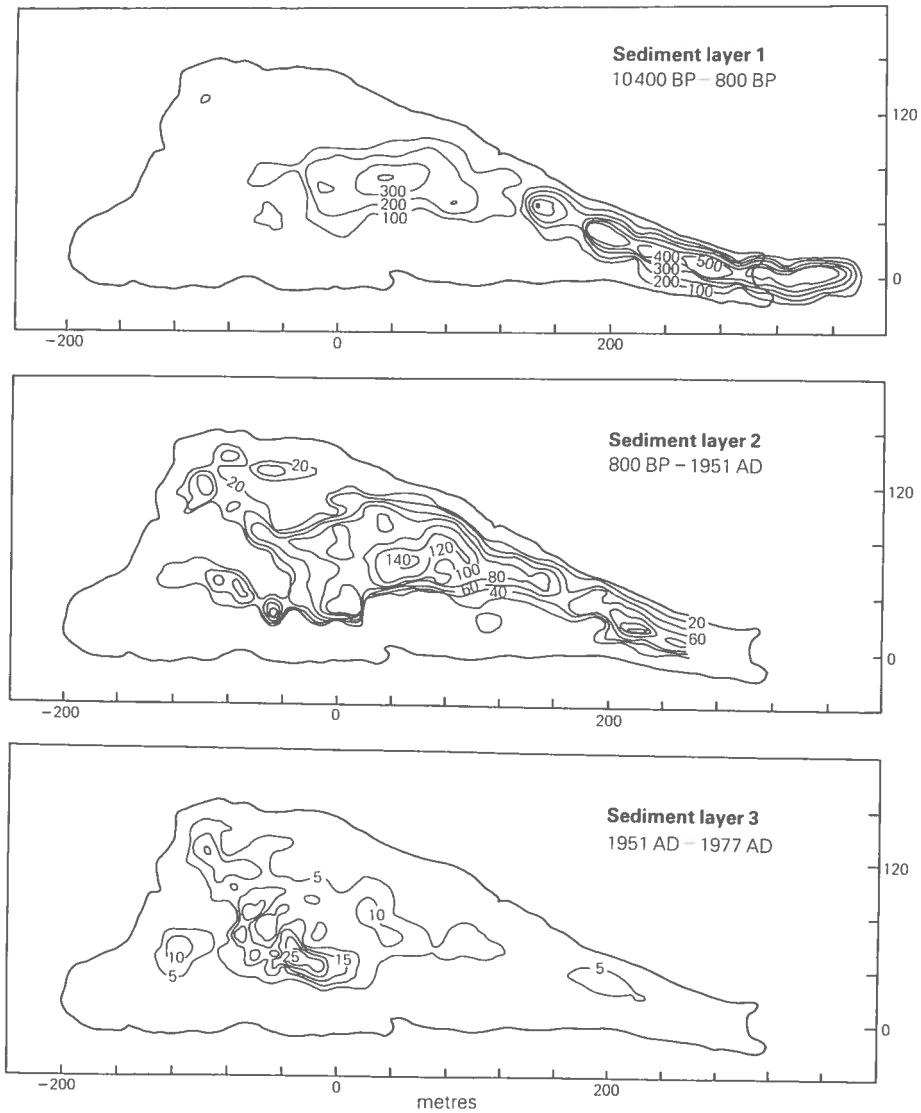

Figure 10.4 Sediment thickness for three time intervals in Llyn Goddionduon, N. Wales. For each interval sediment thickness is contoured in centimetres. The co-ordinated grid is in metres. The diagrams are redrawn and simplified from Bloemendal (1982). ^{210}Pb assay carried out more recently suggests that the 2/3 boundary may predate 1951 AD.

change in the fossil diatom flora preserved in the sediments (Fig. 10.3). Similar independent confirmation of susceptibility-based correlations has come from visual stratigraphy at Havgardsjon in S. Sweden (Dearing 1983) and from X-ray traces at Lake Washington, near Seattle in northwestern United States (Edmondson, pers. comm.).

At Llyn Goddionduon, a comprehensive grid of over 130 short cores was established to provide an empirical basis for estimating total sediment influx to the lake between recent dated horizons. Despite severe stratigraphic complications arising from the relatively large expanse of shallow water, high wind exposure, recent water level changes and widespread truncation and redeposition of sediments, two magnetically distinctive horizons were identified in whole core susceptibility scans and their approximate synchronism confirmed by single sample measure-

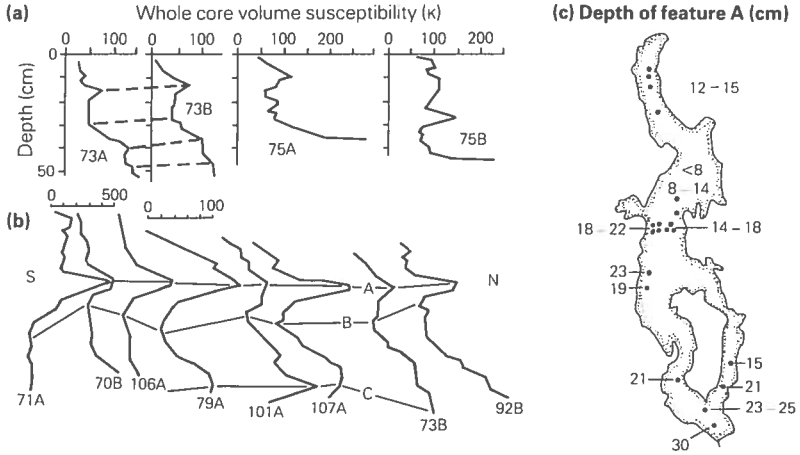

Figure 10.5 Whole core volume susceptibility logs from Lake Washington (see text). Peak A, the depths of which are plotted on the map, is a result of the lowering of lake level and the diversion of the Cedar River into the lake in 1915.

ments (Bloemendal *et al.* 1979, Bloemendal 1982). The lower feature, 'Peak B' (Fig. 10.1a) was dated to 800 BP by correlation with radiocarbon-dated peat formed at the southern end of the lake. The upper feature, 'Peak A' was ascribed to a forest fire in 1951 and the subsequent inwash of magnetically enhanced soil (see 10.7). It was thus possible to provide rough estimates of net sediment input to much of the lake bed for three time intervals: (a) from the end of the late-glacial period at the site (10 400 BP) to 800 BP, (b) from 800 BP to 1951 AD and (c) from 1951 AD to 1977 AD (Fig. 10.4). Although in this pioneer study there are uncertainties arising both from problems inherent in the method and from the particular choice of lake, it demonstrated the power of the new approach and heralded a number of similar studies during subsequent years.

One of the most useful practical applications of multicore studies is in the detection of anomalous, or disturbed sedimentation. Figure 10.5 shows volume susceptibility (κ) logs from sets of 50 cm long recent cores taken from Lake Washington. Numbers refer to coring stations, letters to replicates taken on the same day from each station. Although the features of the traces for the Station 73 cores and for those from Station 75 are replicates, the susceptibility variations are not comparable. By using susceptibility scans as a guide to core selection, and ^{210}Pb for chronology (Schell, pers. comm.), it is possible to establish the intercore correlation scheme outlined in Figure 10.5 alongside a plan which summarises the implications of the scheme in terms of the thickness of sediment accumulated since *c.* 1915 when the lowering of lake level and diversion of the Cedar River gave rise to peak A in the traces. The same approach has been used in Lake Washington for selecting long cores for further study (Oldfield *et al.* 1983a). In Lake Washington, some of the susceptibility peaks are the result of volcanic ash layers including the Mt Mazama tephra recorded over a vast area of the N. W. of the USA. Where the main magnetic variations in a set of cores are the result of synchronous volcanic ash layers, whole core susceptibility scanning can greatly accelerate the development of tephrochronologies not only within but between lakes (Oldfield *et al.* 1980).

Dearing and coworkers (Dearing *et al.* 1981, Dearing 1983) have published two contrasted case studies of total sedimentation, one based on Llyn Peris, north Wales (53°02′ N, 4°06′ W) an oligotrophic lake with a large grazed upland catchment, and one based on Havgårdsjön (55°29′ N, 13°22′ E) a shallow eutrophic kettle-hole lake with a small low lying cultivated catchment in Scania, southern Sweden. In both cases, mineral magnetic studies were combined with ^{14}C, ^{210}Pb and ^{137}Cs as well as palaeomagnetic dating.

In Llyn Peris, rapid sedimentation associated with low susceptibility values is ascribed to slate dust input arising from quarrying in the catchment. High susceptibility values are ascribed to higher stream discharge levels and consequent channel erosion associated with periods of overgrazing by sheep. The period of recent strongly accelerating sedimentation is largely the result of erosion associated with hydro-electric plant construction.

In Havgårdsjön (Fig. 10.6), the changing erosion rates can be closely compared with the detailed record of agricultural history and land-use change available

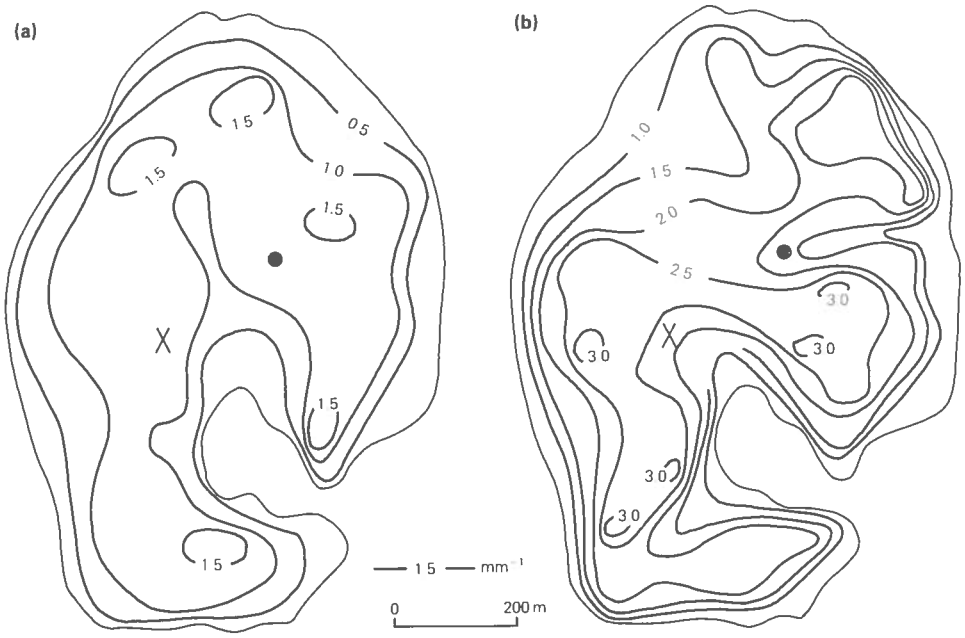

Figure 10.6 Sediment accumulation patterns for two periods in lake Havgårdsjön, Scania, S. Sweden: (a) *c.* 1550 AD – *c.* 1712 AD and (b) *c.* 1712 AD – 1979 AD. ● marks deepest zone of lake basin.

for the catchment. The period of accelerating erosion in the 19th century coincides with a major shift in animal husbandry from cattle to sheep. The overall increase in erosion rates since the late 17th century mirrors the general expansion of ploughed land over the past three centuries. Dearing has used the correlation scheme as a basis for modelling nutrient flux within the lake and catchment (Oldfield *et al.* 1983b).

Magnetic measurements combined with radiometric dating have also made possible a similar reconstruction of erosional loss for the catchment of a small crater lake in the New Guinea Highlands, Lake Egari. Intercore magnetic susceptibility-based correlation is possible here, largely as a result of two major tephra layers dated *c.* 300 and 1200 BP. The combination of susceptibility-based correlations and three ^{210}Pb-dated profiles has provided an extremely detailed picture of changing erosion rates which once more relates closely to the history of land use in the catchment reconstructed in this case from pollen-analytical evidence (Worsley 1983). Periods of forest clearance and subsistence gardening are associated with higher erosion rates, and the post-1950 decades of Australian contact record a further major increase.

Table 10.3 summarises the evidence for changing erosion rates from Llyn Goddionduon, Llyn Peris, Havgårdsjön and Egari, and compares the rates with those derived from other recent studies. In comparing the results and in evaluating the examples outlined, attention must be paid to the limitations of this type of approach, especially in terms of the suitability of particular lakes and catchments, and the many sources of error involved in calculation (Bloemendal 1982, Oldfield *et al.* 1985a).

10.5 Sediment resuspension and focusing

One of the most widespread types of sediment redistribution is that frequently referred to as sediment focusing whereby material from marginal depositional contexts is resuspended and deposited in deeper water. The process is common in dimictic lakes where it results largely from the seasonal episodes of water 'overturn' and mixing between the periods of summer and winter stratification.

The best documented case study of sediment focusing is at Mirror Lake, New Hampshire (Davis & Ford 1982). The Mirror Lake sediments are extremely poor in ferrimagnetic minerals and the volume susceptibility variations are often masked by the

Table 10.3 Erosion rates calculated from lake sediment influx studies using mineral magnetic (A–D) and other methods (E, F). A fuller comparison with estimates derived from Reservoir Surveys and continuous monitoring studies is given in Bloemendal (1982).

	Land-use types and events	Total sed. (kg ha^{-1} a^{-1})	Organic sed. (kg ha^{-1} a^{-1})	Inorganic sed. (kg ha^{-1} a^{-1})	Watershed area (hectares)
(A) Llyn Goddionduon 1951–1977 AD	post forest fire	263–326	80–100	183–226	24.8
800 BP–1951 AD	upland grazing	126	27	99	
10400 BP–800 BP	forest and moorland	36	8	28	
(Bloemendal 1982)					
(B) Llyn Peris 1965–1975 AD	construction	—	—	420	3800
c. 1800 AD	upland grazing	—	—	50	
(Dearing *et al.* 1981)					
(C) Havgårdsjön *c.* 1650 AD	stock farming	—	—	1000	140
c. 1850–1980 AD	and cultivation	—	—	3000	
(Dearing *et al.* 1981)					
(D) Egari 1950–1973 AD	subsistence horticulture and roads	2300			
c. 1600–1800 AD	deciduous forest	200			
c. 1900–1950 AD	peak subsistence	900–1200			
(Oldfield *et al.* 1985a)					
(E) Frains Lake 1830–1970 AD	arable and roads	907	7	900	18.4
Pre-1830 AD	oak forests	96	6	90	
(Davis 1976)					
(F) Mirror Lake (mean Holocene) (Davis & Ford 1982)	forest	—	—	36*	107

* Excludes estimated dissolved SiO_2 input converted to biogenic silica as diatom frustules.

diamagnetic effect of carbon, biogenic silica and water. Whole core susceptibility scans are thus unsuitable for detailed stratigraphic correlation. Instead we have used measurements of isothermal remanence, $IRM_{300\,mT}$, generated by a pulse magnetiser with a peak field of 0.3 T and carried out on single samples.

A grid of forty-six 35–50 cm long cores was obtained by working from the ice of Mirror Lake in February 1982 and 1983 using a modified Gilson benthos corer which preserved an undisturbed mud–water interface. Figure 10.7 plots IRM versus accumulated dry weight for ten of the cores. Cores 35, 38 and 36 are from the western end of the lake in 6–8 m water depth and core 1 is from 7 m at the southeastern end of the lake. The remaining cores are from central locations in greater water depths (8.5–10 m). For all or part of the period between magnetic features A and B, as for the preceding Holocene record as a whole, strong sediment focusing from shallow to deep water is recorded. During the recent post-B period, simple focusing of this type is not apparent and both the deep central and the shallow marginal core sets include cores with light and heavy sedimentation. Cores 18, 34 and 32, with minimum post-B accumulation, lie to the north-east of the axis of the main basin and furthest away from the river-borne supply of sediments from the relatively more disturbed parts of the catchment.

The Mirror Lake IRM variations are also accompanied by changes in hysteresis ratio parameters derived from d.c. demagnetisation experiments and hence not primarily related to concentration. Figure 10.8 plots two of these for all the samples within each magnetostratigraphic subdivision for two marginal (30 and 35) and two deep-water (28 and 34) cores. From this we see that in these cores, during the period of inferred sediment focusing (pre-A and A–B) the magnetic parameters for the central and marginal cores are quite distinct. The mineral magnetic characteristics of the marginal core samples are suggestive of a relatively higher coarse-particle related haematite content, which is consistent

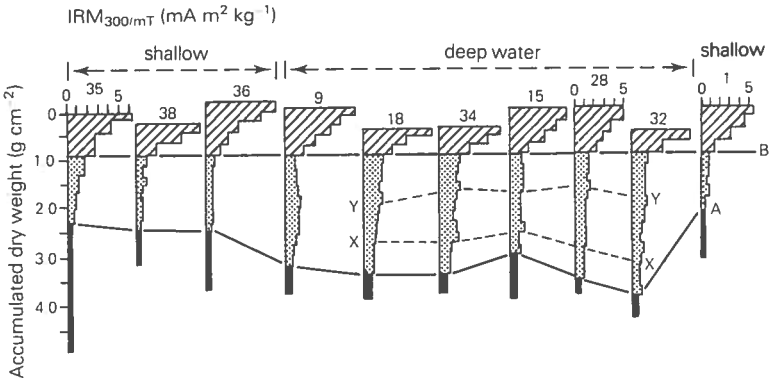

Figure 10.7 Correlated profiles of IRM_{300mT} versus accumulated dry weight for ten cores from Mirror Lake, New Hampshire. Horizon B is a late 19th/early 20th century feature, horizon A is roughly contemporary with the beginning of local colonial settlement in the late 18th century.

with the earlier results of Stober (1979) from comparable granite-dominated lithologies in Finland. By contrast, for the post-B period the parameters for all cores correspond very closely. These results are consistent with a model in which

(a) sediment focusing selectively winnows and redeposits finer/less dense material from marginal to central sites during the earlier period.
(b) either a historically documented rise in water level (Davis & Ford 1982) disrupts the focusing mechanism or an increase in sedimentation rate, coupled with possible changes in sediment type and source, gives rise to more rapid sediment burial and proportionally less effective resuspension and transfer to deeper water.

10.6 Sediment sources and ecological change

SUSCEPTIBILITY AND EROSION

The susceptibility traces from Lough Neagh, Northern Ireland, were the first to suggest a relationship between mineral magnetic variations in the sediments and the record of land-use history in the drainage basin. As Figure 10.9 shows, susceptibility tends to increase irregularly towards the surface in 3 m Core AB9. The timespan of the core is roughly the last 6000 years, beginning in the early Neolithic period characterised, in the pollen record, by reduced tree pollen representation (the 'Elm Decline') and an early increase in weeds and disturbed ground indicators. The pollen diagram from AB9 thus records vegetation history and land-use change for virtually the whole period of significant human impact on the landscape. Forest clearance and farming are indicated by increases in the relative frequency of pollen and spore types such as ribwort plantain, bracken and the grasses. Representation of the first two tends to peak sharply during relatively brief phases of initial clearance and maximum disturbance. The grass pollen trace, which, in Lough Neagh, can be confidently interpreted as an indicator of the spread of open habitats, such as pasture and moorland (O'Sullivan *et al.* 1973), tends more towards a stepwise increase, each rise coinciding with bracken and plantain peaks. Progressive deforestation in a series of discrete episodes is indicated. The parallelism between the grass pollen record and susceptibility curve is remarkable and it is difficult to avoid attributing increases in the latter to the sequence of deforestation indicated by the former. The latest peaks coincide with a steep decline in carbon concentration in the sediment and both features follow the beginning of a continuous cereal pollen record, suggesting that actual tillage as well as deforestation was important in providing increasing volumes of minerogenic sediment. From the evidence summarised, Thompson *et al.* (1975) concluded that susceptibility may be regarded as an erosion indicator in Lough Neagh with the high values reflecting higher inputs of primary titanomagnetites from the basalt bedrock of the large drainage basin as successively more extensive deforested areas were created and the parent material exposed to erosion. More recently, by measuring the magnetic susceptibility of material collected in seston traps in Lough Neagh, Dearing and Flower (1982) have shown that susceptibility peaks correspond with monthly rainfall maxima (Fig. 10.10). They conclude that susceptibility peaks in the sediment record are

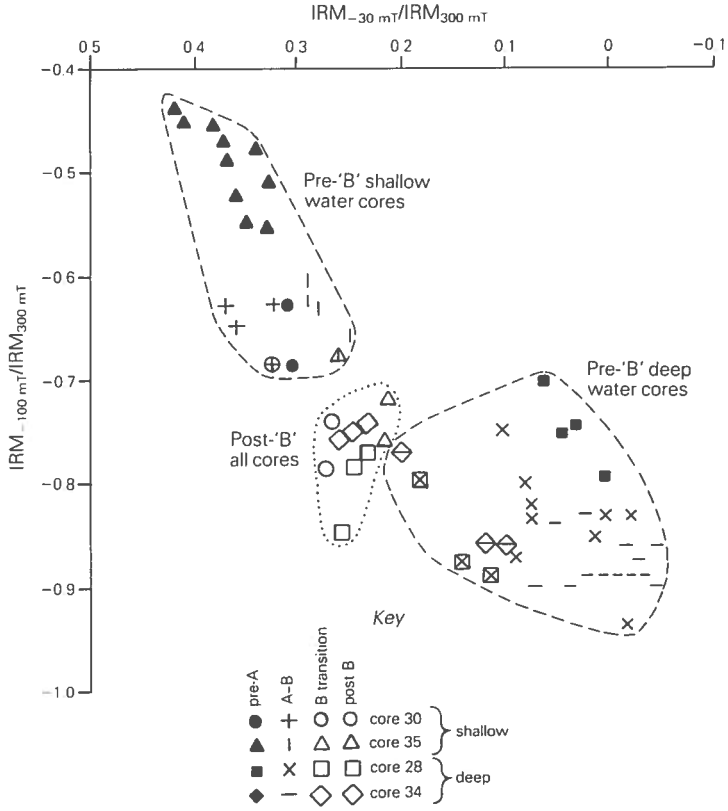

Figure 10.8 IRM_{-30mT}/IRM_{300mT} versus IRM_{-100mT}/IRM_{300mT} plotted for samples from a selection of shallow and deep water cores. The variations within and between cores reflect degrees of sediment focusing within the lake (see text).

the expression of hydrological controls and that they reflect forest clearance and culvitation because these processes accelerate runoff and increase stream discharge, with a resulting increase in the proportion of coarser more magnetic sediments delivered to the lake.

A different example of the dependence of susceptibility on particle size in lake sediments emerges from Thompson and Morton's (1979) study of the Loch Lomond sediments. They show that in contrasted samples the highest specific susceptibility is in the silts below 32 μm. This gives rise to strongly particle size dependent susceptibility variations in the sediments. Peak values coincide with the highest concentrations of fines, and minima with the sandiest horizons throughout (Fig. 10.11). Magnetic crystal size varies little with sediment particle size however and the particle size related variations in susceptibility are interpreted simply as variations in the concentration of primary magnetite from parent material in the catchment. The relationship between susceptibility and pollen is reminiscent of that in the Lough Neagh sediments, so it follows that particle size and, in consequence of this, susceptibility, vary in response to man's impact on erosive processes. In Loch Lomond, it would seem that deforestation and ploughing have provided a higher proportion of fine silt for transport to the lake bed. This theme of particle size related variation is taken up in Chapter 16 which considers sediments and sources in the Rhode River, Chesapeake Bay.

Results obtained from study of a 6 m core from Lough Fea, a small lake lying in the western part of the Lough Neagh drainage basin, cover the whole of the Holocene. Figure 10.12 plots SIRM alongside the concentration of several chemical elements and the relative frequency of *Calluna* (heather) pollen. Zones M and L (*c.*11 000 to 9000 BP) cover the end of the late-glacial and the opening of the Flandrian (Holocene) stage. K, Na and Mg which, because of their relatively high solubility, were used by Mackereth (1965, 1966) and Pennington *et al.* (1072) as indicators of the erosive input of unweathered parent material, all show parallel and synchronous

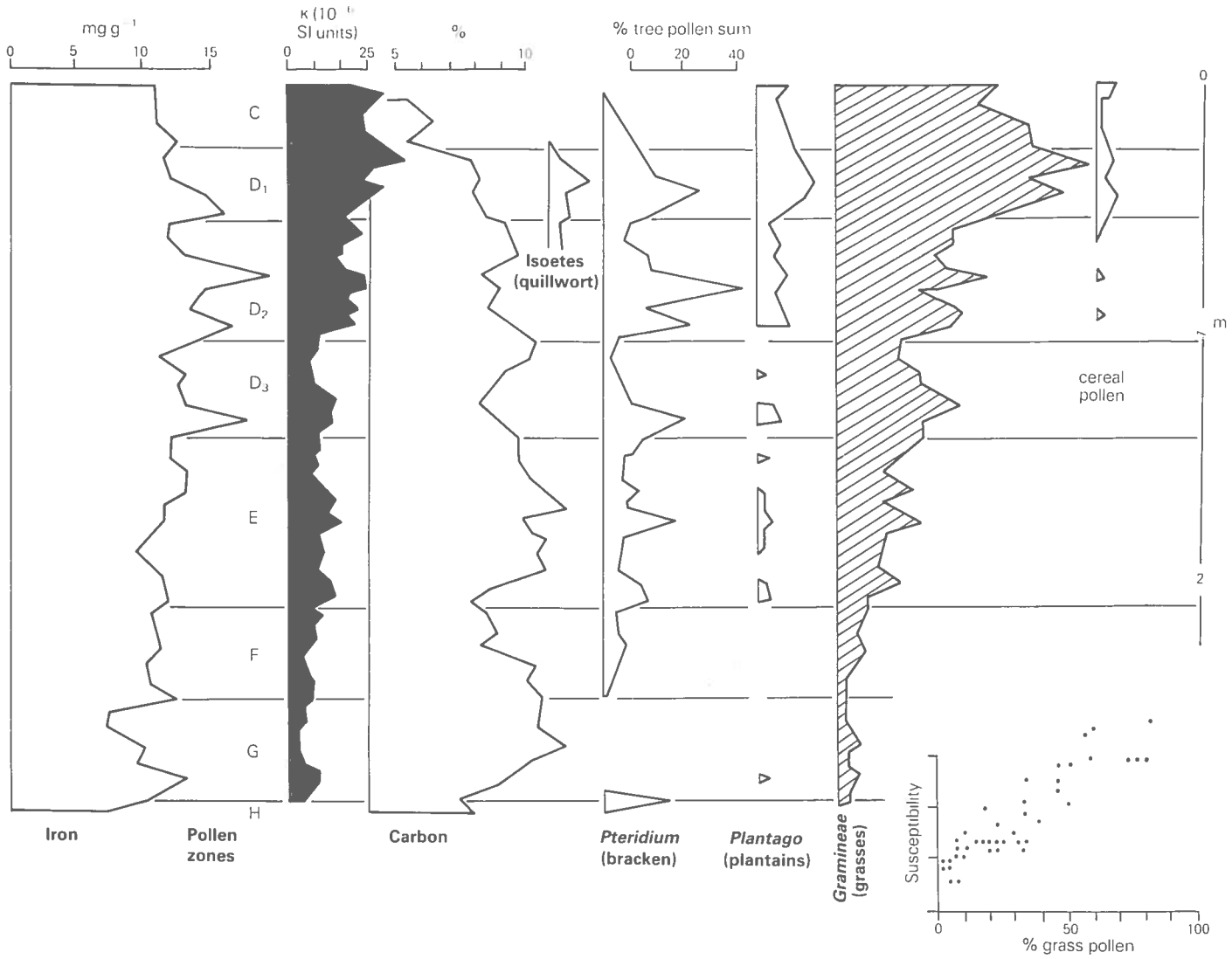

Figure 10.9 Chemical and pollen frequency data for Core AB9, from Antrim Bay, Lough Neagh compared with the magnetic susceptibility values.

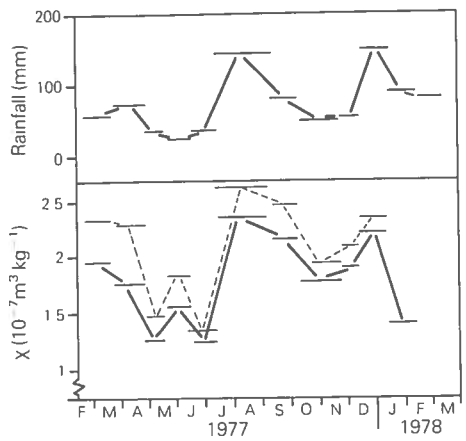

Figure 10.10 Bulk susceptibility of sedimenting material at the Antrim Bay site, Lough Neagh, calculated on minerogenic (solid line) and allogenic (dashed line) bases and compared with monthly rainfall (see Dearing & Flower 1982).

changes of concentration similar to those found in other upland sites in N. W. Britain. Peak concentrations during periods of bare soil and periglacial activity in the late-glacial period are followed by sharp declines as the land surfaces of the drainage basin become clothed in forest and in stable maturing soils. The mid-Holocene period of maximum forest cover and sustained biotic regulation of particulate loss gives rise to minimum K, Na and Mg concentrations but as soon as human activity affects the small upland drainage basin directly at the E/D_3 boundary (*c.*3500 BP), values begin to increase in response to deforestation and agricultural extension. At this stage, heather pollen becomes an important component in the record as a result of soil and peat erosion in the catchment. SIRM values follow the same pattern as the 'chemical erosion indicators' and the results once again indicate a direct link between magnetic mineral concentration and the erosion history of the catchment. The Lough Fea study however shows that at the opening of the Holocene the magnetic record is sensitive to climatically controlled surface processes (see Section 10.8) as well as to human activity later on (cf. Edwards & Rowntree 1980).

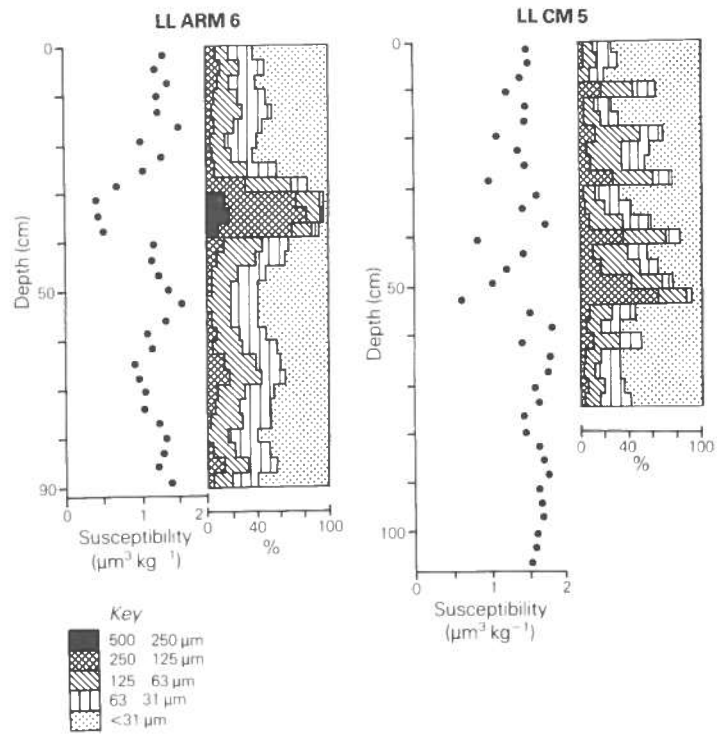

Figure 10.11 Variation in bulk specific susceptibility with depth plotted against changing particle size composition for two cores from Loch Lomond (see Thompson & Morton 1979).

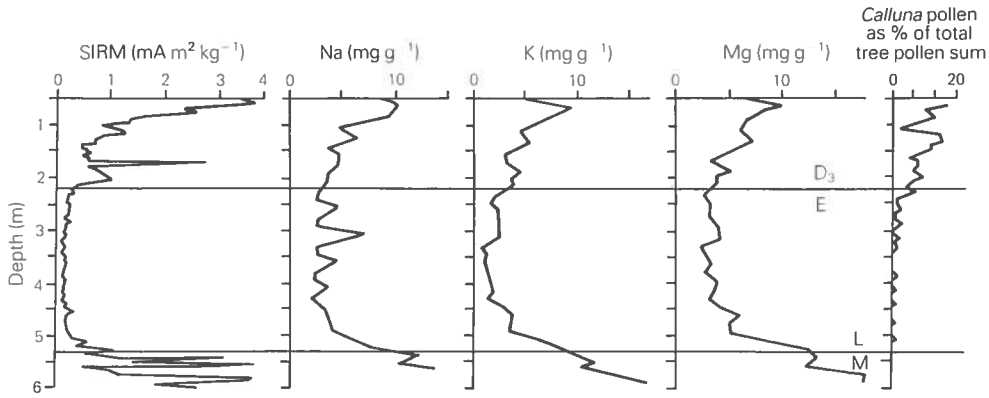

Figure 10.12 Lough Fea, N. Ireland. SIRM versus Na, K, Mg and *Calluna* pollen frequency in a 6 m core spanning the late-glacial and Flandrian sediments at the site.

SEDIMENT SOURCE SHIFTS AND LAND-USE CHANGE

The sites considered in 10.6 are all in catchments based on predominantly basic igneous bedrocks or on drift derived therefrom. In consequence, primary magnetic minerals are abundant and interpretative models of susceptibility–erosion linkage are expressed in terms of the impact, whether direct or indirect, of land-use change on variations in the accumulation rate of these primary minerals on the lake bed. In many other situations, even in some where primary magnetic minerals abound in the catchment, more complex interpretative models are required.

One of the most striking and widespread changes in land use in Britain during the last few decades has been the commercial afforestation of hills, moors and heathland areas by the Forestry Commission. The impact of extensive afforestation on lake sedimentation and especially on mineral magnetic parameters was a major theme of studies in and around Loch Frisa in northern Mull by Dearing (1979).

Loch Frisa is a deep, morphometrically complex lake lying in extensively dolerite-intruded basalts. Until *c.*1930 AD, erosion and sedimentation were dominated by the vicissitudes of crofting and latterly sheep farming in the catchment. Over the past 50 years most of the area round the lake has been planted in conifers. The three planting episodes involved extensive hand digging for drainage during the 1930s, the ploughing of a smaller area near the south-eastern shore in the 1950s and more extensive ploughing of the north-western flank in the early 1970s. Ploughing prior to planting exposed long sloping trenches of orange subsoil to rain splash and water movement, and in the nearby Loch Meadhoin, sediment sampling in July 1976 only 6 months after similar pre-afforestation ploughing revealed a 2 cm thick layer of orange sediment in the centre of the lake. Similar orange sediments were found in the top 10–30 cm of marginal Loch Frisa cores. The Loch Frisa sediments therefore provide an opportunity for examining the impact of afforestation on mineral magnetic properties, and on sedimentation processes and patterns, as well as for comparing the effects of afforestation episodes with those of the preceding agricultural activities.

Cores were correlated by means of whole core and single sample susceptibility measurements and dated by a combination of ^{137}Cs, ^{210}Pb ^{14}C and palaeomagnetic measurements (Appleby *et al.*, 1985). The pre-afforestation susceptibility maxima are related to peak farming activity and settlement density in the area (Dearing 1979), as would be expected from Lough Neagh and Lough Fea studies in similar lithological contexts. The effects of afforestation on magnetic mineralogy are rather the opposite. Soil profile measurements in the catchment (Dearing 1979 and Fig. 10.13) show that the orange subsoil exposed by ditching has a consistently lower susceptibility than either the basalt at the base of the regolith or the enhanced surface layers. It also includes material of much higher coercivity of remanence suggesting that, possibly as a result of tertiary weathering, some conversion to fine-grained goethite/haematite has taken place. High coercivity material can also be found within the zone of low susceptibility in the

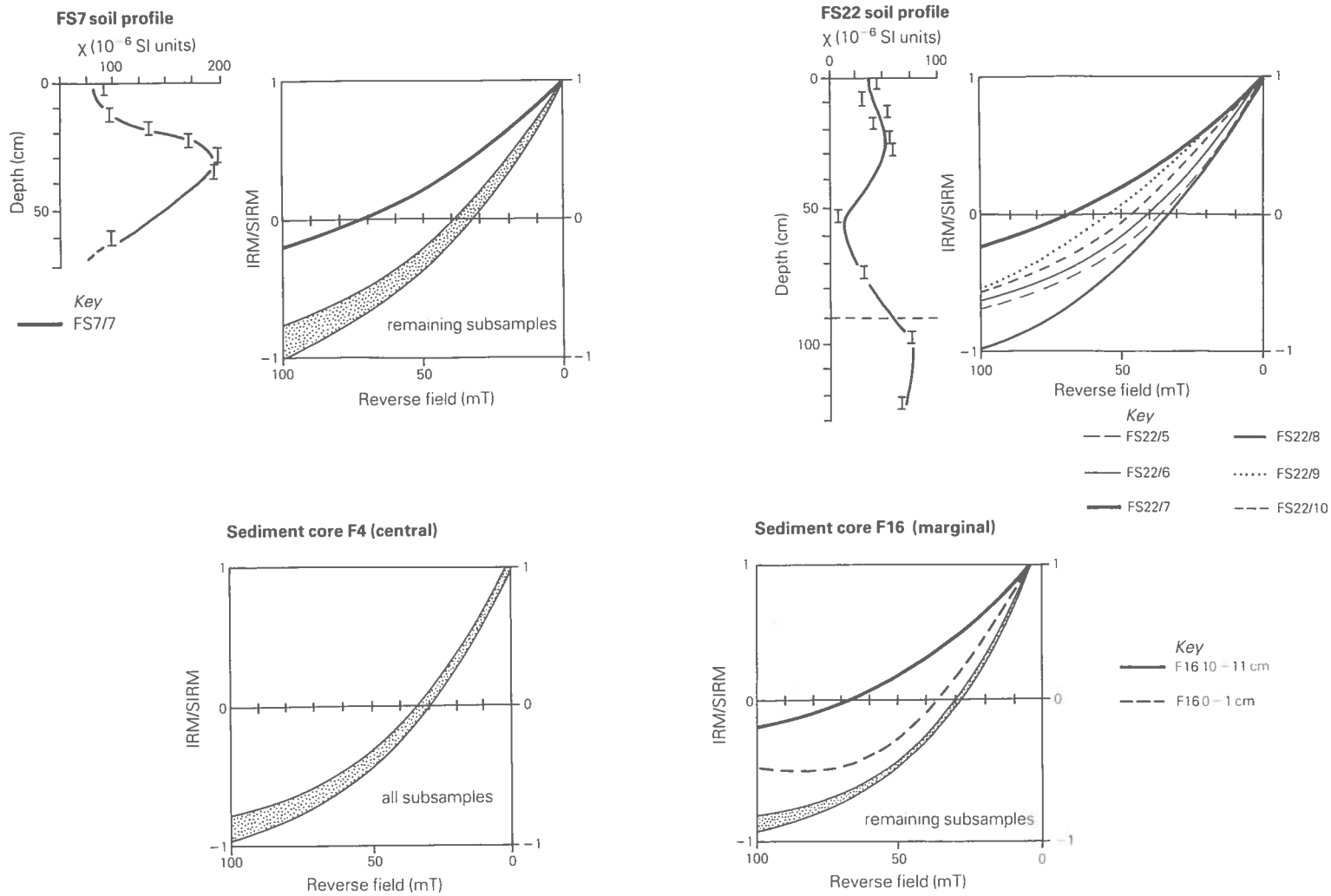

Figure 10.13 Soil–sediment links in Loch Frisa on the Island of Mull, W. Scotland. In both soil profiles one or more samples (e.g. FS7/7 and FS22/7) show high $(B_0)_{CR}$ values coinciding with susceptibility minima (at 60 cm and 50–55 cm respectively). The envelope of curves for the higher samples in FS7 and the individual curves for the remaining samples in FS22 show lower coercivities. All the samples from the central sediment Core F4 plot within a narrow envelope of curves within this lower coercivity range. In marginal Core F16 some samples (e.g. from 10–11 cm within the orange sediment layer) have high coercivities comparable to the separately plotted subsoil samples in FS7 and FS22 (see Dearing 1979).

upper lake sediments from marginal cores (Fig. 10.13). The mineral magnetic evidence thus confirms the postulated derivation from the orange subsoil exposed during the first stage of afforestation. The high value for the most recent sediments in all the marginal cores suggest that the sedimentation regime is now shifting away from dominance by subsoil input.

The Lac d'Annecy provides a strong lithological contrast to those considered so far since the surrounding rocks are almost entirely Jurassic limestones and marls extremely poor in magnetic minerals. Even the residual patches of glacial drift and a local inlier of sandstone are only minor components of the total reservoir of magnetic minerals in the catchment, most of which are present as secondary oxides in the surface soils (Dearing 1979, Longworth *et al.* 1979). Figure 10.14 plots mineral magnetic variations alongside chemical and pollen-analytical changes in a 6 m core from the Petit Lac, the southern part of the Annecy basin. The rapidly accumulating calcareous marls span the past 2000 years. The most distinctive change in all parameters takes place at 3 m in sediments dating from the early-mediaeval period, *c.* 1300 AD. Local land-use history indicates that around this time, there was a phase of expanding human activity under monastic influence. The pollen record suggests that cultivated land and orchards expanded at the expense of forested land in the catchment, the chemical changes show an increased input of the main erosion indicators during this period and the mineral magnetic record includes a major increase in χ, χ_{fd} and SIRM as well as a decline in SIRM/χ. These mineral magnetic changes indicate both an increase in influx and a shift in mineral type towards the fine-grained assemblages typical of surface soil, as a result of erosion associated with the documented land-use change.

Section 10.6 as a whole illustrates the link between mineral magnetic variations and land-use change in various ways. In cases where bedrock completely dominates the magnetic mineralogy of the catchment (L. Neagh, L. Lomond, L. Fea), susceptibility and saturation remanence are related to deforestation and farming through the effect that these processes have on the supply of primary magnetic minerals to the sediment. The mechanism is strongly modulated by hydrological variables and their effect on particle transport. Where the vast majority of magnetic minerals available for erosion in a catchment are found in the surface soil (Lac d'Annecy) the mineral magnetic record is essentially a record of *soil* erosion in response to forest clearance and cultivation, and the magnetic properties can be used to confirm that secondary sources are dominant during episodes of intensive catchment disturbance by man. Commercial afforestation around Loch Frisa presents a special case in which, because of ditching for drainage before tree planting, magnetically distinctive subsoil is

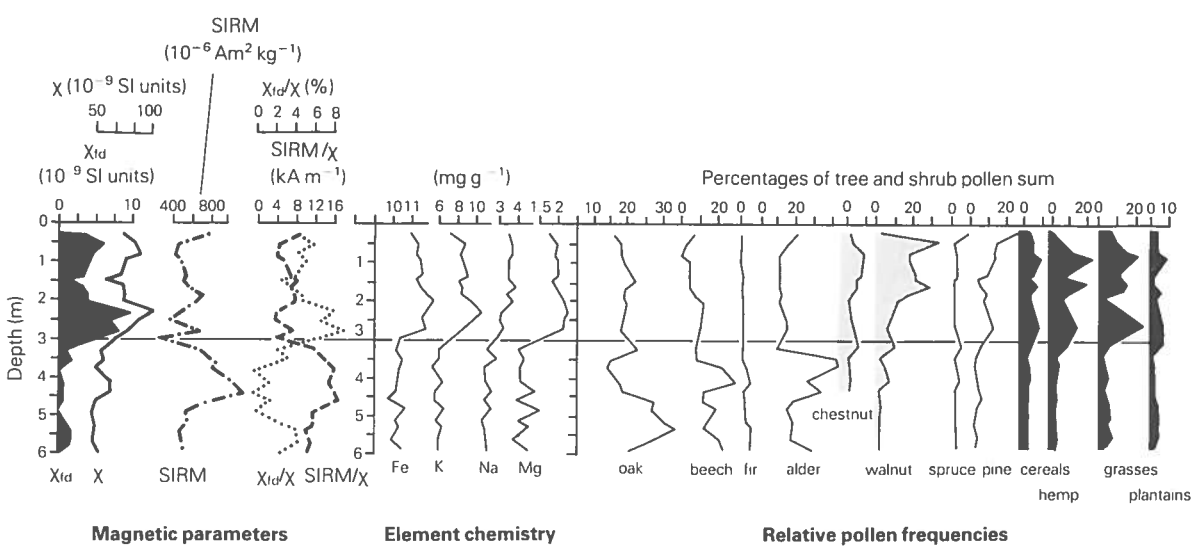

Figure 10.14 Mineral magnetic, chemical and pollen frequency data for a 6 m core from the Petit Lac d'Annecy (Higgitt, 1985). Note the major change in most parameters at *c.* 3 m (see text).

exposed to rapid erosion. The mineral magnetic parameters help to establish the spatial and temporal occurrence of this material and establish a source–sediment linkage characteristic of a specific kind of activity in the catchment. Comparison of these results with those emerging from continuing studies on an ever wider range of lithologies confirms that the scope for both quantifying and characterising erosion processes through mineral magnetic study is very large (cf. Dearing *et al.* 1985). However, its temporal limitations are worth noting. Since inferences of simple and direct source–sediment linkages assume that the magnetic properties used are conservative within the system, the timescales studied should always be much less than those on which the main magnetic mineral assemblage transformations are taking place in the catchment. Where this is not the case, more complex interpretative models will be required. In the next section a specific aspect of source–sediment linkage is considered, arising from the effects of fire on magnetic properties.

10.7 Magnetic measurements and fire

Many studies testify to the immense ecological significance of fire in a wide range of grassland, savannah and forest ecosystems. Not only do we find ample confirmation of man's widespread, sustained use of fire in hunting, forest clearance and land management from prehistoric times through to the present day, but we see, in many widespread ecological communities, such a complex and sensitive range of adaptations to fire incidence that it is clear that fire has been a major controlling factor in the development of many ecosystems. The impact of modern man on many fire-related communities has ranged from and often oscillated between protection and exacerbated risk. Consequently, the nature of the sustained fire–ecosystem interactions reflected in long-term population and community adaptations is difficult to reconstruct from present day observations and experiments. Nevertheless, long-term insights may be vital in formulating management and conservation policies, hence the ecologist's concern with the reconstruction of fire histories. At the same time some ecologists regard injudicious or excessive use of fire by man as a significant factor in accelerated nutrient loss from tropical and subtropical terrestrial ecosystems. Fire incidence and fire histories are also of interest in geomorphological studies. Intense fires which damage or destroy the cover of topsoil and vegetation may be important agents in accelerated erosion, especially where fire increases the exposure of surfaces to rain splash impact or strong winds. On a global scale, forest savannah and grassland fires are important processes affecting the balance, flux and storage states of carbon in the biosphere. From all these aspects, it is important to evaluate the contribution of magnetic measurements to the study of fire histories.

Fire gives rise to secondary magnetic minerals in the soil by converting paramagnetic or antiferromagnetic forms of iron to predominantly ferrimagnetic oxides (Section 8.4). The degree of conversion and hence the amount and type of magnetic mineral thus formed is related largely to the initial concentration of potentially convertible iron in the surface soil, the atmosphere during combustion and the maximum temperature reached. Field observation and laboratory experiments suggest that in most cases, enhancement of soil susceptibility begins between 100 °C and 200 °C, and peaks around 700–800 °C. It is usually greater in a reducing atmosphere such as may be created by the combustion of surface humus and litter layers.

LLYN BYCHAN

In August 1976 a ground and canopy fire on the northwestern edge of the Gwydyr forest area of North Wales destroyed the vegetation and severely damaged soil cover over a wide area including the western half of the Llyn Bychan catchment (Rummery *et al.* 1979). Bedrock comprises mostly slates and shales which are rich in iron but only weakly ferrimagnetic. Soil development is patchy and skeletal with many areas of exposed rock and scree interspersed with pockets of podsolic soils. On flat summits and in slope-foot situations, shallow peats and peaty gleys occur. As a result of the variation in soils, magnetic enhancement of erodable material during the fire proved to be localised. The sites most affected were well drained areas where podsolic soil development provided shallow readily combustible organic cover. As a result, strongly magnetic material formed at and immediately below the contact between the organic and inorganic soil horizons. Where still relatively organic, this was black in colour but where the organic material was completely ashed, the exposed soils were pink and highly susceptible. Curie temperature determinations and Mossbauer effect studies on magnetic extracts

from burnt soils indicated that the main mineral formed by the fire was impure non-stoichiometric magnetite (Longworth *et al.* 1979 and Ch. 8).

Sediment sampling at Llyn Bychan began 16 weeks after the fire. Of six cores taken, only one, from the deepest central point, was affected by the influx of post-fire magnetic minerals (Rummery *et al.* 1979). Measurements made on trapped material confirmed the subsequent consistently high χ and SIRM of the sediment retrieved during 1977 and 1978. Repeat coring in 1979, showed that by then, a larger area of the total lake bed was affected by fire-enhanced material.

The work so far completed at Llyn Bychan confirms a direct link between the forest fire in the catchment and a strong distinctive peak in χ and SIRM in sediment profiles. A rapid sediment response to the fire is indicated, with a time lag of less than 16 weeks between the fire and detection of enhanced material in the central sediments. The relative importance of different pathways from the burnt areas to the lake is considered by Rummery (1981) who suggests that surface wash and overland flow have significantly supplemented stream input.

MAGNETIC MEASUREMENTS AND FIRE HISTORIES

Demonstration that the recent fire in the Llyn Bychan catchment gave rise to distinctive magnetic properties in the surface sediment encouraged attempts to determine the extent to which magnetic measurements in lake sediments might provide an additional method for reconstructing fire histories.

At Llyn Goddionduon, lying only 1 km from Llyn Bychan, the grid of cores used in the correlation exercise (10.4) included many with high χ and SIRM values in the top 10–20 cm. The increase, dated by ^{137}Cs to *c.* 1954, was ascribed to the major fire of 1951 which destroyed much of the forest in the eastern half of the catchment, though recent ^{210}Pb measurements cast doubt on this.

In the Landes, SIRM profiles of cores taken from the Etangs de Biscarrosse and Sanguinet include peak SIRM values which ^{210}Pb and ^{137}Cs dating show to be contemporary with the massive forest fires of the 1940s culminating in 1949 (Rummery 1981). In each lake, Rummery established good agreement between SIRM peaks and other indicators of fire, including charcoal content and pine pollen breakage ratios (Fig. 10.15). The above examples relate to fires within the last few decades. The first attempt to apply magnetic measurements to much earlier fire history is part of a detailed multidisciplinary study of the laminated sediments of the Lake Laukunlampi in Finnish Karelia (Rummery 1983).

It seems probable that in many situations where lake sediments are available for studies of fire history,

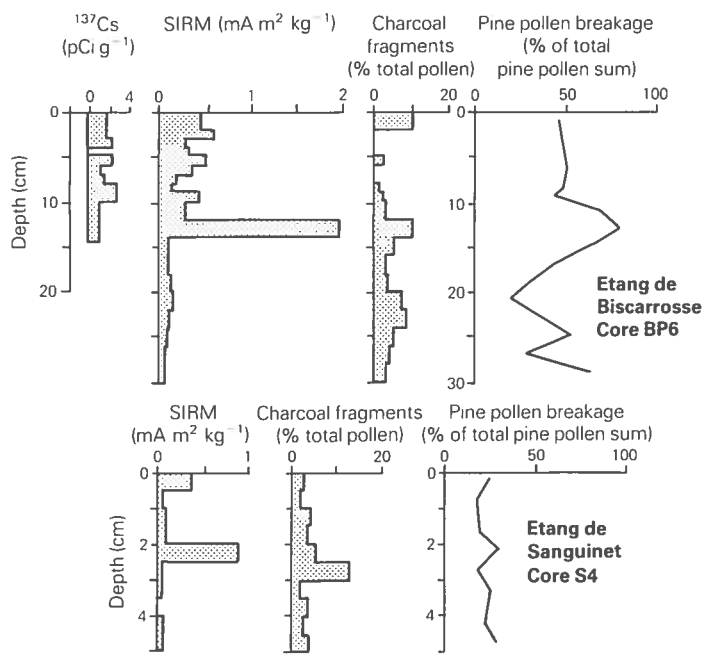

Figure 10.15 ^{137}Cs, SIRM, relative charcoal concentrations and pine pollen breakage ratios for cores from the Etang de Biscarrosse and the Etang de Sanguinet in the Landes area of south-west France (see Rummery 1981 and text).

magnetic measurements may be used to complement evidence from existing techniques such as charcoal counting. Their usefulness will depend on factors such as:

(a) *Fire location.* A fire within the lake catchment is much more likely to be recorded magnetically than one outside, since supply of minerals to the lake by streams and overland flow is likely to dominate airborne input in all but the most extreme circumstances. Magnetic minerals are thus likely to be more 'catchment specific' than charcoal fragments.

(b) *Fire type and intensity.* Intense fires affecting both ground and canopy, where the latter is present, are by far the most likely to be recorded. Fires in the canopy alone will give rise to few magnetic minerals and the low-intensity ground fires of great ecological importance in some conifer-dominated ecosystems are unlikely to give rise to high enough temperatures in surface mineral layers.

(c) *Soil and substrate type.* Where soils are very poor in iron, little fire enhancement can occur. The Landes study does however confirm that the impact on lake sediments is clearly detectable provided 'background' levels of χ and SIRM are consistently low. At the other extreme, where major sources of magnetic minerals already exist within the catchment, they may produce magnetic variations in the sediment sequence unrelated to fire.

From the above, it seems likely that magnetic measurements will contribute to fire history studies by making rapid preliminary surveys feasible and by adding insights on location, type and intensity, less readily deducible from other techniques.

10.8 Lake sediment magnetism and climatic change

Results from many sites suggest that major climatic shifts control weathering and sedimentation regimes in ways which give rise to distinctive mineral magnetic variations.

Oldfield *et al.* (1978) documented a very simple direct relationship between mineral magnetic and pollen-analytical changes in lake sediments from High Furlong, Blackpool, spanning the late-glacial and early-Holocene period from about 1400 to 9000 years BP (Hallam *et al.* 1973). The pollen-analytical subzones record a vegetation succession from grass-herb tundra through to birch woodland during the Windermere (Allerød) interstadial, the subsequent spread of dwarf shrub and herb communities during the Loch Lomond stadial around 11 000–10 000 years BP, and the spread of birch woodland at the opening of the Holocene. Magnetic susceptibility measurements are highest during the cold stadial episodes, decline to a minimum during the interstadial and rapidly fall to around zero at the opening of the Holocene. Episodes marked by poorly developed vegetation cover, soil instability and active solifluction give rise to peaks in χ; episodes of developing

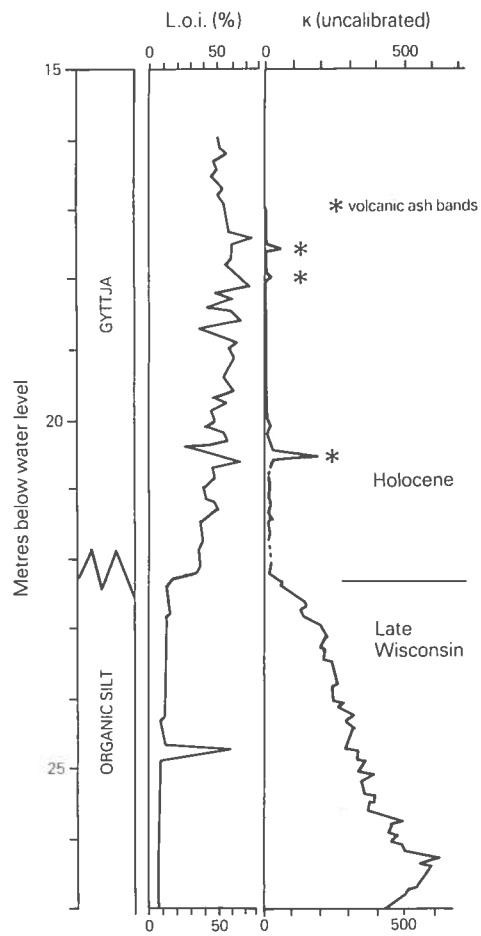

Figure 10.16 Whole core volume susceptibility and loss on ignition values for the late-Wisconsin and Holocene sediment of Battleground Lake, Washington State.

plant cover and soil maturation under milder climatic conditions give rise to minimum χ values.

Figure 10.16 plots volume susceptibility for a series of stratigraphically consecutive piston cores from Battleground Lake in southern Washington State (Oldfield *et al.* 1983a). The 12 m of sediment span late-Wisconsin and Holocene time, with a basal ^{14}C date of 14 840 ± 200 BP (QL-1539). The lake is in a closed crater basin with a small low-rimmed catchment in basalt. The major fall in susceptibility between 7.5 and 7 m clearly identifies the late-Wisconsin/Holocene boundary and reflects a diminution in allochthonous detrital input from the catchment with the development of more stable soils and complete vegetation cover (Oldfield *et al.* 1983a).

In both cases, the magnetic mineralogy reflects the course of climatic changes by recording evidence of the associated changes in sedimentation, weathering and pedogenic regimes.

Figure 10.17 plots coercivity of SIRM profiles for sets of samples from the sediments of Lynch's Crater, northeastern Queensland, Australia. The tropical soil profile discussed in Section 8.6 was collected from a river section close to Lynch's Crater. Whereas in

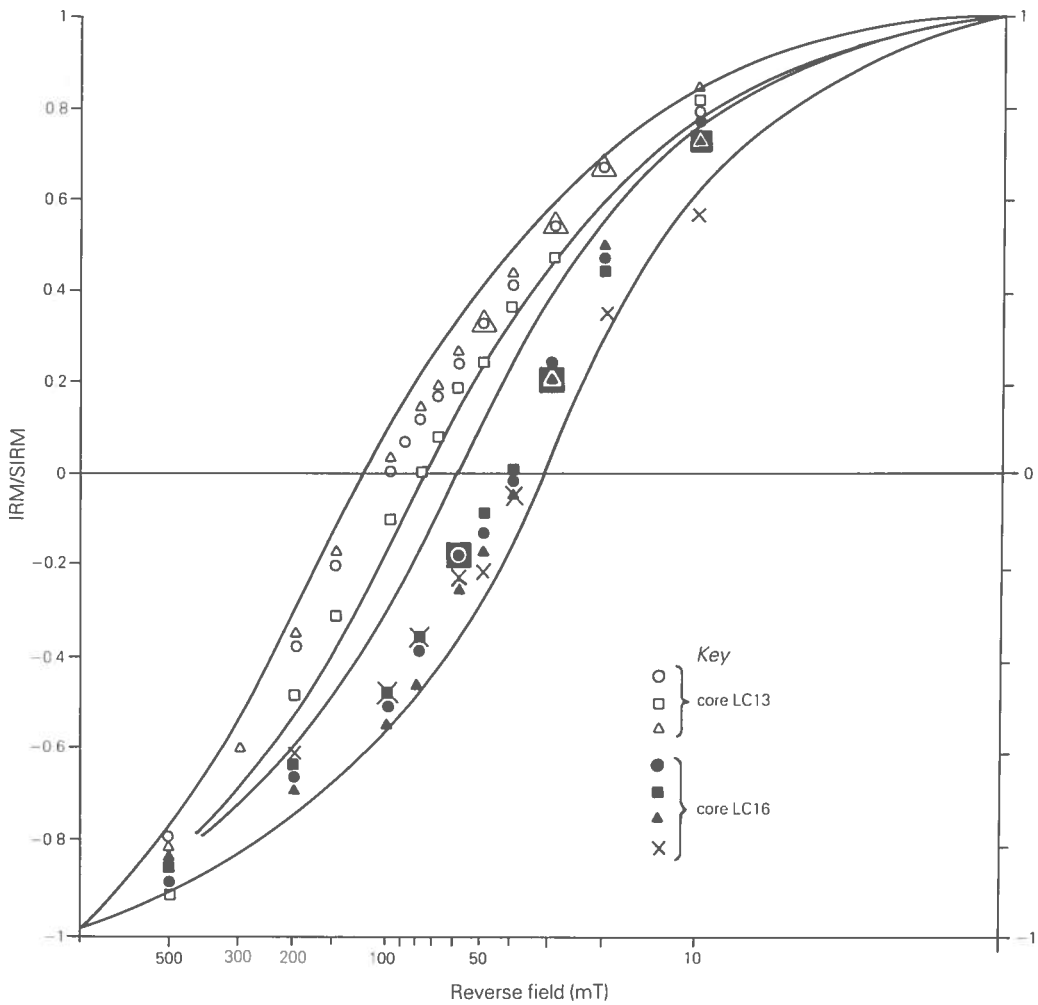

Figure 10.17 Coercivity of SIRM curves for groups of sediment samples from Lynch's Crater in northern Queensland (Kershaw 1978).

Figure 10.16 the parameter plotted is largely concentration dependent, here the values are normalised and hence not primarily a function of concentration. Virtually all the points lie within two quite separate envelopes of values, one for samples from Core section LC13, the other for samples from Core section LC16. For the LC13 samples $(B_0)_{CR}$ is just under 40 mT, but for the LC16 samples it lies between 70 and 110 mT. Core section 13 comes from Kershaw's (1978) pollen zone E1, Core section 16 from zone E2. In E1, pollen of complex vine forest taxa dominate the pollen record, and the mean annual rainfall suggested by the reconstructed vegetation type is a little in excess of contemporary rainfall at the site. In E2 higher pollen representation of scherophyll and gymnosperm elements suggests drier conditions than those prevailing at present. Here the *normalized* mineral magnetic parameters are related to palaeoclimate in ways which are not immediately apparent, though the linkage between the two persists for most of the very long 41 m deep sediment record at the site. In all probability, complex interactions between weathering, and hydrological and sedimentological regimes are involved.

From the above we may conclude that mineral magnetic measurements whether concentration dependent or not, can reflect palaeoclimatic conditions as a result of the effect that changing climate has on the environmental processes which control the concentrations and types of magnetic minerals deposited in lake sediments. A fuller discussion of these linkages is included in Oldfield and Robinson (1985).

10.9 Summary and conclusions

Mineral magnetic measurements can contribute to lake sediment studies in a wide variety of ways, ranging from initial core logging to the detailed analysis of sediment sources and sedimentological processes in the catchment or lake. The rôle of mineral magnetism in lake catchment studies and in palaeolimnology will vary with the main thrust of the investigation to be undertaken and with the nature of the lake-watershed ecosystem under study. The speed and versatility of the instrumentation now available coupled with the non-destructive nature of the measurements means that there are few areas of lake sediment based study to which this emerging methodology cannot fruitfully contribute. Further progress, as distinct from the pragmatic application of the approaches illustrated above to new sites, will depend on a closer and more quantitative specification of the implications of the measurements in terms both of sediment source (cf. Stott, 1986) and of magnetic grain size and mineralogy (cf. Parry 1965, Dankers 1978, King *et al.* 1982), especially where complex mixtures of natural magnetic oxides co-exist; on a more thorough appraisal of the relative significance of diagenetic, authigenic and bacteriological magnetic minerals in lake sediments; and on critical detailed studies relating magnetic parameters to sedimentological, granulometric and geochemical variables in a wider variety of lakes.

[11]
Magnetic minerals in the atmosphere

And Sheffield, smoke-involved; dim where she stands
Circled by lofty mountains, which condense
Her dark and spiral wreaths to drizzling rains,
Frequent and sullied.

W. G. Hoskins
Anna Seward as quoted in *The making of the English landscape*

I recall that Osvald, upon his first excursion into the South Pennine *'Eriophorum* moors' was staggered to find that his pale-grey flannel trousers (quite suitable for a Swedish trip) were soon generously striped with black soot collected from the stems and leaves of the vegetation; it was a sharp reminder of the influence of the industrial north.

H. Godwin 1981
Archives of the peat bogs

11.1 Introduction

Less is known about the presence of magnetic minerals in the atmosphere than about their presence in any other major environmental system. This is a function not only of the unfamiliarity of atmospheric scientists with the techniques of magnetic measurement appropriate to dust and aerosol studies, but also of severe problems involved in obtaining sufficiently large, uncontaminated samples representative of the full range of particle sizes present. The sections which follow identify particular themes and outline the very modest progress made so far in each case. No attempt at a comprehensive review of atmospheric magnetism is yet possible.

11.2 Sources of magnetic minerals in the atmosphere

The main sources of magnetic minerals in the present-day atmosphere are fourfold:

(a) *Volcanic eruptions.* Magnetic measurements of lake and marine sediments in volcanic areas show that tephra layers are often marked by peaks in magnetic susceptibility (e.g. Radhakrishnamurty *et al.* 1975, Oldfield *et al.* 1980, 1983b). This is especially the case with basic tephra rich in ferro-magnesium minerals. Volcanic dust makes a significant contribution to the total particulate content of the atmosphere

as a whole and makes a proportionally greater contribution to the stratosphere especially within the Junge aerosol layer at about 20–25 km. The long residence time of submicron particles in the stratosphere coupled with the high frequency of volcanic eruptions contributing both tropospheric and stratospheric dust ensures the persistence of a volcanic dust veil, the density of which is believed to have varied markedly through time. Viewed on a timescale of centuries, Lamb (1970) sees the period 1750–1900 AD as one of high dust veil in the Northern Hemisphere. On a much longer timescale, Kennett and Thunell (1975) see the past 2 million years of the Pleistocene as marked by a peak in explosive volcanism suggestive of a link between volcanic ash concentrations in the atmosphere and climatic change. Haggerty (1970) and others have suggested that volcanic dust is a major contributor to magnetic mineral assemblages in deep-sea sediments.

(b) *Wind erosion.* As noted in Chapter 8, surface soils are often strongly ferrimagnetic as a result of enhancement mechanisms such as fire which is also a major agent in wind erosion. Even in hot arid areas, where because of the paucity of organic matter both fire-induced and 'pedogenic' enhancement are rare, and in high latitude deserts and periglacial areas, where soil development is absent, fine material deflated from the surface will rarely be less magnetic than the underlying bedrock. Soil loss by wind erosion can be a byproduct of overexploitation of marginal land as in the American Dust Bowl of the 1930s and the more recent environmental crisis in the Sahel during the 1970s. At the present-day deflation of arid areas naturally susceptible to wind erosion thus combines with the effects of marginal tillage and fire use, especially in Savannah areas, to provide a second major source of magnetic particulates in the atmosphere. Chester (1978) has summarised the evidence for heavy dust-loadings in the lower atmosphere over the Atlantic as a result of terrestrial deflation, and many other authors (e.g. Windom 1969, Prospero 1968) have documented the abundance of 'soil'-derived dust in the lower atmosphere elsewhere both on land and over the sea. It is, however, difficult to tell how representative contemporary concentrations and distributions are of the long-term situation. Increased human pressure on soils over the past few decades will almost certainly have given rise to significant changes. Moreover, we know from loess deposits and the like that in the longer term the sequence and pattern of Pleistocene climatic change have been of great importance in controlling the exposure of fine surface materials to wind erosion and the atmospheric transport of deflation products.

(c) *Industrial and combustion processes.* Until recently the abundance of magnetic spherules in the

Table 11.1 Estimates of direct global particle production for potentially magnetic components. Based on Prospero (1978) Table X, and NRC report (1979) Table 2-1. All figures are 10^6 tonnes per annum.

Direct particle emission type	Peterson and Junge (1971)		Hidy and Brock (1971)	SMIC (1971)	Other authors	Reference
	all sizes	5 m		20 m		
man-made	133.2	29.6	36.8–110	10–90	54	(1)
					126	(2)
windblown dust (soil and rock debris)	500	250	60–360	100–500	60–360	(3)
					128± 64	(4)
					200±100	(4)
forest fires and slash and burn debris	35	5	146	3–150		
volcanic emissions		25	4	25–150	4.2	(5)
meteoric debris	10	0	0.02–0.2		0.02–0.2	(6)
					1–10	(7)

* (1) Goldberg (1975); (2) Ellsaesser (1975; (3) Judson (1968); (4) Joseph *et al.* (1973); (5) Mitchell (1970); (6)Bhandari *et al.* (1968); (7) Rosen (1969).

atmosphere was ascribed to the cosmic flux of extraterrestrial particles. We know now that most spherules are the product of human activities such as fossil (especially solid fuel) combustion, metal smelting and iron and steel manufacture. The increase in spherule concentrations since the beginning of the industrial revolution is the theme of Section 5 in this chapter.

(d) *Extraterrestrial particles.* In light of the above, we may expect this source to be of significance only very locally in association with meteorites, and in those areas most remote from any form of terrigenous input such as the Central Pacific. In terms of the contemporary atmosphere and of the historical record of atmospheric particulates considered in this chapter, cosmic spherules can be ignored (but see Ch. 12).

Table 11.1 summarises various estimates of the relative importance of these sources.

11.3 Magnetic properties and aerosol modes

Atmospheric aerosols have rarely been examined with regard to their magnetic properties. Even where magnetic separation techniques have been used to differentiate between emission categories (e.g. Hansen *et al.* 1981, Linton *et al.* 1980, 1981) no subsequent magnetic measurements have been carried out to test the efficiency of the magnetic separation. Attempts to characterise more fully the mineral magnetic properties of the separated fraction are also very rare (e.g. Chaddha & Seehra 1982). In consequence, it is not yet possible to provide reliable information on the relationship between magnetic properties and atmospheric particle modes for the range of aerosol types which include a magnetic component. Such direct determinations as are available relate only to restricted samples of power station fly-ash and roadside material and these are summarised in Section 11.6. Whitby and Cantrell's (1976) scheme suggests that virtually all the magnetic material generated by the mechanisms outlined above will be within the 'coarse particle' range from *c.* 2 μm diameter upwards. In the case of urban and industrial particulates, this is consistent with all the measurements on magnetic spherules made by Puffer *et al.* (1980) in the New York area and over the nearby parts of the N. Atlantic, as well as with studies of coal fly-ash by Hansen *et al.* (1981) and Ondov *et al.* (1979), who record insignificant amounts of magnetic iron in particle sizes below 2.2 μm and 1.6 μm respectively. Keyser *et al.* (1978) also show that auto-exhaust particles above 10 μm are rich in iron, but that the finer particle mode <1 μm contains little or no iron. At the same time it is important to note that total iron is often poorly correlated with χ and SIRM (e.g. Thompson *et al.* 1975). Consequently, until more critical magnetic measurements have been carried out on size-fractioned material, the results are inconclusive. In terms of health implications, the main concern is usually with fine particles, partly because deposition efficiency in the pulmonary and trachaeo-bronchial tracts increases with declining particle diameter and partly because some of the main toxic metals discharged for example in coal-fired fly-ash (Davidson *et al.* 1974) are enriched in the fine fractions.

11.4 Magnetic–heavy metal linkages

Although the relationship between magnetic oxides and heavy metals in fly-ash, industrial particulates and auto-emissions is poorly understood, several authors point to the possibility of close links. Theis and Wirth (1977) note that most metals in the eleven coal-fired fly-ash samples they considered were associated with specific surface oxides of iron, manganese or aluminium. Copper, chromium, arsenic and zinc they record as being associated with iron oxides in almost all cases, cadmium and nickel mostly with manganese, and finally, lead with either. Hansen *et al.* (1981) show that chromium, manganese, cobalt, nickel, copper, zinc and beryllium are all significantly enriched in the 'magnetic' fraction of coal fly-ash. Linton *et al.* (1980) and Olson and Skogerboe (1975) note an association between 'magnetic iron' and lead in automobile-exhaust particulates sampled on roadways. Hansen *et al.* (1981) suggest that 'magnetite may also be a hazard to health because of its ability to occlude biologically active transition metal ions such as Mn and Ni by isomorphous substitution . . . and thus act as a slow release carrier agent for toxic elements'. Lauf *et al.* (1982) have suggested that magnetic spherules generated during coal combustion may be derived directly from the conversion of pyrite framboids present in the coal. They also note that the

framboids are associated with trace metal enrichment. Hulett *et al.* (1981) who identify the magnetic component in their fly-ashes as predominantly an aluminium-substituted ferrite ($Fe_{2.3}Al_{0.7}O_4$), suggest that trace elements occur as substitutions in the spinel structure. They record enrichment factors between 10 and 50 times for first-row transition elements (V, Cr, Mn, Co, Ni and Zn) in the magnetic phase of their samples. Thus despite many gaps in our knowledge and great uncertainty about the extent to which demonstrated magnetic–heavy metal linkages reflect surface association or incorporation into the crystalline matrix of particulate emissions, it is nevertheless reasonable to explore contexts in which, in purely empirical terms, the linkage appears to occur or in which, the linkage would, if confirmed by further studies, be of major value in both historical and contemporary particulate pollution monitoring.

11.5 Peat magnetism and the history of atmospheric particulate deposition

Ombrotrophic peat bogs are those built up above the ground water table so that their surfaces of deposition and accumulation are no longer influenced by inflowing drainage. As they accumulate they often preserve a record of atmospheric deposition. Here we are primarily concerned with the magnetic record in the peat, and its value in reconstructing the history of and spatial variations in particulate pollution.

The concentrations of magnetic minerals in peats, ice and snow are usually much less than in most of the lacustrine, soil and fluvial samples discussed in the previous three chapters. As a consequence, for all but the 'dirtiest' samples, mineral magnetic characterisation must often be restricted to the most sensitive

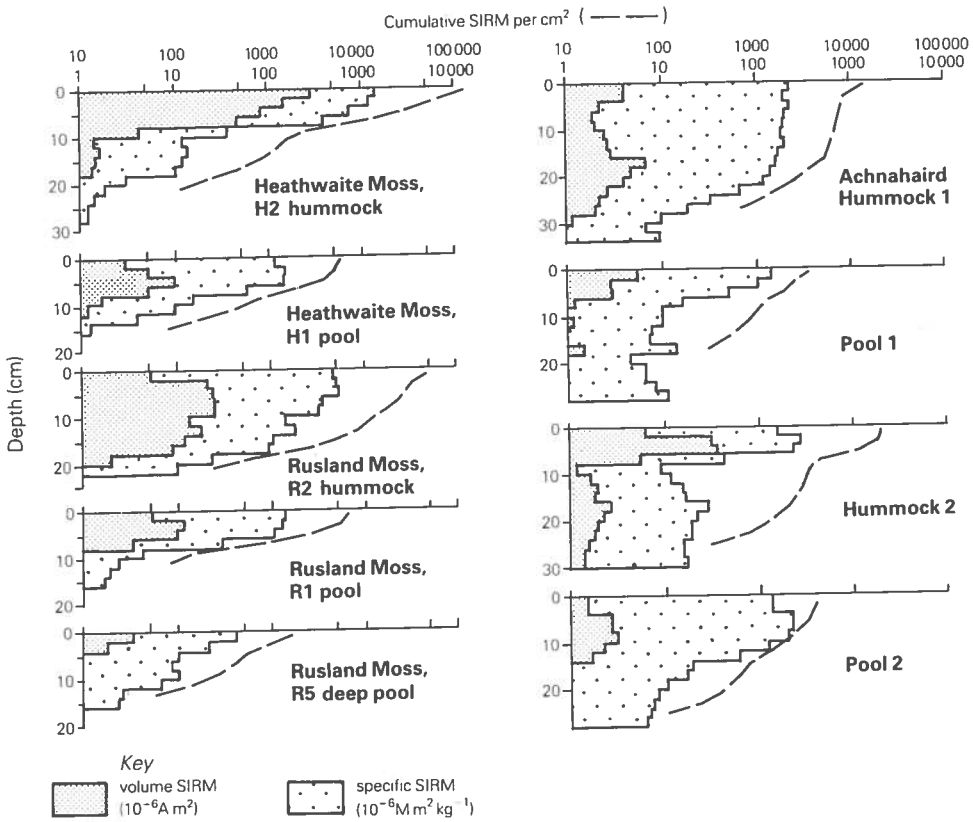

Figure 11.1 Magnetic deposition recorded in recent ombrotrophic peat at two sites to the south of the English Lake District (Heathwaite and Rusland Moss) and four profiles from the remote Achnahaird peninsula in north-west Scotland. The histograms plot SIRM values on a volume- and mass-specific basis, the dashed lines are cumulative totals for each core.

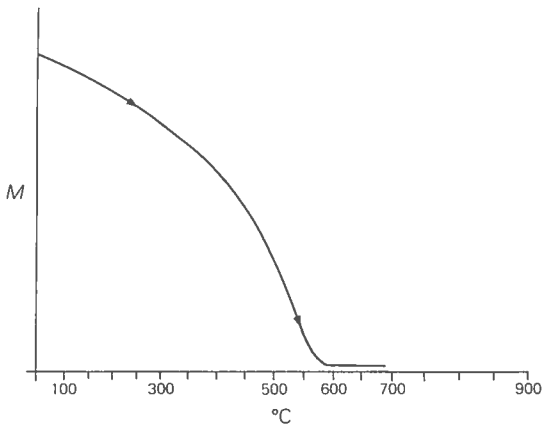

Figure 11.2 High-field Curie temperature determination for a magnetic extract from the upper 6 cm of Ringinglow Bog (see Fig. 11.12), near Sheffield, England. The results identify the dominant magnetic mineral in the extract as magnetite.

techniques of isothermal remanence and back-field ratio measurements.

Figure 11.1 shows the SIRM record in shallow, recent peat profiles from Heathwaite and Rusland Moss, which lie between the English Lake District and the heavily industrialised areas of Lancashire, and from the Achnahaird peninsula on the northwestern coast of Scotland, very remote from urban settlements and industrial activity. In all the profiles, SIRM increases upwards and invariably peaks in the top 2–6 cm. Peak values are an order of magnitude or more higher than the minima near the base of each profile. These increases have been interpreted (Oldfield *et al.* 1978) as a record of the deposition of magnetic spherules discharged into the atmosphere as a result of fossil-fuel combustion and heavy industry. Mineral magnetic parameters in these most recent peats vary relatively little from site to site in Britain and are all consistent with an assemblage dominated by magnetite (Fig. 11.2, and cf. Hansen *et al.* 1981, Chaddha & Seehra 1982). If we take SIRM as a crude index of the volume of ferrimagnetic spherules deposited, then from the cumulative totals plotted against each profile, variations in mean flux density can be seen on three spatial scales. The southern Lake District sites as a whole have trapped, on average, between four and five times as much as the Achnahaird sites. Within the southern Lake District sites, Heathwaite which lies directly down wind of the Millom Steel Works has trapped almost twice as much as Rusland. However, at each site there is an even greater contrast when we compare hummock and pool deposition totals.

In the southern Lake District, hummock profiles contain 10–100 times more spherules than do pools. In Achnahaird, although the contrast is less marked, it is nevertheless consistently present. The difference has been interpreted as the effect of hummock vegetation filtering out particulates moving subhorizontally across the bog surface by dry eddy diffusion (Oldfield *et al.* 1979b) though it is possible that under some circumstances, magnetite dissolution below the water table may contribute to the contrast. From published evidence (National Academy of Sciences 1979) we would expect washout by rain to dominate 'pool' deposition and filtering from eddy diffusion to dominate hummock deposition. Washout is relatively

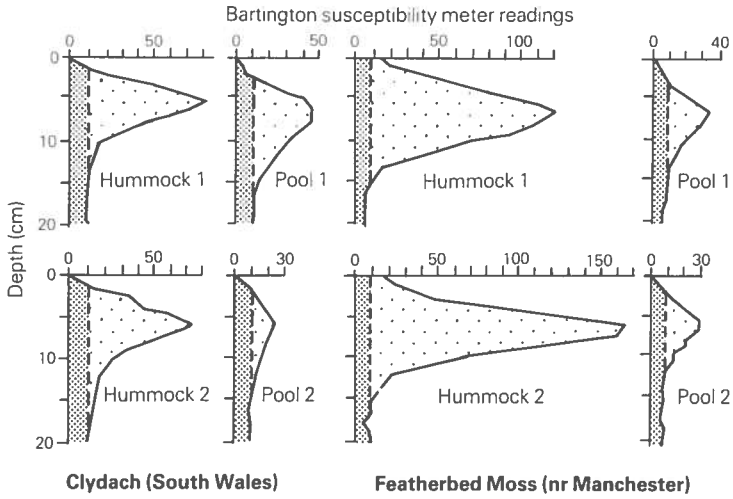

Figure 11.3 Characteristic drainpipe scans of the volume susceptibility of recent British ombrotrophic peats using the Bartington core loop sensor. The Clydach site is in South Wales, Featherbed Moss is in the south-west Pennines some 15 km down wind of Manchester. In all cores, the pre-industrial levels record low and relatively constant deposition. Above this, the contrast in total deposition between pools and hummocks is evident. Total cumulative 'industrial' fall out at each site is estimated by calculating the approximate area of the lightly stippled part of each core trace.

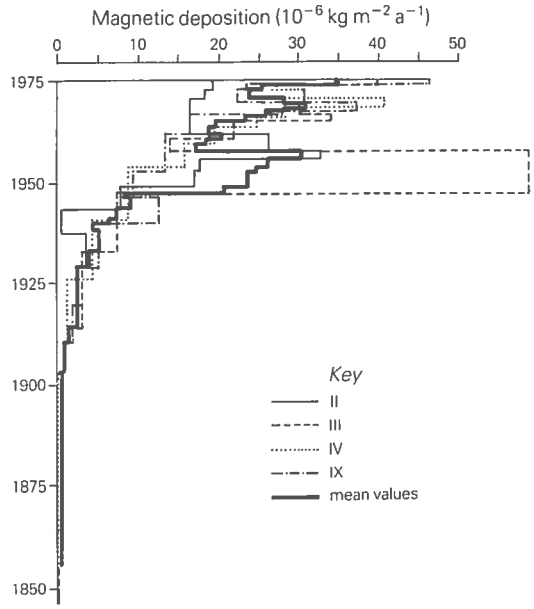

Figure 11.4 Magnetic deposition at Karpansuo Bog, south-central Finland. Dates have been determined by moss increment counting and SIRM values have been used to estimate the annual deposition of magnetite at the site since 1840 AD (see Oldfield *et al.* 1981b).

effective only for the finest and for the very coarse particles. As starting points for further study, these profiles pose a series of interesting challenges and opportunities.

Given the link between magnetic deposition and industrialisation and the relative speed with which measurement can be made, the method holds out some promise of allowing its use as a surrogate particulate pollution monitoring technique, not only historically, but also in terms of both cumulative and contemporary deposition. Significant questions and problems are evident at the outset. Peat chronology for the past 200 years is very poorly known in Britain. The link at source between spherule discharge and both heavy metal and sulphate generation may not persist through transport and deposition. Spatial patterns of variation on a regional or continental scale may be masked by the variations arising from bog micro-topography. Such progress as has been made in appraising these problems is outlined below.

In most British peat bogs the point at which presumably pre-industrial values begin to increase lies in the top 25–30 cm of the profile. This has permitted development of a rapid and convenient method for identifying the industrial 'magnetic take-off point' in relatively polluted sites and for calculating cumulative deposition per unit surface area above this. Plastic drainpipes pushed into the peat and then dug out can be scanned using the Bartington whole core sensor (Fig. 11.3). This permits rapid estimation through multiple coring and, where desirable, on-site measurement. In practice, scans from two hummocks and two pools at a given site have been used to compensate for microtopographic variation and provide an estimate of mean cumulative deposition for each locality.

Problems of chronology have so far proved rather intractable in the British context. Critical evaluation of ^{210}Pb dating in ombrotrophic peats (Oldfield *et al.* 1979a) suggests that it is not invariably reliable. However, the synchroneity of recent magnetic increases within and between sites has been confirmed by pollen-analytical study at six sites (Hughes, 1978, Richardson 1984 & 1986). Moreover the evidence from Ringinglow Bog near Sheffield shows that the dramatic rise in magnetic deposition at that site coincides with the sharp change from *Sphagnum imbricatum* to *Eriophorum vaginatum* peat believed to reflect the effects of 19th century atmospheric pollution and especially the increased concentrations of atmospheric SO_2 associated with fossil-fuel combustion.

Only in areas where, as a result of more continental

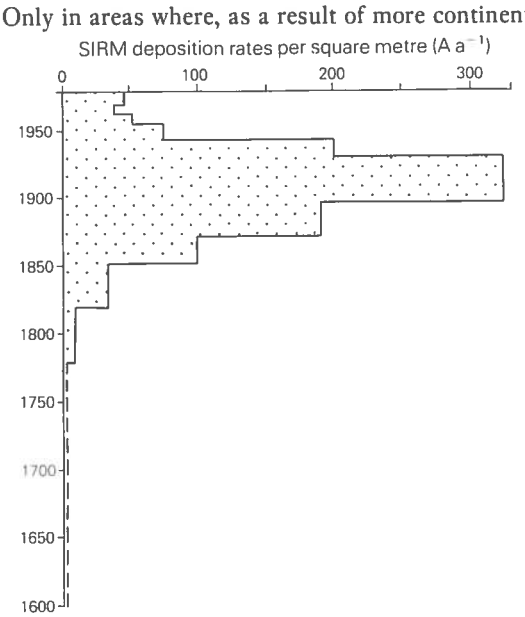

Figure 11.5 Magnetic deposition at Regent Street Bog, Fredericton, New Brunswick. The timescale has been determined from moss increment counts and bulk density calculations by K. Tolonen. The decline in SIRM deposition since World War 2 is characteristic of many north eastern North American sites.

climatic conditions, annual moss-increments can be identified and counted, has a satisfactory chronology been available. Under these circumstances magnetic deposition can be plotted in terms of both concentration and flux density versus time. Figure 11.4 shows that at Karpansuo Bog, a rather remote site in Central Finland, increased deposition begins in the mid-19th century, rises more steeply in the 20th and peaks in the past 30 years. This mirrors the late spread of heavy industry to southern Finland during the post-war period. At Regent Street Bog, near Fredericton New Brunswick (Fig. 11.5), the increase begins earlier and the post-war period shows a steep decline. This is probably primarily an expression of the history of the local iron and steel industry which it parallels with remarkable accuracy (Tolonen & Oldfield, 1986).

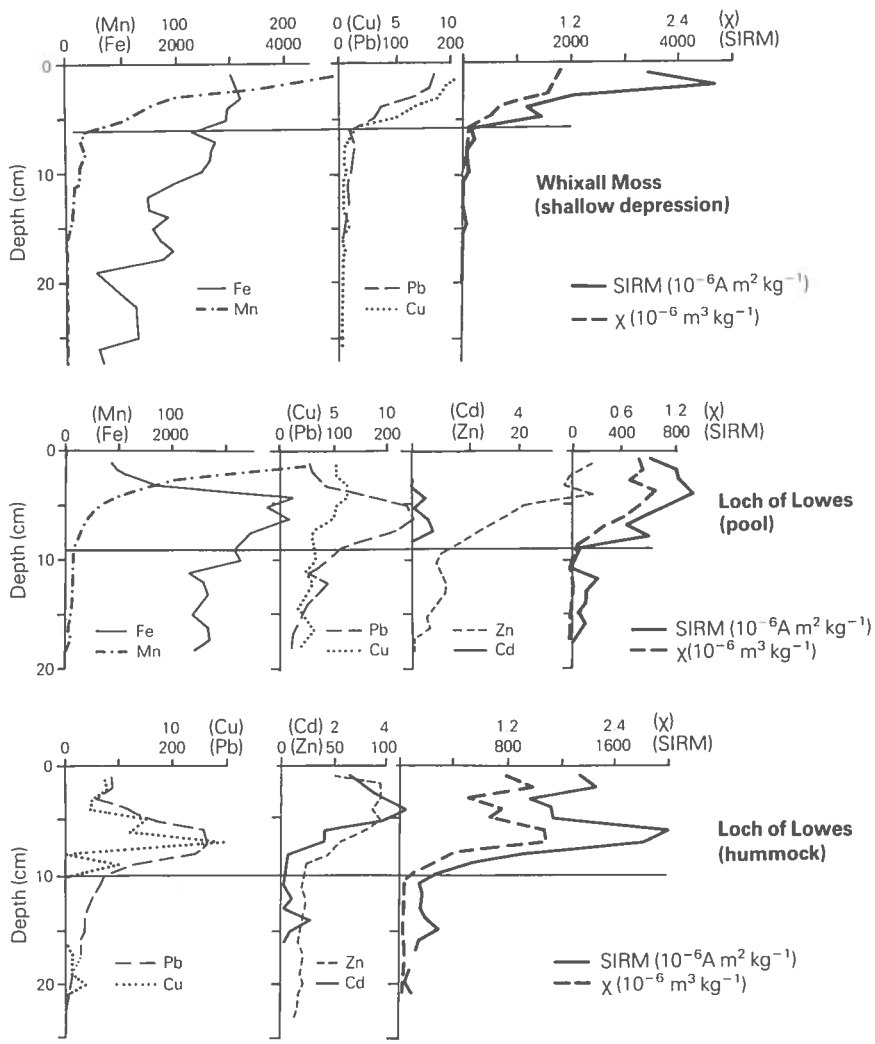

Figure 11.6 The stratigraphic record of heavy metal element concentrations in recent ombrotrophic peat from two British sites compared with χ and SIRM measurements. Whixhall Moss is in Shropshire, England. The location of the Lowes site is between Dunkeld and Blairgowrie close to the south-eastern edge of the Scottish Highlands. The horizon of rapid increase is synchronous between these metals and the χ and SIRM curves. The data have been provided by J. M. Jones.

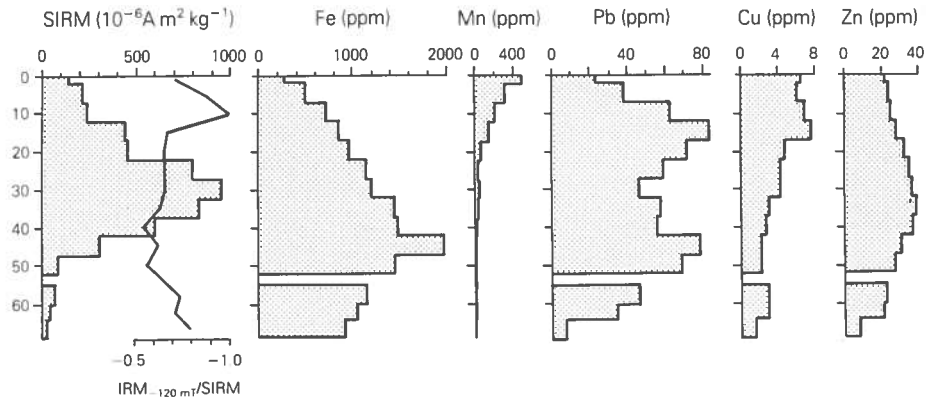

Figure 11.7 SIRM and IRM$_{-120mT}$/SIRM plotted against heavy metal element concentrations for a core from a hummock of ombrotrophic peat at Regent Street Bog, Fredericton, New Brunswick (Fig. 11.5). Compare the lack of synchronism between the increases in SIRM values and in the concentrations of Pb, Cu and Zn, with the British results plotted in 11.6.

The possible link between magnetic and heavy metal deposition has been examined both stratigraphically and spatially. Oldfield *et al.* (1981b) record such a link in a series of peat profiles taken from west to east across Finland. From the Harparliltrasket site in the west, close to the power station and heavy industry, to the remote sites of Karelia in the east, close to the Russian border, there is, in each profile, a clear parallel between magnetic and total iron deposition in the post-war period. Moreover the proportion of total iron accounted for by magnetic deposition declines from west to east with increasing distance from industrial sources (see Oldfield *et al.* 1981b). In British peats, comparisons between the stratigraphic records of SIRM or χ and copper, lead and zinc deposition show a strong similarity (Fig. 11.6), suggesting that after more detailed study, χ and SIRM may be used realistically as surrogate measurements for reconstructing the history of deposition of these elements in the peat. By contrast in N. American and in continental sites where the chronology is more readily resolvable, the levels in the peat at which the heavy metal concentrations increase, lie almost invariably well below the magnetic 'take-off' (Fig. 11.7). Critical factors in the contrast may be the relatively more open 'fluffy' character of the *Sphagnum fuscum/Polytrichum* hummocks from which the North American and continental evidence comes, as well as the much greater seasonal water level fluctuations experienced at these sites. Both factors would be conducive to greater vertical mobility of soluble metals in the peat column. Significantly, Aaby *et al.* (1979) report a convincing stratigraphic record of lead deposition in the pool site at Draved in Denmark, but a much less satisfactory record in the hummock. At the very least, magnetic measurements in recent peat will often provide an early industrial marker horizon, as well as a stratigraphic record against which to compare that of the heavy metals when questions of their mobility in the peat column are considered.

Figure 11.8 summarises an exercise designed to compare cumulative magnetic and heavy metal deposition as they have varied spatially from very heavily to lightly polluted areas in Britain. Paired hummock and pool 'drainpipe' cores from each site were volume susceptibility scanned and the top 8 cm

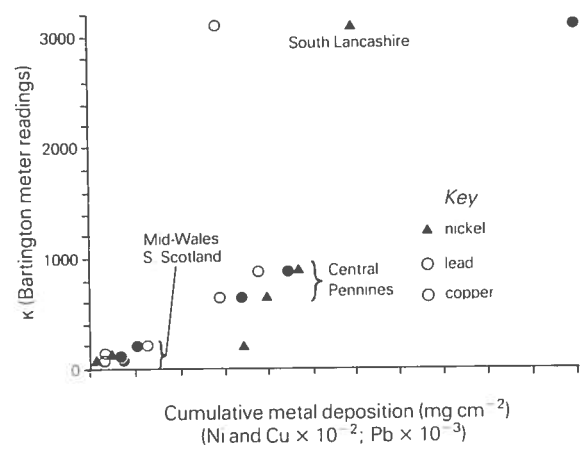

Figure 11.8 Cumulative metal and magnetic deposition at six British sites ranging from S. Scotland to S. Lancashire using the methods outlined in the text (Section 11.5).

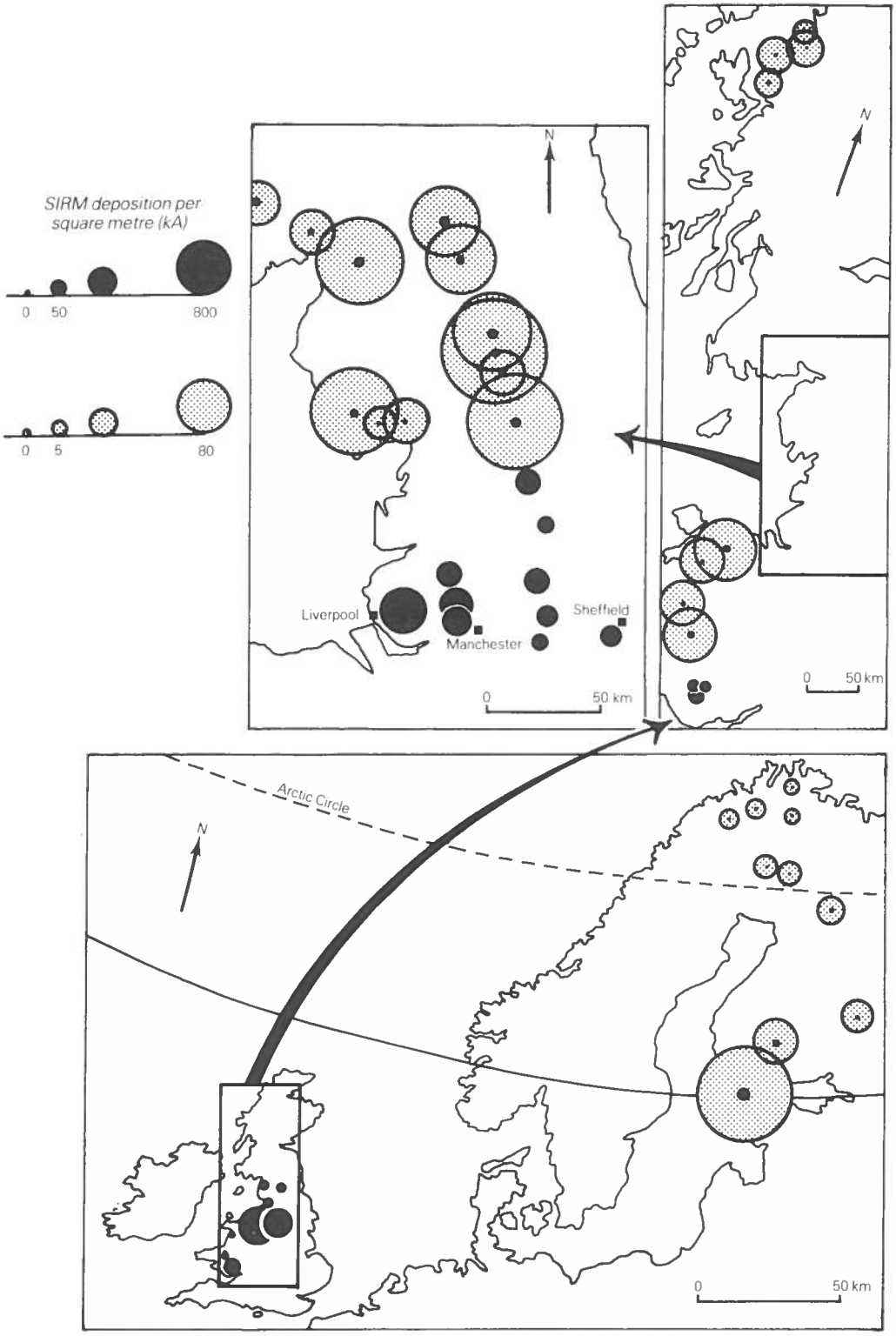

Figure 11.9 Cumulative 'industrial' magnetic deposition for British and Finnish ombrotrophic peat sites. The figures have been calculated from Bartington loop scans (cf. Fig. 11.3), single-sample SIRM measurements (cf. Fig. 11.1) and accumulated flux values (cf. Figs 11.4 & 5).

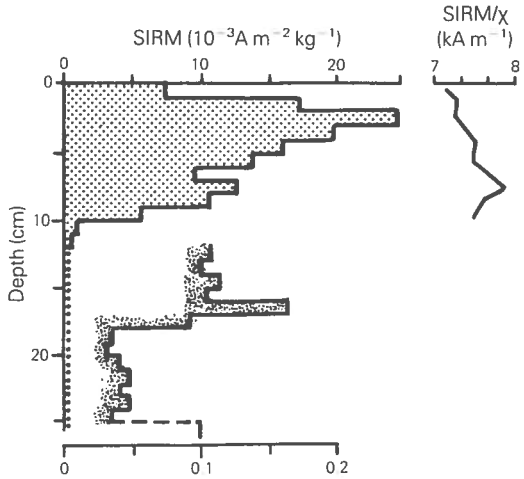

Figure 11.10 Magnetic deposition at Ely Lake Bog close to the Mesabi iron range in N. Minnesota. The profile records an initial increase at 18 cm depth coinciding with the first phase of exploitation and a later major increase at 8–10 cm. SIRM/χ tends to decline in the top 10 cm. This is one of six measured cores taken by E. Gorham.

of each sliced for heavy metal determinations on replicates at 2 cm intervals using a 'total' extraction technique (Mackereth 1969). Each co-ordinated point represents the mean of 40 susceptibility whole core readings and 16 element concentration determinations at each site. Over 80% of the points show a strong linear relationship and in the case of copper the correlation is very strong across the full range of variation.

In the light of all the above evidence SIRM measurements were carried out on samples from moss-increment dated cores from Finnish and Norwegian Lapland and these also show patterns of increased magnetic deposition, less strong than but closely parallel to the patterns from further south in Finland. Even in these remote areas the post-war period has been marked by a sharp increase in the flux density of magnetic particles. By calculating post-'magnetic take-off' cumulative deposition per cm^2 for all the sites studied so far it has been possible to compile Figure 11.9. From this we see that the Lancashire Plain in north-west Britain has the highest level of recent magnetic deposition while at the 'cleanest' end of the scale the far north-west of Scotland and the remotest sites in Finnish Lapland have values two orders of magnitude lower. Although this pattern must be subject to many sources of error, arising from soil contributions in remote areas, from regional variations in bog microtopography and from the imperfections of SIRM values as a basis for estimating ferrimagnetic volumes, it provides a useful first insight into spatial variations in cumulative deposition which now require a great deal of more detailed study.

In both stratigraphic and spatial terms the patterns of variation in eastern and central North America appear to be rather different. As at the Fredericton site (Fig. 11.5), most profiles show a sharp decline in concentration towards the surface. Where, as in several moss-increment dated profiles from Nova Scotia (Tolonen, pers. comm.) chronological control is available, it is clear that this reflects a real decline in flux density, and it is tempting to see it as a possible effect of the greater American dependence on oil as against solid fuels over the last few decades (cf. Henry & Knapp 1980). Spatial variations in cumulative deposition at the sites studied so far seem dominated by 'point' sources such as the Mesabi iron range, and the Sudbury nickel smelting complex. Sharp increases in magnetic deposition within the peat profiles near each site give good chronological markers, and in both quantitative and qualitative terms, distance decay effects can be clearly seen in the magnetic measurements (Figs 11.10 & 11.11).

At all sites, whether from Europe or North America, it is clear that there are significant and readily measurable mineral magnetic variations below the main industrial 'take-off' horizon (Fig. 11.12). Moreover, the levels immediately below often have higher susceptibility and SIRM than do ombrotrophic peats of earlier historical or prehistoric age. Much work remains to be done to determine whether these variations are natural or anthropogenic, and to explore their possible implications in terms of palaeoclimates and human activity.

The foregoing account touches on many ways in which the mineral magnetic record in peat may be of value. Having set out in brief and with only a modest amount of critical evaluation the full range of possibilities so far considered, a great deal of detailed work lies ahead in the evaluation of any single aspect.

11.6 Contemporary particulate pollution monitoring

One of the most attractive possibilities opened up by the magnetic measurement of atmospheric samples is in the area of contemporary particulate pollution

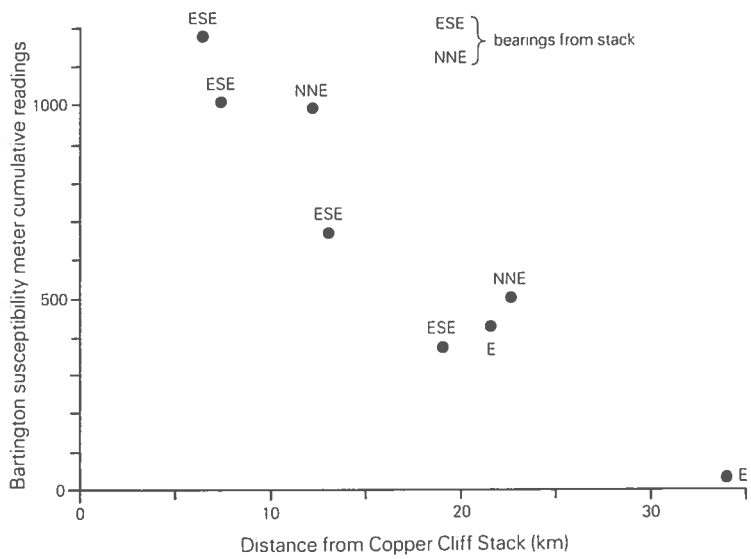

Figure 11.11 Cumulative magnetic deposition calculated from drainpipe scans of shallow peat profiles in the Sudbury region of Ontario. Volume susceptibility readings calculated in the way illustrated in Figure 11.3 are plotted against distance from the major point source. For each site two profiles have been used to give a mean value as plotted, and the approximate bearings from the main smelter are shown against each point.

monitoring. Table 11.2 and Figure 11.13 provide some preliminary results obtained in Britain by measuring material trapped using a high volume (HI-VOL) air sampler. One data set refers to measurements on fly-ash from Hams Hall power station near Birmingham, the other to measurements obtained on filters exposed for periods of 12–18 hours in the two road tunnels under the Mersey, linking Liverpool with the Wirral peninsula to the south-west (see Hunt *et al.* 1983). These latter measurements are therefore believed to reflect mostly particulate vehicle emissions. The hysteresis ratio and coercivity parameters suggest that both magnetic mineral assemblages are dominated by magnetite with a proportionally higher haematite contribution in the fly-ash. There is also relatively little relationship between particle size and mineral magnetic parameters, especially between 1 and 7 μm, suggesting that in all but the coarsest spherules the mineralogical and domain size assemblages vary little and are independent of granulometry. Where heavy metal/magnetic ratios have been determined, these also often appear to be relatively constant for each source over the same range of particle sizes, though appraisal of a larger data set certainly confirms wide variations in element concentrations and ratios between coal-fired fly-ash

Table 11.2 Mineral magnetic parameters and SIRM/heavy metal ratios for fly-ash and roadside particulates. All samples are particle-size fractions obtained by a HI-VOL air sampler. The fly-ash was resuspended in the laboratory and for these samples the SIRM element ratios are relative. In the case of the roadside particulates the magnetic concentrations were too low for χ and ARM measurements. (Hunt, pers. comm.)

		ARM	SIRM	SIRM/ARM	$(B_0)_{CR}$ (mT)	$IRM_{-100\,mT}$/SIRM	SIRM/Fe	SIRM/Mn	SIRM/Al	SIRM/Pb	SIRM/Zn	SIRM/Cu
Ham's Hall fly ash	1	0.04	19	525	40	−0.63	—	—	—	—	—	—
	2	0.04	17	422	42	−0.53	0.19	9	—	10	1.6	121
	3	0.04	16	354	42	−0.55	0.18	8	—	9.5	1.3	133
	4	0.04	15	341	42	−0.52	0.19	6	—	7	0.9	104
Birkenhead tunnel 8/6/82	1	—	—	—	—	—	0.44	10.4	0.83	2.3	9.0	80
	2	—	—	—	—	—	0.42	15.1	0.84	1.3	8.2	39
	3	—	—	—	—	—	0.27	12.2	1.11	0.4	4.6	23
	4	—	—	—			0.39	14.6	1.32	0.6	3.0	29
Wallasey tunnel 20/7/82	1	—	—	—	—	—	0.49	16.1	1.3	9.9	16.3	86
	2	—	—	—	—	—	0.42	19.4	2.0	6.5	14.8	56
	3	—	—	—	—	—	0.34	28.5	1.6	14.3	9.5	24
	4	—	—	—	—	—	0.44	—	3.6	0.6	8.6	26

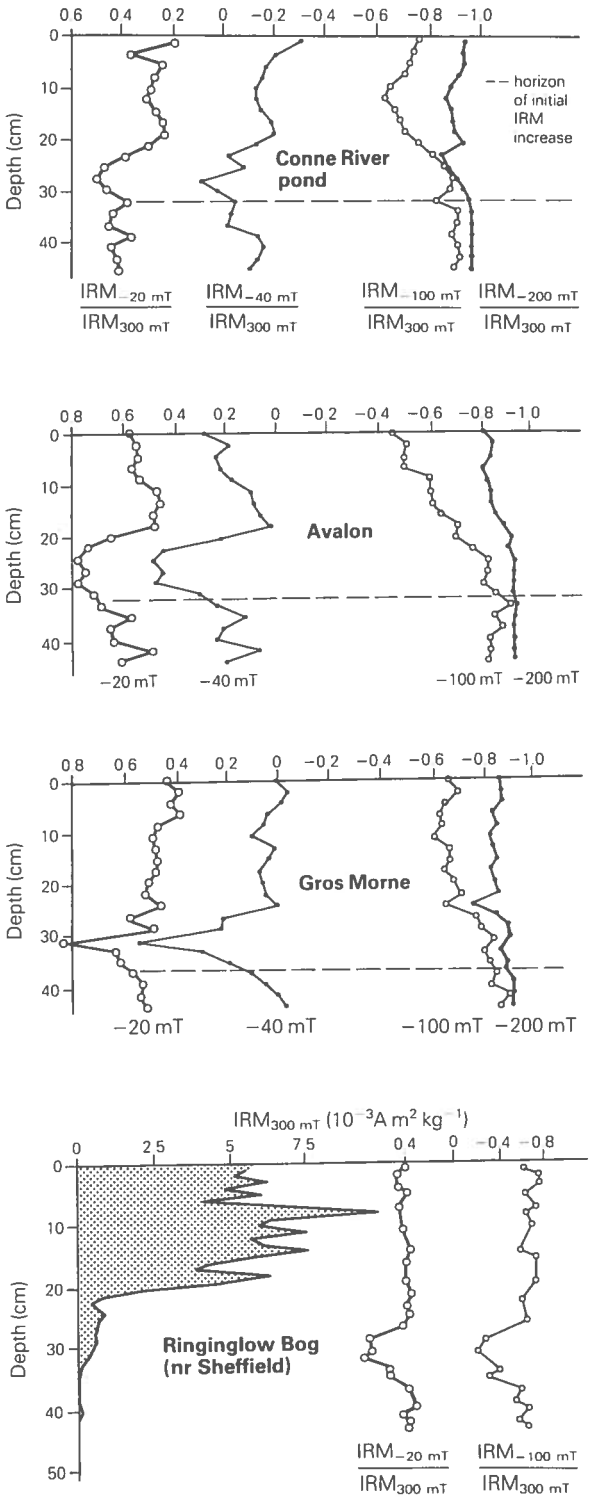

Figure 11.12 Parallel changes in IRM/IRM$_{300mT}$ plots are shown for three peat profiles from different Newfoundland sites. In each case, low reverse field values indicate 'harder' IRMs around the time of the earliest magnetic increases. The high reverse field values also show parallel trends from site to site above this level. At Ringinglow Bog (see Fig. 11.2) the IRM/SIRM values identify a zone of relatively 'hard' IRM coinciding approximately with the first SIRM increase. Newfoundland samples supplied by E. Gorham; Ringinglow Bog data supplied by J. M. Jones.

samples of different source (Furr *et al.* 1977), as well as between these and the particulates derived from vehicle emissions (National Academy of Sciences 1979). Moreover oil-fired fly-ashes, contain on average, over an order of magnitude less iron than do the coal-fired ashes (Henry & Knapp 1980).

Provided these initial results are not unrepresentative of locations where coal-fired power generation and automobile emissions are the main sources of heavy metals and magnetic minerals, and bearing in mind both the temporal and spatial mineral magnetic–heavy metal linkages outlined in Section 11.5, and the urban stormwater and near-shore marine data summarised in Chapters 9 and 12, magnetic monitoring would appear to be feasible and to have potentially important implications.

In order to pursue this possibility further, it is necessary not only to extend detailed studies of potential sources but also to determine ways of field sampling and sample preparation which complement magnetic measurements in terms of speed, ease and economy. A recent survey by Maxted (1983) suggests that leaf measurements may provide useful results. Fifty-one sites were chosen in West Yorkshire ranging from highly urbanised and industrial areas to relatively remote open moorland. Each site corresponds to one used in the National Air Pollution Survey (1971) and at each one several leaf types were sampled. The best spatial coverage was obtained using leaves of *Chamaenerion (Epilobium) angustifolium* (rosebay willowherb) and *Acer pseudoplatanus* (sycamore). Measurements were expressed on the basis of a constant leaf surface area which was achieved by using the 2.4 cm diameter cylinders in which discs were packed, as the templates for cutting them out. Close comparability of magnetic mineral assemblage from site to site was confirmed by calculating SIRM/χ, IRM$_{300\,mT}$ χ and back-field ratios for samples across the full range of IRM$_{300\,mT}$ and χ variation. The magnetic mineral assemblage of these samples saturated in a field of 300 mT or less,

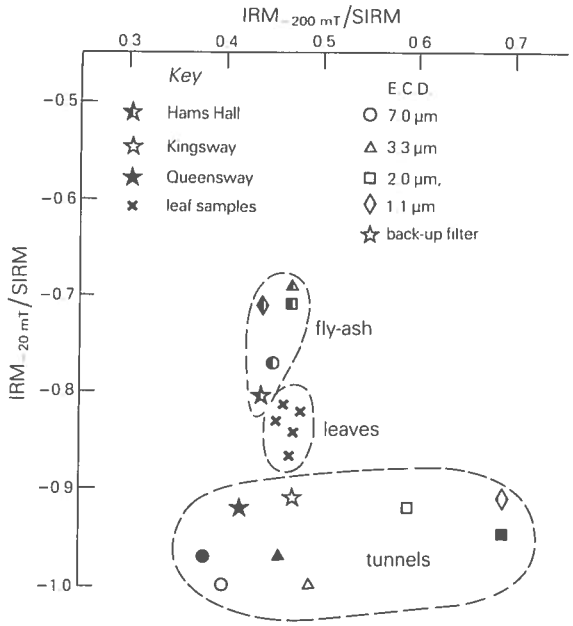

Figure 11.13 $IRM_{-20mT}/SIRM$ versus $IRM_{-200mT}/SIRM$ for particle-sized power station fly-ash and samples from the Mersey road tunnels near Liverpool (see text) (from Hunt *et al.* 1984).

suggesting that the dominant iron oxide is magnetite (cf. Fig. 11.2). Viscous loss of $IRM_{0.3\,T}$ between 10 and 2000 seconds after magnetisation is low and along with the low χ_{fd} measurements suggests that the assemblages mostly lack both coarse multidomain and fine viscous grains. The range of evidence available so far indicates a rather uniform magnetite assemblage relatively independent of particle size and source or concentration. We may therefore expect χ and $IRM_{300\,mT}$ to be equally useful as rough concentration indicators. Maxted records a 95% correlation between the two for his total sample set. For routine measurement $IRM_{0.3\,T}$ is preferable since it obviates any need to include compensation for the diamagnetism of the leaves and moreover the high sensitivity required is more readily attainable in the remanence measurements. The results, as well as showing a general response to rural–urban gradients, conurbation size and the proximity of industrial development, suggest that local factors, for example proximity to major roads, are important. Despite the lapse of time and the fact that magnetic measurements identify only one component of 'smoke', the rank correlation between 1961–71 smoke concentrations and $IRM_{0.3\,T}$ in 1982 was 90–95%. Clearly the next stage in any follow-up study will involve comparing heavy metal concentrations on leaf surfaces with the IRM measurements. The method, if validated would allow almost instantaneous on-site measurements using portable pulse magnetisers and magnetometers. The present study uses the leaves of deciduous species and is thus integrating results over a single summer growing season at most. Using conifers and winter evergreens for comparison it would be possible to determine winter levels equally effectively. The same sort of approach may also be suitable for assessing the filtering effects of trees in contexts where this process is believed to be a significant contributor to acid rain or heavy metal pollution.

11.7 Magnetic particulates in ice and snow

In view of the relative ease with which both spatial and temporal patterns of mineral magnetic variation have been resolved by measurements of ombrotrophic peat (Section 11.5), two preliminary studies have been carried out aimed at developing a comparable approach to ice and snow samples. In both studies, ice or snow was melted through a filter upon which the magnetic properties of the retained particulates were then measured.

Figure 11.14 summarises the results obtained from samples prepared by Dr A. Mannion from the Okstinden area of western Norway (Oldfield & Mannion, in prep.). The Corneluissens Glacier and Skoltbrae samples were taken from recent snow accumulated in nevee fields, the others come from cave ice and include rock debris. The parameters for the nevee field ice are comparable to all the measurements on industrial and combustion related spherules summarised elsewhere (e.g. Section 11.6) and they can be clearly differentiated from the material in the debris ice by means of their coercivity profiles. SIRM readings of 4.2 and 5.6×10^{-3} Am^2l^{-1} may well reflect the influence of the Mo i Rana steel works lying roughly down wind and some 40 km away on the coast. Obtaining comparable results from pre-industrial (*c.* 1600 AD) Camp Century Greenland ice has, not surprisingly, proved a great deal more challenging. The only measurements carried out so far have been obtained using the clean room facility at the Ice Core Laboratory, SUNY, Buffalo. In order to measure to the required sensitivity a cleaned pulse magnetiser and fluxgate magnetometer were used, with holders

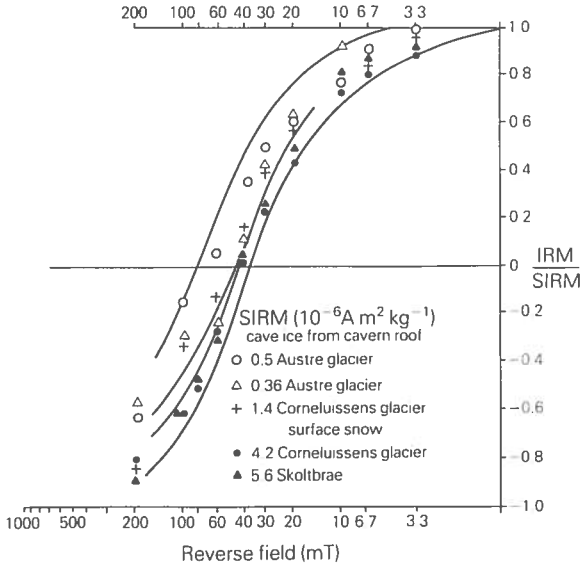

Figure 11.14 SIRM and $(B_0)_{CR}$ for surface snow and cave ice from the Okstinden region of Norway. Samples provided by A. Mannion.

and sample platforms designed to obviate the need for sample pots. Folded (0.22 μm) fluoropore filters were used without sample holders and rigorous cleaning procedures were followed at each stage. With some reservations (Oldfield, unpub.) we may tentatively infer that litre samples can provide enough material for SIRM measurements up to around 15×10^{-6} A m^2 total moment. This is about an order of magnitude above the noise level of the most sensitive portable magnetometers currently available. Comparison with the measurements from Norway suggests that concentrations in the pre-industrial Greenland ice are only about 0.3% of those in the surface snow from Okstinden. Magnetic techniques, suitably modified to contend with the low volume concentrations encountered in ice and snow samples, can be applied to historical studies paralleling those on recent post-industrial peat, to longer-term studies of dust-veil variations and to contemporary studies of local dust sources.

11.8 Global dust studies

Some dust samples supplied by D. R. Chester and collaborators from the lower atmosphere over the world's oceans have been measured. All of these were obtained on board ship, by means of mesh samples and on HI-VOL air filters. In addition 20 samples provided by Dr Prospero from his collection of dusts obtained during the course of the Barbados Oceanographic and Meteorological Experiment (BOMEX) have also been measured. A preliminary evaluation, pending more comprehensive analysis of all these data (Hunt, pers. comm.), is set out below.

The magnetic properties of most samples are clearly dominated by ferrimagnetic crystals. The clearest indications of a significant antiferromagnetic component come from some of the samples believed to have resulted from the deflation of hot desert areas. Maximum susceptibility and SIRM per unit mass of sample or volume of air is associated with proximity to major ports, coastal conurbations and industrial complexes. Peak mass specific values may be over 10 times greater than the mean of all the atmospheric samples measured so far. The samples with peak susceptibility and SIRM are indistinguishable magnetically from those dominated by 'particulate pollution' spherules and discussed in Sections 11.5 and 11.6.

Mineral magnetic parameters are modified not only close to industrial/urban sources but also in areas of high input as a result of soil erosion. Under these latter conditions dust loading often increases dramatically and both susceptibility and SIRM

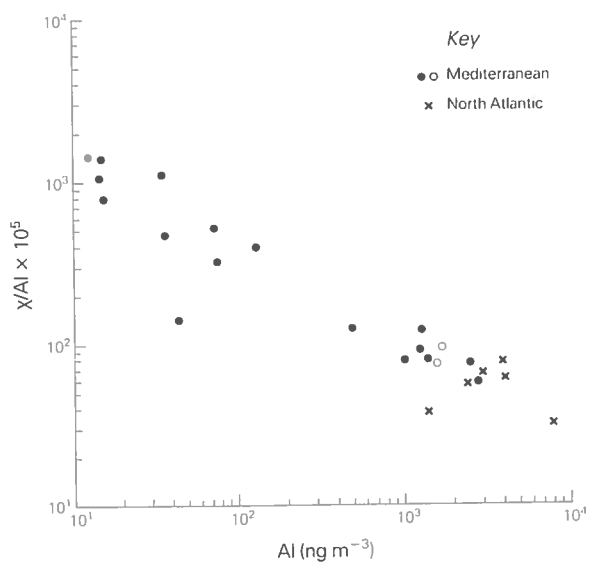

Figure 11.15 χ/Al versus Al for atmospheric dust samples from the Mediterranean and North Atlantic (from Chester *et al.* 1984).

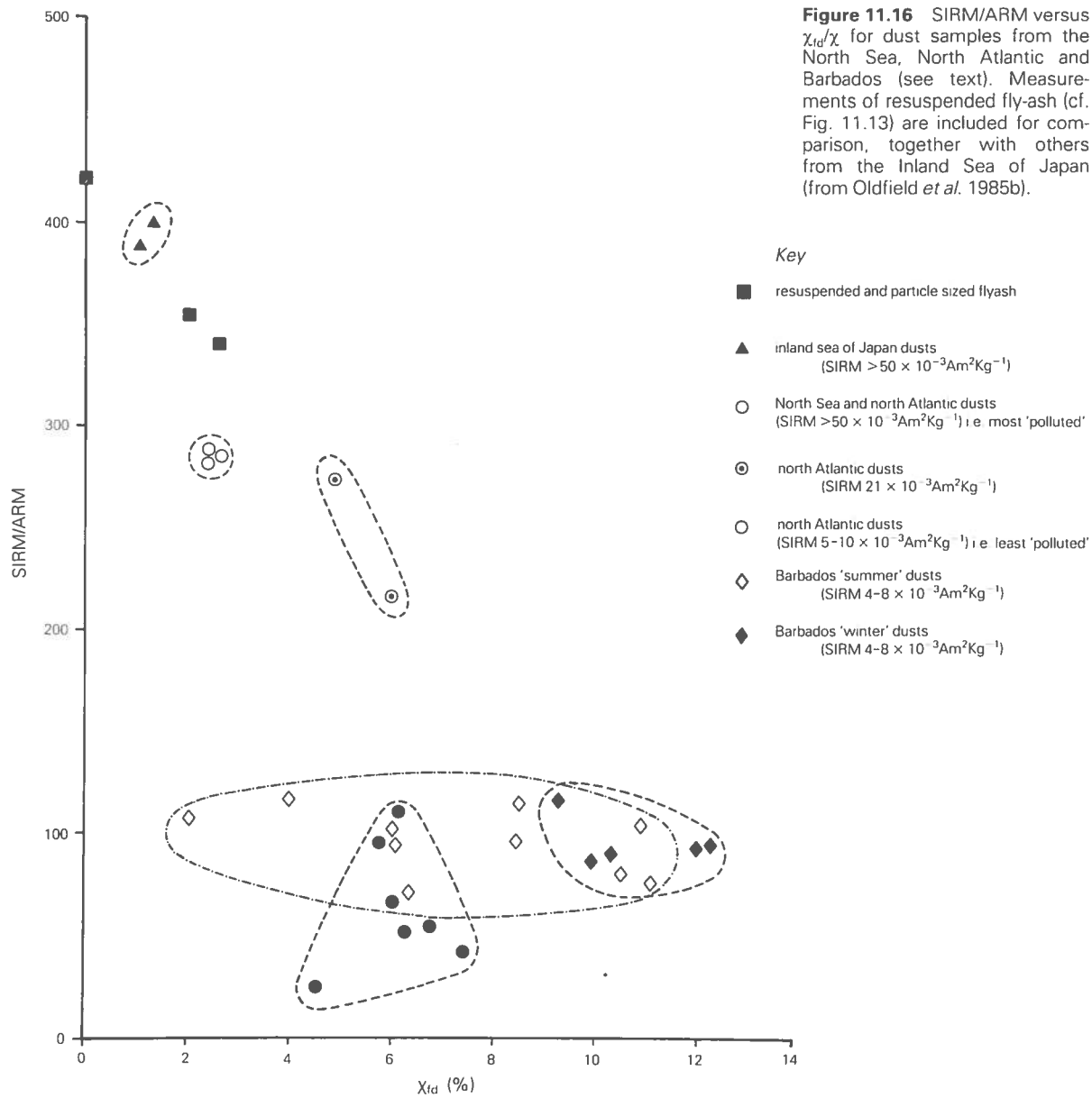

Figure 11.16 SIRM/ARM versus χ_{fd}/χ for dust samples from the North Sea, North Atlantic and Barbados (see text). Measurements of resuspended fly-ash (cf. Fig. 11.13) are included for comparison, together with others from the Inland Sea of Japan (from Oldfield *et al.* 1985b).

decline steeply and consistently to minimum values. Chester *et al.* (1984) (Fig. 11.15) show that there is a direct correlation between χ and the χ/Al ratio in the samples collected from the Mediterranean. Moreover the high χ and χ/Al values are generally associated with low dust loadings and *vice versa*. These relationships they interpret as the result of soil derived particulates from major areas of deflation reducing the susceptibility of a more or less ubiquitous background urban and industry-related aerosol during specific meterological episodes. High dust loadings associated with large concentrations of soil-derived magnetic minerals are associated with relatively steep viscous loss of SIRM and with higher χ_{fd} values.

Table 11.3 summarises results obtained from Barbados samples dating from 1966–68 taken by

Table 11.3 Barbados dusts mean values ± standard deviation (October and November dusts omitted).

	χ_{fd}/χ (%)	SIRM/χ (kA m^{-1})	IRM_{LR}/SIRM*	IRM_{HR}/SIRM†	$(B_0)_{CR}$ (mT)
grey dusts (Dec.–April)	10.7 ± 2.8	8.0 ± 0.23	0.24 ± 0.06	−1.44 ± 0.09	35 ± 1.7
red-brown dusts	9.5 ± 3.9	9.25 ± 0.63	0.45 ± 0.11	−1.22 ± 0.13	42 ± 4.1

$$IRM_{LR}/SIRM^* = \frac{IRM_{-20\,mT}}{SIRM} + \frac{IRM_{-40\,mT}}{SIRM}$$

$$IRM_{HR}/SIRM\dagger = \frac{IRM_{-100\,mT}}{SIRM} + \frac{IRM_{-200\,mT}}{SIRM}$$

Prospero (1968). Only normalised parameters are recorded and the mean value and standard deviation are quoted in each case. Out of a total sample set of 20, four samples from October and November, were omitted. The rest were identified as either red-brown, Sahara-derived 'summer' dusts or grey, more locally derived, South American 'winter and spring' dusts (Prospero *et al.* 1981). All the parameters used clearly distinguish the two sets. The higher coercivities, 'harder' IRM/SIRM and higher SIRM/χ values for the Saharan set are consistent with a relatively high haematite component, and in the 'hardest' samples up to 30% of the original SIRM is unsaturated in a reverse field of 0.4 T. The grey dusts have a very high χ_{fd} and are almost entirely reverse saturated at fields less than 0.4 T. All the parameters are consistent with a derivation largely from secondary ferrimagnetic grains at the surface of 'enhanced', probably burnt, soils.

Figure 11.16 plots SIRM/ARM versus χ_{fd}/χ for a larger sample set from the North Sea and North Atlantic. The Barbados dusts are grouped into seasonal sets as in Table 11.3. The cruise samples are placed in three well defined groups according to SIRM values. The gradient from highest to lowest SIRM reflects the declining relative importance of anthropogenic sources (cf. Chester *et al.* 1984) within the samples which span a large area from the coasts of Britain to low latitudes. ARM is believed to be more discriminating of true stable single-domain grain size than is SIRM, so we may expect the ratio of SIRM/ARM to decline as magnetic grain size changes, from multi- to single domain (Dankers 1978, King *et al.* 1982). χ_{fd} will increase with the greater relative importance of even finer crystals at the lower size limit of the single-domain range. Soils are thought to be the main sources of fine stable single-domain and smaller crystals. The diagram shows that the samples least affected by anthropogenic emissions have the lowest ratios and highest χ_{fd}/χ percentages, while those most affected have values for SIRM/ARM and χ_{fd}/χ close to those for the particle-sized fly-ash samples considered by Hunt *et al.* (1983) and plotted in Table 11.2. These results reinforce the proposition that magnetic parameters may be valuable aids to dust and aerosol source identification.

11.9 Summary and conclusions

On the basis of the studies summarised above, several prospective uses for mineral magnetic measurements of atmospheric samples can be tentatively advanced. The techniques clearly have a rôle to play in the historical monitoring of particulate and possibly heavy metal pollution. It is also possible that longer-term historical studies of dust-veil variation will be feasible using older ice and peat core material, though in the latter case it is possible that solution of magnetic minerals under reducing conditions may degrade the long-term record. Applying the methods to contemporary particulate and heavy metal pollution monitoring studies will require much additional work on the relationship between the magnetic properties and element chemistry of characteristic sources, as well as pragmatic evaluation of alternative sampling strategies. Because the atmosphere lacks the largely materially bounded characteristics of lake-watershed ecosystems for example, confidence in applying the techniques to such problems as aerosol identification and tracing (Hunt, 1986), or to plotting deposition patterns and distance-dependent effects from point sources, requires a large body of contextual data with very wide spatial coverage. Initial indications are that on a variety of spatial scales mineral magnetic parameters, used perhaps in conjunction with element ratios (cf. Kleinman *et al.* 1980), will be of considerable value in helping to identify dust and aerosol sources and to plot plume dispersal and deposition. Several additional possibilities are not considered in

the present account. For example, long-distance transport of sulphur compounds from power stations is believed to be partly in particle-associated form. It may therefore be possible to use magnetic properties as tracers of 'acid rain' sources. On a much smaller scale, the complex theoretical problems involved in modelling particle deposition to naturally 'rough' and heterogenous vegetated surfaces are no less daunting than the practical constraints involved in obtaining empirical data on deposition using even relatively simplified contexts (Chamberlain 1966, Clough 1973). Magnetic measurements could certainly be used in experiments designed to study particle deposition on natural surfaces.