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Mineral magnetic characteristics of podzolic soils developed on sand dunes in the Lake Gosciaz catchment, central Poland

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A number of samples from the A_0, A_2, B and C horizons have been collected from podzolic soils in the Lake Gosciaz catchment in central Poland. The catchment is very uniform consisting of 2–6-m-high sand dunes with sparse stands of pine and a grass undervegetation. Radiocarbon dates of fossil soils covered by dune sand, within the same type of environment as the Lake Gosciaz catchment, indicate that the main dune-forming phase is of Older Dryas age. Magnetic measurements have been carried out on bulk samples and on particle size fractions from the different soil horizons. With respect to our mineral magnetic study it can be concluded that the soils are very uniform over the entire catchment. Relatively high concentrations of magnetic grains are found in the humus layer, particularly in the < 4 μm size fraction, as indicated by the highest X, X_{fd}, SIRM and HIRM values. The most likely mechanism for the magnetic enhancement in these podzolic top soils is continued burning processes. Low magnetic concentrations in the A_2 horizon are due to eluviation and chelation. Local conditions can lead to a range of magnetic minerals precipitating in the B horizon.

1. Introduction

Mineral magnetic studies allow very small concentrations of ferrimagnetic minerals to be detected and studied in soils. Concentrations as low as 10 parts per million may be measured without undue difficulty. This concentration level is well below the detection threshold of heavy minerals separates, optical, X-ray, Mössbauer or chemical methods.

The physical and chemical properties of soils partly depend on the composition of the parent soil material, partly on the weathering reactions of the parent material and partly on pedogenic soil-forming processes. These varied factors can in some areas lead to very heterogeneous magnetic characteristics of soils, but in other regions to quite consistent magnetic patterns.

Ever since the pioneering soil magnetic studies of Le Borgne (1955) a constant magnetic theme has been that of the 'enhancement' of magnetic susceptibility in surficial soil layers. The two main processes that are envisaged as leading to this top soil enhancement are (i) pedogenic reduction–oxidation cycles and (ii) burning. A third possibility is that the magnetic enhancement is caused by 'industrial revolution' pollution from either atmospheric deposition of magnetic minerals produced by coal burning in chimneys, or else magnetic iron/steel contamination fragments derived, for example, from rusting agricultural implements. The two main processes of pedogenic cycling and

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burning are both visualized as leading to magnetic enhancement through the production of secondary ferrimagnetic minerals from weakly paramagnetic iron minerals (Mullins, 1977; Tite and Linington, 1975; Maher, 1986). These secondary minerals are considered to be cubic iron oxide spinels, close in composition to magnetite, maghaemite or their solid solutions. However, such interpretations of magnetic formation, based around the mineral magnetic characteristics of soils, are not in agreement with some chemical observations. Schwertmann (1988), for example, suggests that "no pedogenic magnetite has yet been detected".

A secondary recurring theme of magnetic studies on soils has been concerned with the observation of viscous or time/frequency dependent magnetic properties in top soils (Le Borgne, 1955; Özdemir and Banerjee, 1982). Such viscous properties, in which magnetizations or remanences change with time, are relatively rare in bedrock samples, where they tend to be associated with large multidomain grains. The strongly viscous and frequency dependent magnetic properties of top soils point instead to the presence of unusually fine-grained (~ 0.03 μm diameter) magnetic iron oxides formed in the enhancement process.

These two characteristics of higher concentration and unusually small grain size proffer the opportunity of using magnetic measurements in tracer studies connected with top soil erosion and movement (Oldfield et al., 1983).

The magnetic properties of the podzolic soils surrounding Lake Gosciaz have been studied in order to investigate further both the process of magnetic enhancement and magnetic methods of distinguishing between top soil and subsoil. The magnetic characteristics of different particle size functions of the soils have been studied in some detail as they have been found to provide a particularly clear way of differentiating the top soils and subsoils.

2. Site description

2.1. General geology and hydrology

Lake Gosciaz is situated ~ 100 km west of Warsaw in the Płock Basin (latitude 52.5° N, longitude 19.7° E). The Płock Basin, trending NW–SE, is part of a Pleistocene ice marginal valley now occupied by the Vistula River. During the maximum extent of the Weichselian (Vistulian) glaciation the basin was covered by ice (Fig. 1). The thicknesses of the Quaternary deposits, resting on Tertiary bedrock, range between 20 and 60 m. Sandy gravels and sands of fluvioglacial origin predominate in the basin, while the surrounding, slightly higher, undulating areas are made up of a till cover (Fig. 1).

The main dune-forming phase is assumed to be of Older Dryas age. Fossil soil covered by dune sands found some 50 km to the west of Lake Gosciaz has been dated to $12\,230 \pm 260$ years BP.

Lake Gosciaz is the biggest lake (45 ha) in the area and is part of a lacustrine complex called Jeziora na Jazack. Close to some of the smaller lakes there are also small peat bogs. The lake drains to the west by a small stream called Ruda (Fig. 2). The downstream run-off is large compared with that expected from a small 5.3 km^2 catchment in this flat landscape. These observations suggest that there is a considerable supply of ground water to the lake.

The entire catchment has a remarkably uniform character, consisting of sand dunes some 2–6 m high. The landscape slopes gently from around 90 m above sea-level in the south to about 70 m around the lake. The lake level lies at 64.4 m. The vegetation is dominated by sparse stands of pine with a grass undervegetation. Before 1950 no agricultural activity took place north of the lake. The pine forest to the south of the lake is even older. It was planted in the time of Napoleon.

2.2. Soils

The soils developed on the sand dunes are podzolic (cf. Duchaufour, 1982, p. 309) with an upper A horizon, a light reddish B horizon and a light yellowish to creamy C horizon. The A horizon is in the upper part dark brown to brown in colour with a thickness of between 4 and 10 cm. The bleached greyish layer of the A_2 horizon is generally ~ 2 cm thick with a well-defined upper boundary. The lower boundary in contrast tends to be very gradual with the transition to the B

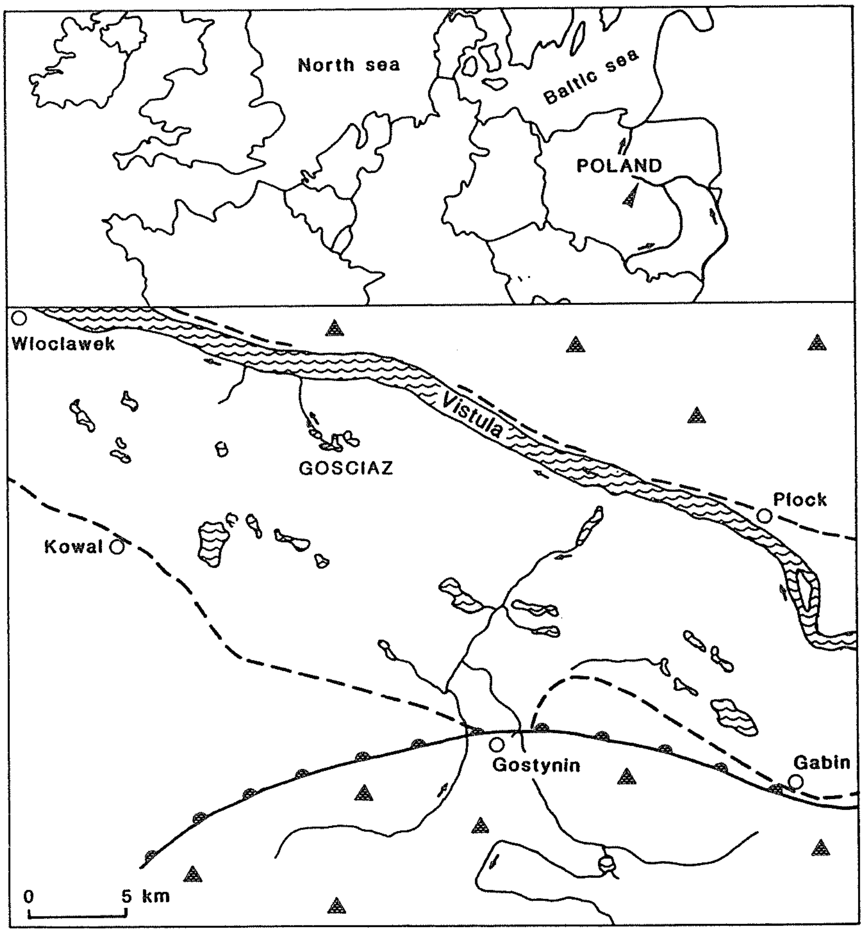

Fig. 1. Map of Lake Gosciaz and its surroundings. Maximum southward extent of the Weichselian (Vistulian) ice sheet (line with half circles); limits of the Płock Basin (dashed line); morainic hills (triangles); sand plain (central open part). Upper figure shows the general location of the study area in central Europe.

horizon taking place over some 10–15 cm, or occasionally even more. The A–B transition can be recognized by a gradual change in colour shade from greyish to reddish. The transition from the B horizon to the C horizon is also very gradual.

The particle size distribution in the Gosciaz soils is very narrow (Fig. 3) reflecting the efficient wind-blown sorting of the parent material. About 70% of each sample falls within one phi class.

3. Methods and techniques

3.1. Field work

Soil samples were collected from 11 localities in the catchment (Fig. 2). From six of these localities (1, 3, 4, 8, 10 and 11) soil profiles were sampled by collecting between four and five samples of ~ 1 kg from different depths. The deeper samples were

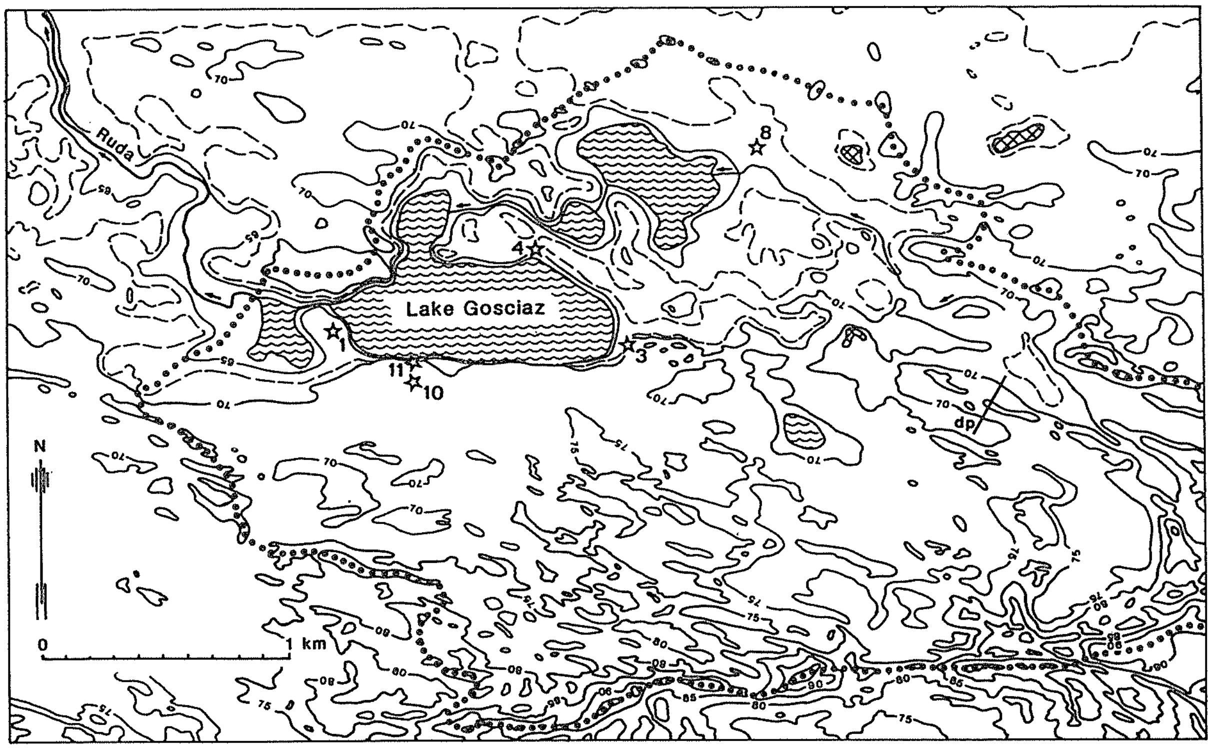

Fig. 2. Topographic map of the Lake Gosciaz catchment and surrounding areas. Watershed marked by dotted line. Sampling localities numbered. Dp denotes the trend of the dune transect in the eastern part of the catchment. The dunes trend west-northwest to east-southeast. Contours at 5 m intervals.

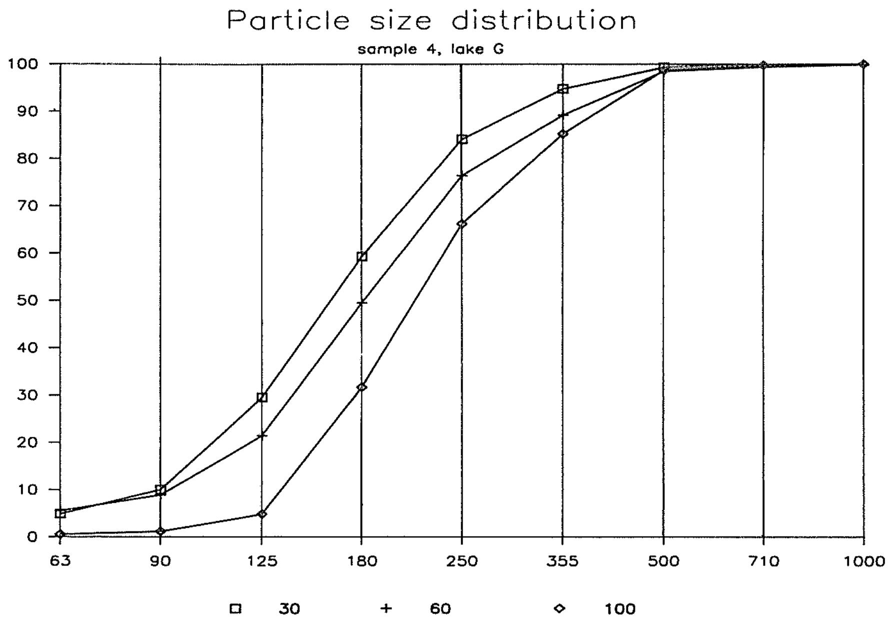

Fig. 3. Cumulative particle size diagram for the three soil horizons from the profile at locality 4.

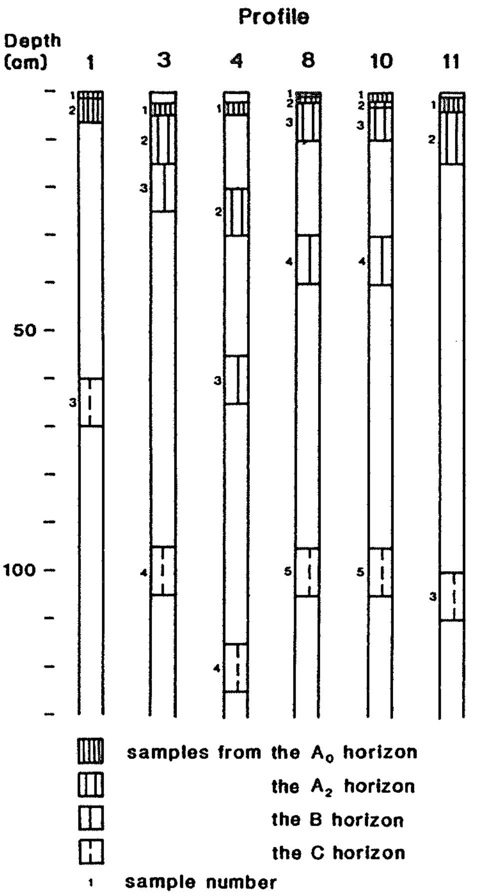

Fig. 4. Sample depths and soil horizons for six soil profiles.

recovered with a hand operated auger. Figure 4 summarizes the sampling depth of these six soil profiles in relation to the main soil horizons. All the samples from these localities were later split into particle size classes. At a further five localities (2, 5, 6, 7 and 9), catchment samples were taken from small streams or in the lake. Of these five localities only the samples from localities 5 and 7 yielded enough material to be split into different particle size fractions.

From the final locality, a 10-m-high dune in the eastern part of the catchment, a complete transect of 16 soils was collected, perpendicular to the trend of the dune. Samples were obtained at each of two horizons for the 16 sites along this dune profile (Figs. 2 and 5). An upper sample was collected from the A_0 horizon and a lower sample was collected from the B horizon at a depth of 30–40 cm.

On account of water making sampling difficult, only one sample was collected from site 9 on the dune transect. The two samples at site 10 were also considered to be semi-gleyed.

Similarly, because of the ground-water level at 60 cm, only three samples were collected at locality 1. The lowermost sample from this locality was collected below the ground-water table whereas all the other catchment soil samples were taken from above the ground-water table.

3.2. *Laboratory analyses*

3.2.1. *Particle size distribution*

In order to determine the particle size distribution of the soils of the lake catchment three samples were analysed from different depths of soil profile 4 by normal dry-sieving procedures (Fig. 3).

3.2.2. *Particle size splits and dispersion*

Two methods were used in order to split the bulk soil samples into 12 particle size classes. Dry

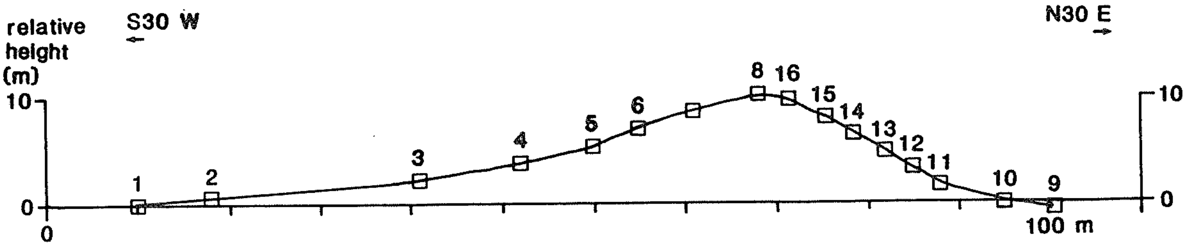

Fig. 5. Dune transect with position of sampling sites. The profile is hand levelled. Heights are relative. The crest of the dune lies at about 75 m above sea-level.

sieving was used for the > 63 μm material and wet settling for the < 63 μm material.

Samples from the A_0 horizon were initially placed in an ultrasonic bath for ~ 10 min with a few drops of NH_3 to disperse the material. Then the organic fraction was floated off. Samples from all the four soil horizons were wet sieved through a 63 μm sieve. The coarse sand fraction (> 63 μm) was dried at a temperature of 40°C, and dry sieved into seven 0.5 phi particle size classes of between 63 and 1000 μm.

The clay, silt and fine sand of < 63 μm in diameter, which makes up < 5% of the soils, was collected for separation into particle size classes by settling based on Stoke's law. It was placed in a container and carefully stirred in order to provide homogeneity. Then, after settling for a known period of time, material of a specific particle size range was removed. This stirring, settling and removal procedure was repeated several times in order for each fraction to become as pure as possible. The < 63 μm fraction was thus separated into five particle size classes (< 4, 4–8, 8–16, 16–32 and 32–63 μm). Because there was very little minerogenic top soil material, once the organic fraction had been removed, the top soil samples could only be separated into two particle size classes (< 32 and 32–63 μm). All these samples were also placed in an oven set at a temperature of 40°C to dry before magnetic measurements were made on them.

3.3. Instrumentation and magnetic parameters

The magnetic analyses were carried out on the dried particle size fractions. The dried material was put into pre-weighed cubic polystyrene boxes and weighed. Cubes not entirely full were filled with non-magnetic foam to prevent the dry soil from moving during measurement.

3.3.1. Susceptibility

Low- and high-frequency initial susceptibility (X_{lf} and X_{hf} respectively) were measured on an air-cored susceptibility bridge (Bartington susceptibility bridge). One decade separated the two frequency measurements.

3.3.2. Laboratory induced remanences

An electromagnet was used to grow remanences in artificially imposed magnetic fields. The remanences were measured on a Digico complete-result balanced fluxgate spinner magnetometer interfaced to a M16V mini-computer (Molyneux, 1971). The maximum capacity of the electromagnet was 0.72 T which is, for convenience, considered as producing magnetic saturation in our samples.

3.3.3. Additional magnetic parameters

Specific frequency-dependent magnetic susceptibility (X_{fd}) is calculated as the absolute difference between the two susceptibility measurements. The S ratio is based on the ratio of the magnetization in a reversed field of 100 mT divided by saturation isothermal remanence, i.e. $S = -\mathrm{IRM}_{-0.1T}/\mathrm{SIRM}$. Forward IRMs in gradually increasing fields up to the saturation level were measured on pilot samples. All samples were subject to measurements in the maximum 'saturating' field and in a reversed field of 100 mT. High field isothermal remanence, HIRM, is calculated as $(1 - S) \times \mathrm{SIRM}/2$.

3.3.4. Magnetizations

A vibrating sample magnetometer was used to measure M–H hysteresis loops in fields of up to 1 Tesla.

4. Magnetic measurements

4.1. Magnetic susceptibility

Magnetic susceptibility is largely a measure of the concentration of magnetic minerals in a sample. Average susceptibility values of the four soil horizons for the fine (< 63 μm), intermediate (90–180 μm) and coarse (250–500 μm) particles are shown in Table 1. Depth profiles of the susceptibility for the 16–32, 63–90 and 180–250 μm particles are presented in Fig. 6. Although some variations can be noted, the susceptibilities on the whole display a clear pattern with respect to both soil horizon and particle size. Average susceptibility values are highest in the finest fractions (< 63

μm) of the top soils, with an average value of 1.38 $\mu m^3\ kg^{-1}$ (Table 1). This same trend is also seen in the depth profiles. For example, the lowest susceptibility values are recorded in the coarsest fraction of the samples from the basal C horizon, where a mean of 0.009 $\mu m^3\ kg^{-1}$ is found.

The difference in susceptibility between the coarse C horizons and the top soil fines is two

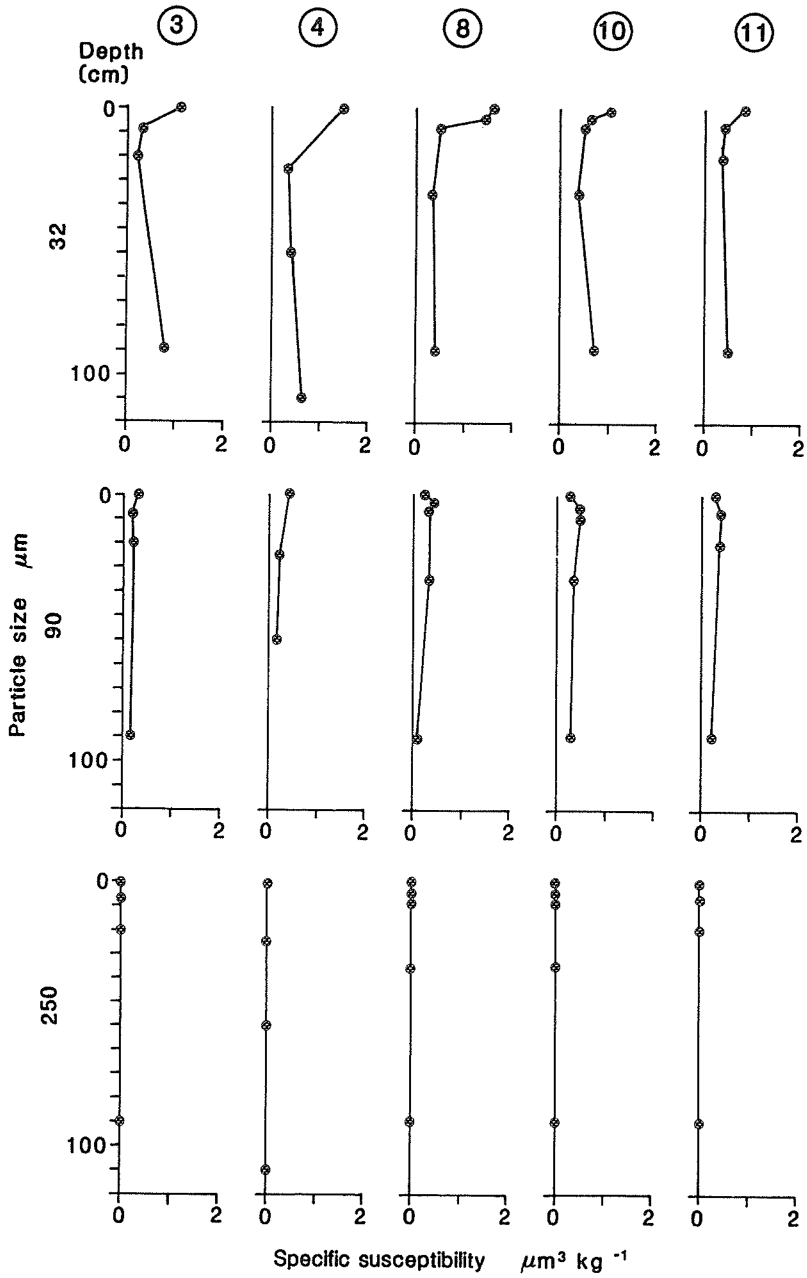

Fig. 6. Variations of specific susceptibility with depth for localities 3, 4, 8, 10 and 11 (of Fig. 3) for each of three different particle size classes.

TABLE 1

Average magnetic value for three particle size classes

Soil horizon	Particle size (μm)		
	< 63	90–180	250–500
X_{fd} ($\mu m^3\ kg^{-1}$)			
A_0	0.05	0.002	0.001
A_2	0.03	0.002	0.002
B	0.02	0.002	0.001
C	0.01	0.001	0.001
X_{lf} ($\mu m^3\ kg^{-1}$)			
A_0	1.38	0.15	0.039
A_2	0.49	0.15	0.028
B	0.40	0.11	0.015
C	0.46	0.12	0.009
SIRM (mA $m^2\ kg^{-1}$)			
A_0	20.5	2.3	0.86
A_2	7.2	2.3	0.52
B	5.8	1.6	0.33
C	6.0	1.7	0.25
HIRM (mA $m^2\ kg^{-1}$)			
A_0	3.0	0.35	0.11
A_2	1.2	0.41	0.08
B	1.0	0.29	0.06
C	1.2	0.27	0.06
SIRM/X (kA m^{-1})			
A_0	15.8	17.0	23.4
A_2	15.0	16.3	22.7
B	14.6	15.8	21.9
C	13.7	17.6	29.1

orders of magnitude. For the < 63 μm particle size range, average susceptibility values are about three times lower in the three deeper horizons compared with the top soil samples. Susceptibility values in the 90–180 μm particle size range are, in all horizons, less than in the finest particle size range. In the 250–500 μm particle size range, susceptibility values are an order of magnitude lower than in the intermediate sized particle range. Increasing susceptibility is particularly marked in the < 63 μm fractions of all the localities.

Looking at the susceptibility variations in closer detail we can see how each soil horizon has its own distinct pattern of variation with respect to particle size. These patterns are shown in Fig. 7.

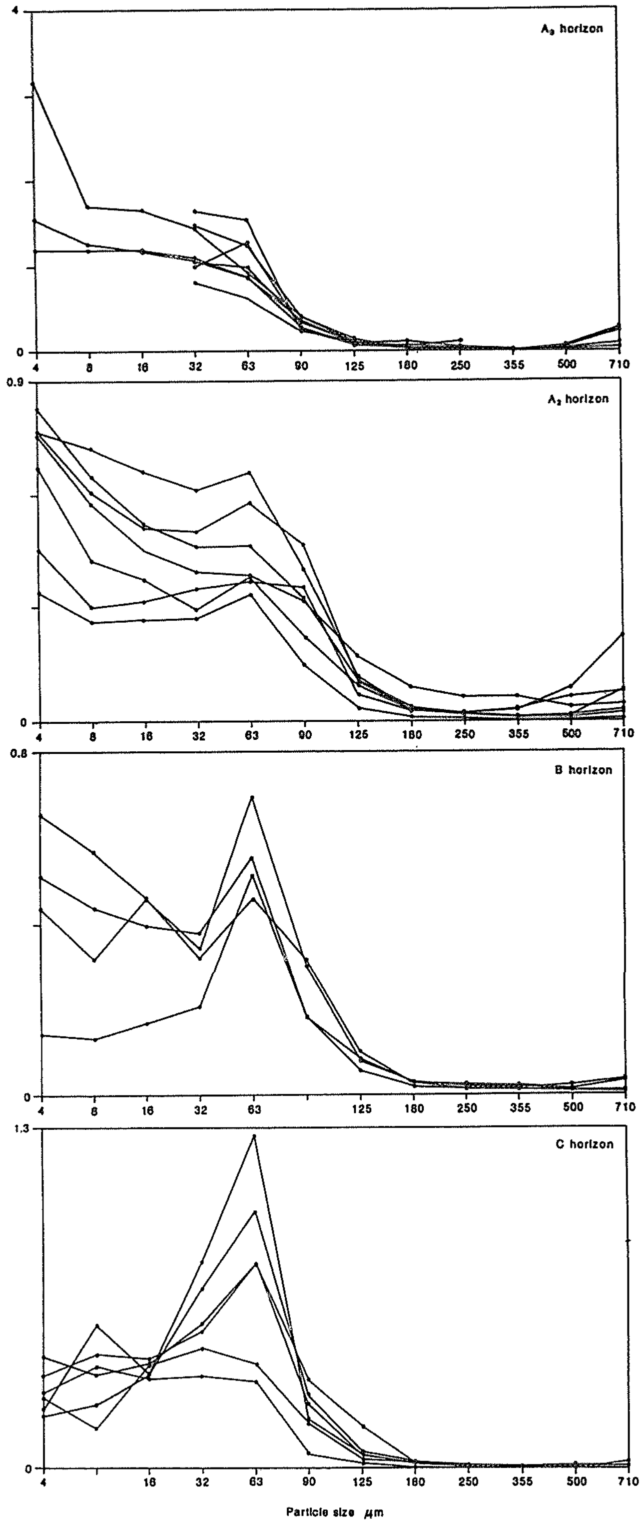

Fig. 7. Specific susceptibility versus particle size at eight localities from the four soil horizons A_0, A_2, B and C.

Firstly, in the top soil samples, susceptibility is consistently high in the five finest fractions (< 4–< 63 μm). Between particle sizes 63 and 90 μm there is a significant drop in susceptibility in all samples, followed by very low values between 125 and 500 μm, while in the coarsest fraction of all there is a slight increase in the susceptibility of most samples. Secondly, within the A_2 horizon, a susceptibility peak begins to be revealed in the 32–63 μm fraction, followed by a significant decrease. Thirdly, although there are only four samples representing the B soil horizon, a similar but even clearer pattern to that of the A_2 horizon is revealed, with a susceptibility peak in the 32–63 μm fraction. The overall trends seen in the top soil samples of high values in the < 63 μm fractions are again seen in the A_2 and B horizons. In the A_2 horizon the highest susceptibility values were consistently found in the < 4 μm fraction. In the C horizon there is in contrast no evidence of the < 4 μm susceptibility peak, but instead a very pronounced peak occurs in the 32–63 μm fraction.

The susceptibility measurements from the dune transect are in close agreement with those of the soil profiles. The dune top soil samples have an average susceptibility of 1.006 $\mu m^3\ kg^{-1}$ compared with 1.038 $\mu m^3\ kg^{-1}$ for the top soils of the soil profiles, while average bulk susceptibility values from the B horizon are 0.556 $\mu m^3\ kg^{-1}$ for the transect compared with 0.604 $\mu m^3\ kg^{-1}$ for the soil profiles.

4.2. Frequency dependent magnetic susceptibility

Frequency dependent magnetic susceptibility X_{fd} (X_{lf}–X_{hf}) is a measure of the occurrence of very fine magnetic grains on the superparamagnetic – stable single-domain boundary, i.e. grain sizes of around 0.03 μm diameter (Mullins and Tite, 1973). Individual X_{fd} values vary from a maximum of 0.137 $\mu m^3\ kg^{-1}$ in the ≤ 4 μm top soil fraction at locality 2 to values generally < 0.002 $\mu m^3\ kg^{-1}$ in the ≥ 90 μm fraction in the other horizons. Average frequency dependent values (Table 1) are always highest in the finest top soil samples (Fig. 8). The frequency dependent value of 0.094 $\mu m^3\ kg^{-1}$ recorded in the < 4 μm range of the top soils is typically four times higher

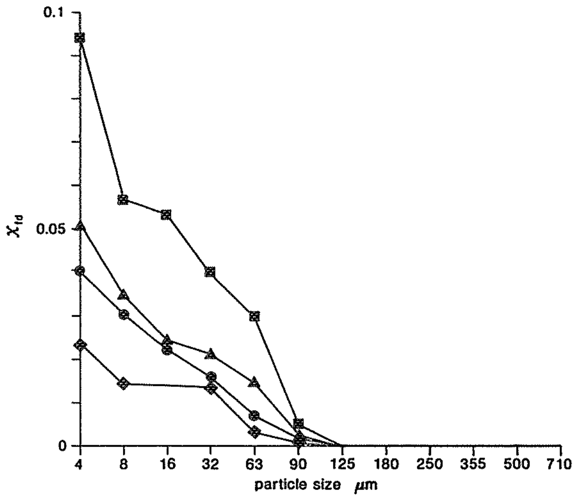

Fig. 8. Frequency dependent susceptibility vs. particle size of the average Gosciaz catchment values for the four soil horizons A_0, A_2, B and C. (A_0 horizon = squares, A_2 = triangles, B = circles, C = diamonds).

in these top soils than in the C horizon subsoils and is about twice the X_{fd} of the A_2 horizon. In all of the horizons there is an almost linear decrease in frequency dependence with particle size up to 90 μm. Above this limit, in the coarsest fractions all the X_{fd} values are very low, generally < 0.002 $\mu m^3\ kg^{-1}$.

4.3. SIRM

Like susceptibility, SIRM is largely a measure of the concentration of ferrimagnetic minerals in a sample. SIRM is more strongly affected by the magnetic grain size and by any antiferromagnetic minerals present than susceptibility, but it is unaffected by paramagnetic components. The overall trends of SIRM values with respect to both particle size and depth in the soil profile reveal clear correlations with those of susceptibility (compare Fig. 7 and Fig. 9). Average SIRM values for the fine, intermediate and coarse particle size fractions (Table 1) show that the highest SIRM values occur in the finest fraction of the top soil samples (20.5 mA $m^2\ kg^{-1}$). These SIRM measurements are two orders of magnitude greater than those of the coarsest fractions in the C horizons. Once again, as in the case for susceptibility, the drop in magnetic concentration between the top soils and

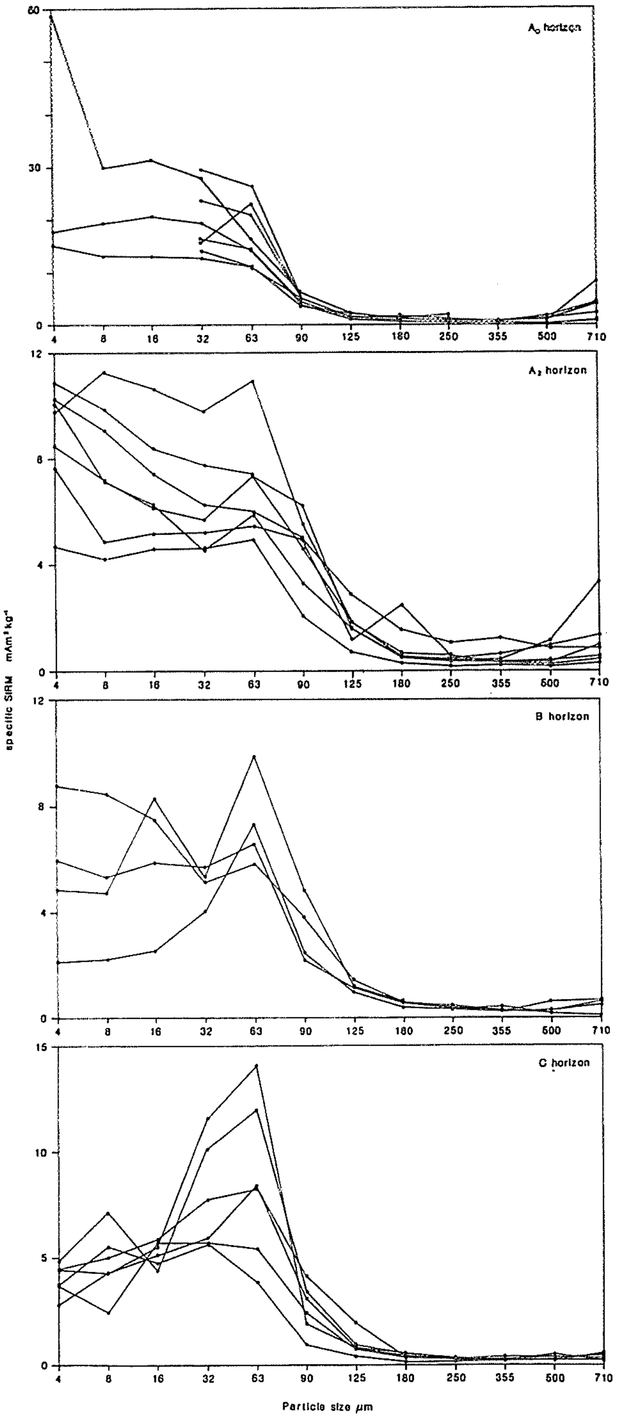

Fig. 9. Specific SIRM vs. particle size for the four soil horizons of Fig. 7. Note the same trends in the SIRM for all four horizons as in the susceptibilities of Fig. 5.

the A_2 horizon spans about a factor of three in the finest particle size range, while in the intermediate and coarse particle size fractions the magnetic differences are consistently small. Inspection of the average SIRM values of individual particle size classes for individual samples (Table 1) reveals that the trends of the relationship between magnetic concentrations and particle size are almost identical to those for susceptibility.

4.4. HIRM

High field isothermal remanence can sometimes be used as a measure of the concentration of antiferromagnetic minerals in a sample (Bradshaw and Thompson, 1985). The magnetic patterns recognized for X and SIRM are also seen in HIRM in these podzolic soils. Average HIRM values range between 3.0 mA m^2 kg^{-1} in the fine fractions of the top soil samples to 0.06 mA m^2 kg^{-1} in the coarsest fraction of the C horizon samples (Table 1).

4.5. S *ratio*

The S ratio (calculated as $-IRM_{-100}/SIRM$) mainly reflects the relative proportion of antiferromagnetic to ferrimagnetic minerals in a sample. A ratio close to 1.0 reflects almost pure magnetite while ratios of < 0.8 indicate the presence of some antiferromagnetic minerals, generally goethite or haematite (Thompson, 1986).

S ratios in the soil samples range from 0.24 to 0.86. Looking at average ratios of all fractions the highest S ratios occur in the top soil samples with gradually decreasing ratios in the deeper soil horizons. There is a decrease in the ratio of approximately 0.5 between each soil horizon, the A_0 horizon having an average ratio of 0.71 and the C horizon having an average ratio of 0.55. This decrease points to an increasingly higher proportion of antiferromagnetic minerals in the deeper part of the soil profiles.

Considering the individual particle size fractions of the various soil horizons this simple pattern in S ratio can be further elaborated upon (Fig. 10). In the 16–90 μm range of particle sizes the differences in S ratio between the soil hori-

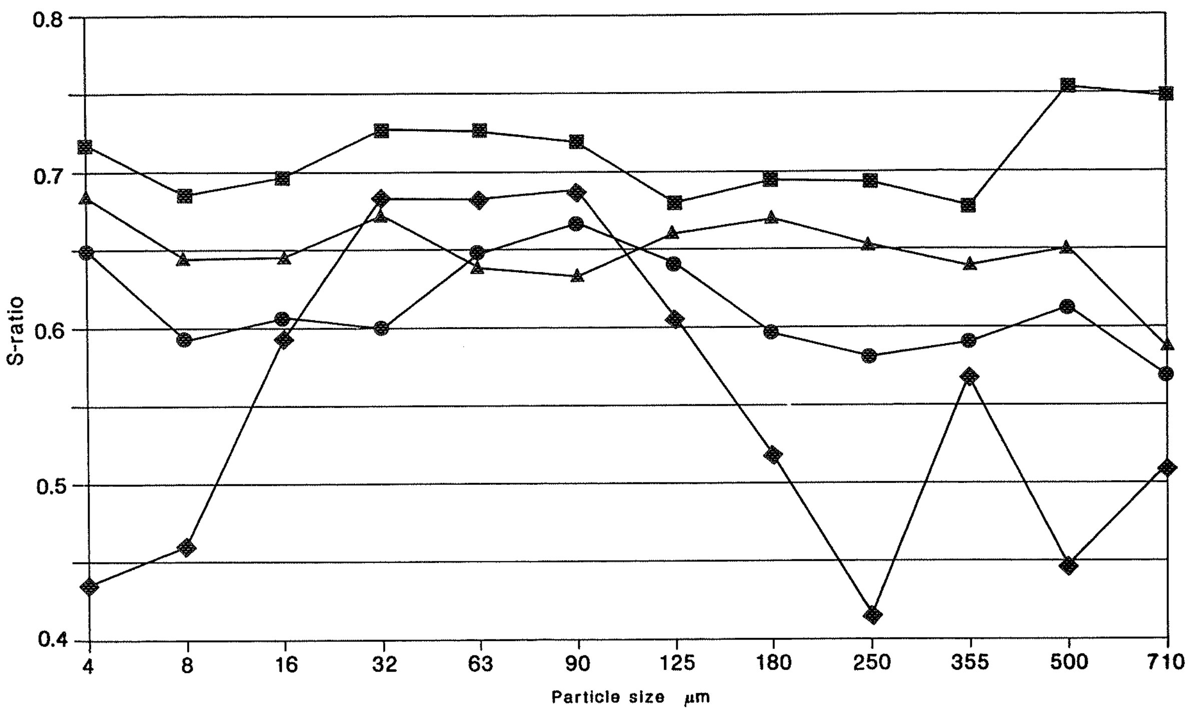

Fig. 10. Average S ratios for the 12 particle size fractions of the four soil horizons of Figs. 7 and 9 (A_0 horizon = squares, A_2 = triangles, B = circles and C = diamonds).

zons are small. In particular, the subsoil samples have only slightly lower S ratios than the top soils. The particle size samples immediately above and below this range make up transitional fractions in that the absolute difference in S ratio between the uppermost and lowermost horizon is small (solid circles and diamonds in Fig. 10). The two finest (< 16 μm) and six coarsest (> 90 μm) fractions all display the simple pattern of the bulk soil samples in which the S ratio decreases with depth.

4.6. Hysteresis properties

Major hysteresis loops were measured on a selection of 14 samples. Two examples are shown in Fig. 11 for a 32–63 μm subsoil fraction at site 10 and for a 63–90 μm fraction at site 15 on the dune profile. All the 14 hysteresis loops measured revealed similar coercive forces of between 7 and 12 mT, while 'saturation' remanence to 'saturation' magnetization ratios (M_R/M_s) were found to vary between 0.036 and 0.1. The most obvious differences between the loops relate to high field susceptibility characteristics, as revealed by the gradients of the loop tips in Fig. 11. These high field changes in magnetization are caused by a paramagnetic component in the soils. For example, the more pronounced high field gradient of Fig. 11a compared with the shallower gradient of Fig. 11b reflects a more important contribution to the susceptibility by paramagnets. The paramagnetic contribution to the initial susceptibility can be calculated from the loops to be 12% for Fig. 11a and 1.7% for Fig. 11b.

5. Magnetic grain size, SIRM/X ratio

In a study of Icelandic sediments, Bradshaw and Thompson (1985) compared the SIRM and X of their samples with measurements on pure magnetite of known grain sizes (e.g. Dankers, 1978) to construct grids showing the variation of SIRM/X

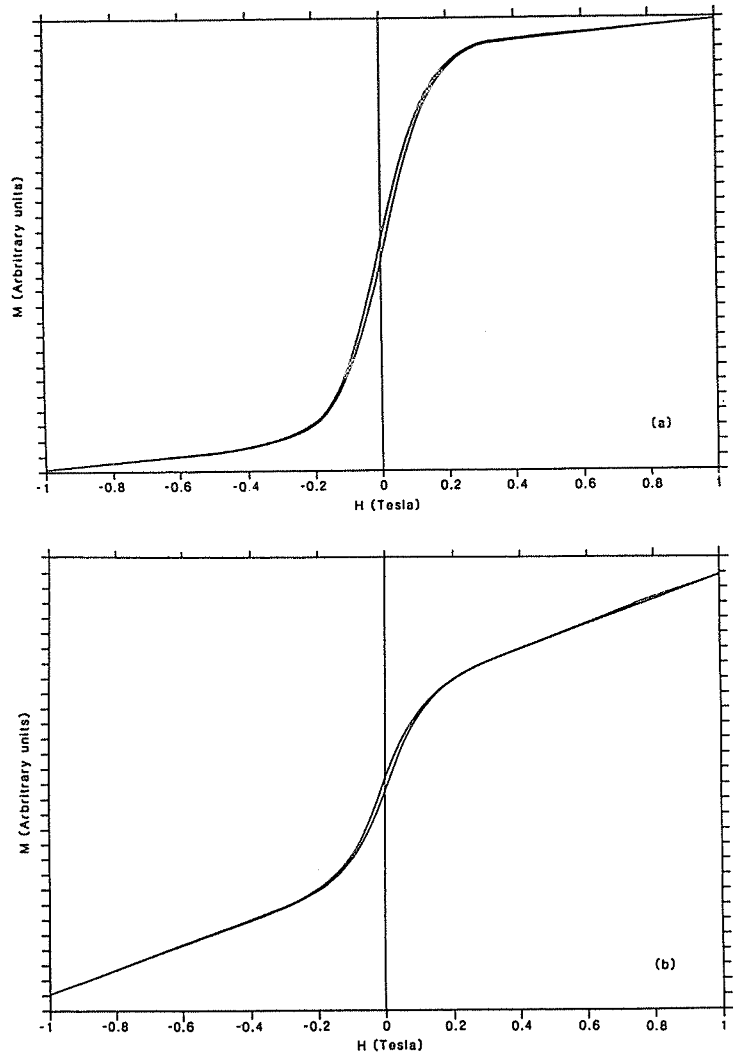

Fig. 11. Hysteresis loops for (a) 32–63 μm particle size fraction of dune subsoil site 10 and (b) 63–90 μm fraction of dune subsoil site 15. Note the difference in the relative importance of the high field susceptibility between the two samples.

ratio with magnetic grain size and concentration. The same approach has been used to provide a first approximation of the magnetic grain size of the Gosciaz soil samples (Fig. 12).

In the top soils, X is significantly higher in the 63–90 μm particle size fractions than in the coarser fraction. In the A_2, B and C horizons, X peaks in the < 63 μm fraction. The SIRM/X plot shows firstly the high magnetic concentrations of the < 63 μm size fractions compared with the 250–500 μm particles, and secondly a small difference in grain size as reflected in the different average SIRM/X ratios. The average magnetic grain sizes of the A_2 and B horizons are similar to each other and slightly coarser than the top soil averages. The coarsest average magnetic grain sizes occur in the subsoil samples.

As most clearly reflected by the S ratios, these Polish soil samples do not contain only pure magnetite. Some antiferromagnetic minerals must also be present and have an effect on the SIRM/X ratios, as to a certain extent will variations in the

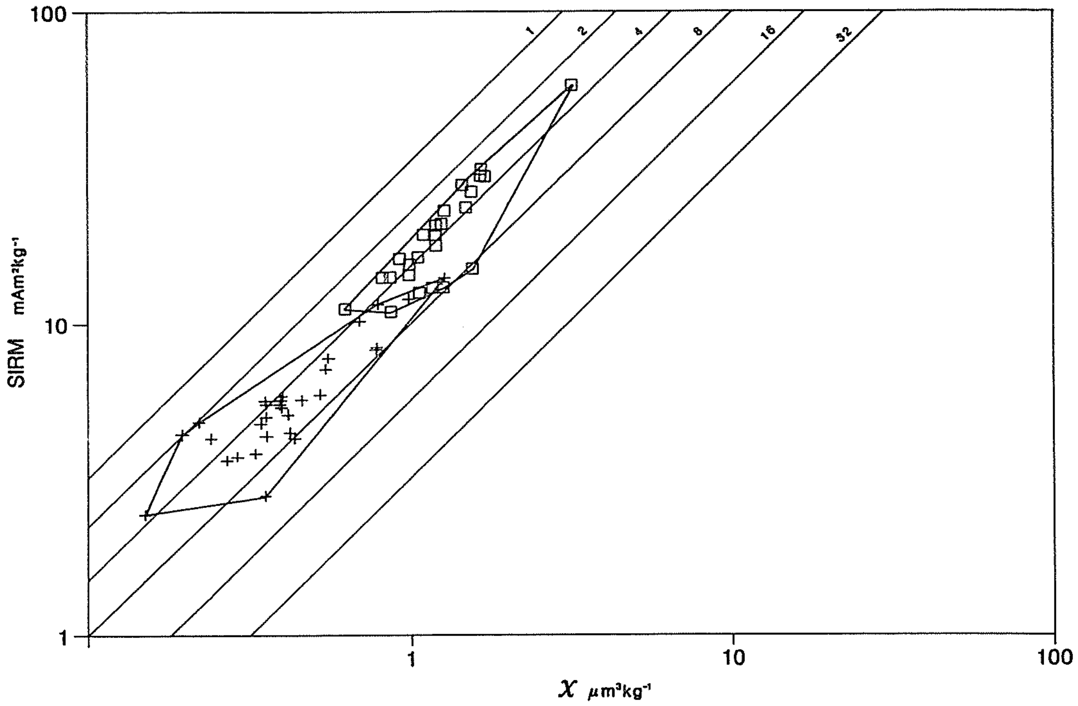

Fig. 12. Bi-logarithmic plot of specific susceptibility against specific SIRM for fine (< 63 μm) and coarse (250–500 μm) catchment top soils for localities 3, 4, 8, 10 and 11 of Fig. 3. The grid shows the properties of magnetite for various grain sizes (μm) (after Thompson and Oldfield, 1986). Convex hulls separate fine (squares) and coarse (crosses) particle size clusters.

importance of the paramagnets. A higher proportion of antiferromagnetic minerals was especially noted in the C horizon samples, with the exception of the 16–90 μm size fractions.

6. Summary of Gosciaz podzolic soils magnetic properties

6.1. Magnetic concentration

The pattern of variations in the concentration of magnetic minerals in the podzolic soils is remarkably uniform across the whole catchment. The highest bulk magnetic concentrations are consistently found in the uppermost top soils. These high concentrations occur predominantly within the < 90 μm particle size ranges. In particular, the < 4 μm size fractions often have the highest X, X_{fd}, SIRM and HIRM values of all. The overall increase in magnetic concentration, from subsoil to top soil, averages about a factor of three. We attribute this overall increase to the Le Borgnean enhancement mechanism of growth of new magnetic particles in the top soils. Magnetic enhancement through contamination by atmospheric pollution particles is most unlikely at Gosciaz because the additional magnetic component of the top soils is greatly in excess of the atmospheric fallout that has been documented in lakes and bogs.

As podzolic soils are particularly hostile, destructive soils, in which iron is strongly eluviated down profile (e.g. Duchaufour, 1982), they could be thought of as being unlikely sites for magnetic enhancement to occur through pedogenic reactions. Hence magnetic enhancement taking place through continued burning processes is thought to be the most likely mechanism operating in the top soils at Gosciaz.

The magnetic properties of the B horizon at Gosciaz are generally intermediate between those of the A and C horizons. The striking peak in magnetic concentration in the 63 μm particle size fraction can be explained as either (i) reflecting the original magnetic properties of the parent material, or (ii) resulting from new magnetic minerals associated with the 63 μm diameter particles. New magnetic crystals could, for example, grow as part of cementation and reprecipitation processes, forming a coating around existing silicate and aluminosilicate grains as iron is precipitated following eluviation. The C horizon magnetic concentration properties could be adequately explained as either (i) a combination of magnetic characteristics of minerals translocated down profile from the A and B horizons over and above an effectively non-magnetic parent material, or (ii) simply the characteristic of the parent dune material.

6.2. Magnetic mineralogy

The major variations to be observed in magnetic mineralogy, as with magnetic concentration, reflect down-soil-profile changes. Once again between-site changes are small. Of the various magnetic parameters that mainly reflect mineralogy, the 'S ratio' picks out changes in magnetic composition most clearly in these soils. The S ratio is here taken to be largely a reflection of changes in the balance of ferrimagnets (e.g. magnetite or maghaemite) to imperfect antiferromagnets (e.g. goethite or haematite). The imperfect antiferromagnets are most in evidence in the C layer, especially in the finest and coarsest grain size fractions, where they lead to low S ratios of ~ 0.24–0.5. As evidenced by the S ratios, imperfect antiferromagnets are of lesser importance in the top soils, throughout the whole particle size range, and also in the intermediate grain size fractions of the B horizon. Consequently, ferrimagnets magnetically dominate the top soil and intermediate size fractions of the B and C horizons. Nevertheless, an imperfect antiferromagnetic contribution to the magnetic properties is always present in these materials as their S ratios rarely exceed 0.85 and HIRM values remain above 0.5 A m^2 kg^{-1}.

6.3. Magnetic grain size

In mixed mineralogies, such as in these soils, magnetic grain sizes are difficult to determine. Nevertheless, frequency dependent susceptibility is a clear indicator of the presence of very fine ferrimagnetic grains. SIRM/X ratio is a further useful pointer to magnetic grain size.

In this work it is important to distinguish between the grain sizes of the magnetic crystals and that of the sediment particles within which the magnetic grains lie. For example, the 4–8 μm particle size fraction can contain magnetic grains of any diameter ranging from superparamagnetic grains, a few tens to hundreds of Ångströms across, through to multidomain grains of 8 μm diameter.

The proportional importance of frequency dependent susceptibility increases, particularly, in the fine particle fractions of the top soils over that of the subsoils. It reaches 47% in the fine top soils (Table 1) compared with the 10% of the subsoils, emphasizing the importance of the fine particle enhancement in the soils. SIRM/X ratio, however, does not vary so greatly (Table 1), suggesting that growth of new magnetic minerals in the enhancement process covers a range of grain sizes from supermagnetic and viscous through stable single domain to pseudo-single domain. Further evidence for this wide range of newly formed ferrites comes from a limited number of anhysteretic remanence measurements. X_{ARM}/X_{lf} and SIRM/X_{ARM} ratios, in these soils, fall at around 5 and 3 mT, respectively, as would be expected from a population of magnetic grains spanning a wide size spectrum (Thompson and Oldfield, 1986).

The generally fine magnetic grain size of these podzolic soils is further testament in favour of enhancement through burning, as opposed to pollution from extraneous industrially derived contaminants. Ferrimagnets produced by burning in smoke stacks or derived from rusty iron/steel fragments tend to belong to quite the opposite particle size ranges, being large multidomain particles tens of microns in diameter.

6.4. Top soil–subsoil contrasts

Figures 13 and 14 summarize the contrasts in magnetic properties between the top soils and

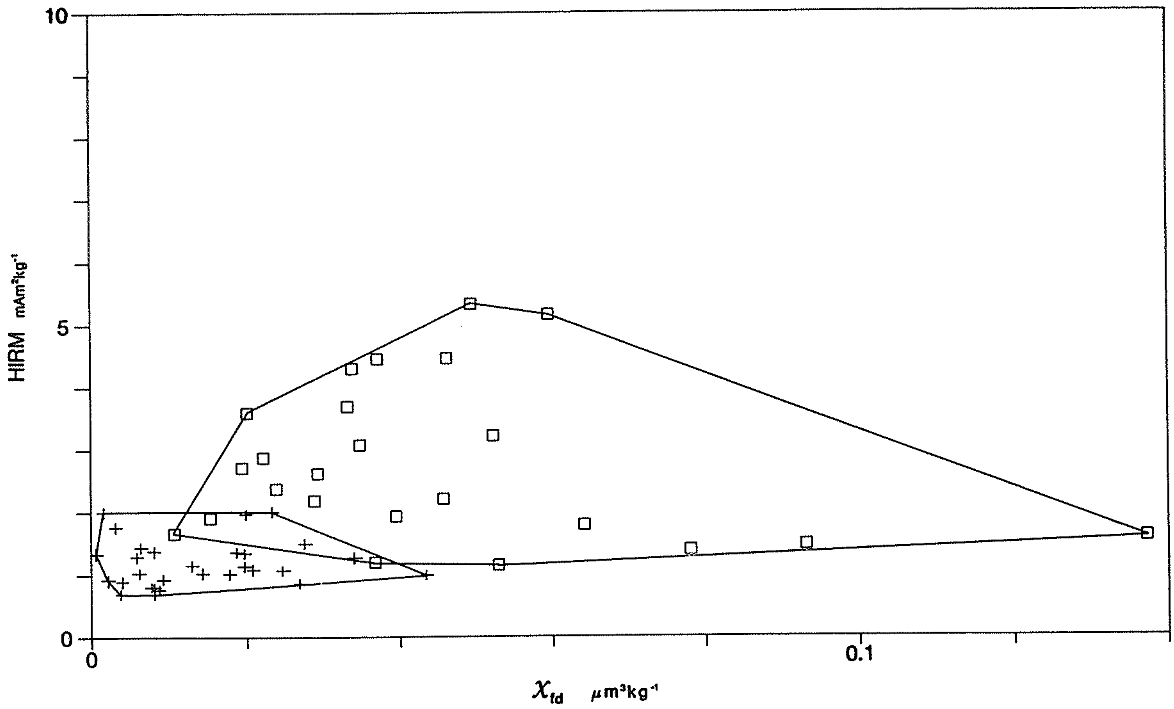

Fig. 13. Bi-plot of specific HIRM against specific frequency dependent susceptibility (X_{fd}) for the same localities as in Fig. 12. Convex hulls separate top soil (squares) and subsoil (crosses) clusters.

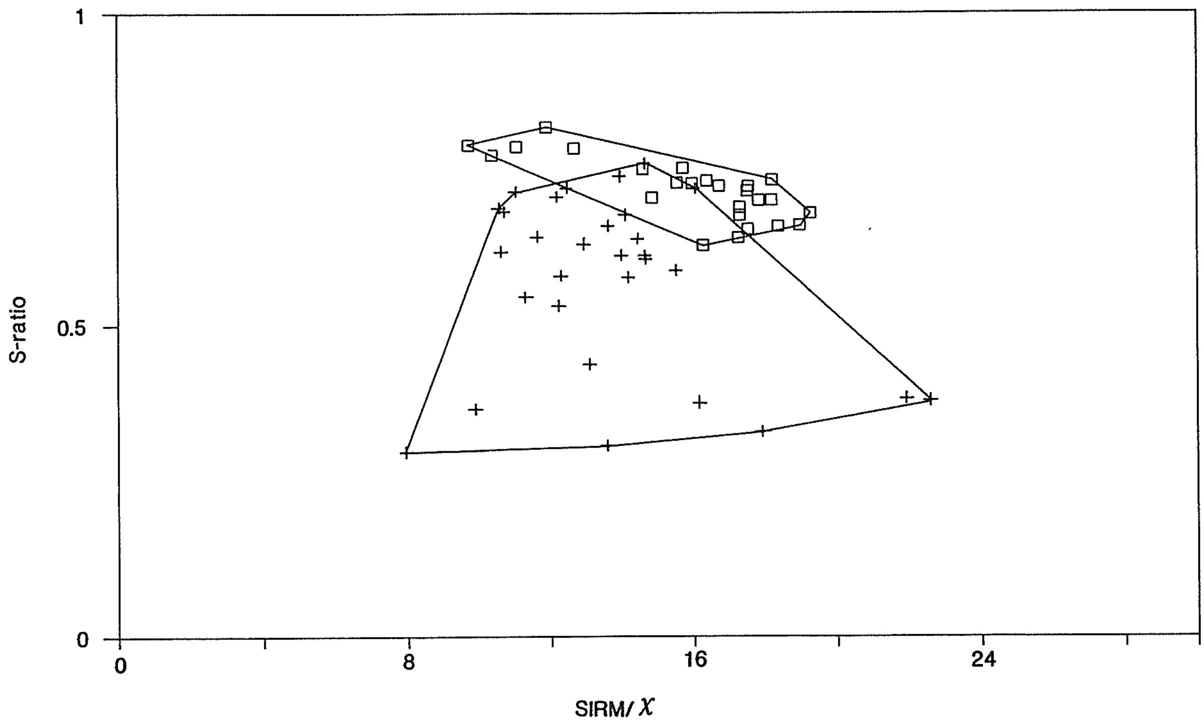

Fig. 14. Bi-plot of SIRM/X ratio against S ratio for top soil and subsoil samples. Samples, symbols and convex hulls as in Fig. 12.

subsoils. Figure 13 plots one susceptibility and one remanence-dominated parameter against one another. In this plot all the samples have been taken from the same particle size splits in order to minimize size-dependent effects. The top soil enhancement of both magnetic parameters, in the top soils, leads to minimal overlap of the two clusters. Figure 14, in contrast, plots the mineralogical and grain-size dominated parameters of S and SIRM$/X$ ratios against one another. Again the top soil and subsoil samples lie in different regions of the diagram, illustrating contrasting magnetic mineralogies.

6.5. Comparison with other studies

Our basic results are in excellent agreement with Le Borgne's (1955, 1960) early studies. In particular, we have found, in Le Borgne's words, (i) "high susceptibility in the humus-bearing top layer", that (ii) "the finest argillaceous fraction is the most magnetic", and that (iii) "susceptibility is relatively high because the soil contains very fine grains of neoformation". The Gosciaz podzolic soil horizons have very uniform magnetic properties in contrast to some poorly developed soils in upland glaciated regions of Europe (e.g. Stober 1978; Bloemendal, 1982; Hirons and Thompson, 1986).

In detail, however, the magnetic properties of the Gosciaz podzols contrast with podzolic soils from other areas. Lukshin et al. (1968), Vadyunina and Babanin (1972), and Vadyunina and Smirnov (1976) have investigated the magnetic properties of soils in the U.S.S.R. While Lukshin et al's (1968) results on podzolic soils from Udmurt region contrast strongly with ours, Vadyunina and Babanin's (1972) and Vadyunina and Smirnov's (1976) data are more comparable to the present study.

One reason for the difference in Lukshins et al.'s (1968) data might be that they worked with volume measurements whereas we have followed the now prevalent procedure of working in terms of dry mass, having first removed any organic detritus. Lukshin et al. (1968) found low susceptibility in the uppermost "plough layer" in their Sod-Podzolic soils and maximum susceptibility in their illuvial horizons. On one sandy Sod-Podzol they found that susceptibility varied insignificantly with depth. In contrast, Vadyunina and Babanin's (1972) results from several regions of the European and Asiatic U.S.S.R., always showed higher susceptibility in the humus accumulation horizon compared with the eluvial horizon, as is the case in all our soils. Vadyunina and Babanin (1972) also, however, had high susceptibility in the B horizon. They attribute these high susceptibilities to the migration of particles from the A_s–A boundary. Vadyunina and Smirnov (1976) found viscous magnetic properties in their medium Sol-Pozols and again high susceptibility and also high isothermal remanence in their B horizons. They noted, in particular, the high coercivity of the B horizon magnetizations, which they explain through "the single domain state of ferrimagnetic hematite particles which ... becomes fixed in the ferruginous films of soil particles in the podzolic horizon apparently as a result of physicochemical processes".

Maher (1984, 1986) in a Stagnopodzol from Exeter found high susceptibility and isothermal and anhysteric remanence in the B horizon, and, in particular, in a B_{fe} layer, combined with very high coercivities and very low magnetic values above this horizon. Maher (personal communication) on the basis of Mössbauer studies attributed those high values to the formation of goethite. Thompson (unpublished data) found high susceptibility and laboratory remanence values in the B horizon of a podzol from Blekinge in south Sweden. Coercivity of remanence values of 30 mT point to a ferrimagnetic rather than haematite or goethite component growing in the B horizon of this Swedish podzol.

7. Summary

The following conclusions can be drawn about the magnetic properties of podzolic soils. (1) Classic enhancement 'sensu' Le Borgne can take place in the humus layer through the neoformation of fine-grained magnetite or maghaemite. (2) Eluviation and chelation consistently lead to low magnetic concentrations in the A_e horizon.

(3) Local conditions can lead to a range of magnetic iron oxides precipitating in the B horizon of podzolic soils. These iron minerals include goethite, magnetite, maghaemite and haematite. (4) There is evidence for translocation of fine ferrimagnetic grains down to the B and C horizons in certain podzolic soils. (5) Particle size fractions are particularly useful for discriminating top soil and subsoil materials in these podzolic soils.

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