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The influence of periglacial activity on the remanent magnetization of sediments

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Abstract
The palaeomagnetic investigation of an ice-wedge cast in Late Pleistocene loess deposits in Belgium demonstrated that the upturned strata adjacent to the wedge have retained a stable remanence which can be used as a marker to visualize the strain.

Different wedge fillings could be differentiated and identified on the basis of their remanent magnetization and magnetic susceptibility properties.

Deformations due to periglacial activities easily escape observation, particularly in cores, and hence large associated anomalous magnetization directions may be erroneously interpreted as 'excursions' of the geomagnetic field.

Introduction

During the past few decades, much information has been collected on periglacial features and periglacial environmental conditions during the Pleistocene, and much attention is paid to their relation with the climate. For Belgium and the Netherlands, the most detailed information is available for the last glacial period, the Weichselian (Haesaerts & Van Vliet-Lanoë 1981, Vandenberghe & Van de Broek 1982, Haesaerts 1984, Vandenberghe 1985), but evidence for periglacial conditions during the preceding glacial stages is increasing (Maarleveld 1960, Paepe & Van Hoorne 1967, Gullentops et al. 1981, Vandenberghe & Kasse 1989). A stratigraphical framework was built up mainly by lithostratigraphical correlations, palaeobotanical information, radiocarbon analyses and correlation with the oxygen-isotope stages (Zagwijn 1957, 1961, 1974, Van der Hammen et al. 1967, Paepe & Vanhoorne 1967, Zagwijn & Paepe 1968, Paepe & Zagwijn 1972, Vandenberghe 1985). Palaeomagnetic investigations may provide a chronostratigraphical framework based on the global synchronous reversals of the geomagnetic field during the Early and Middle Pleistocene (Hus et al. 1976, Hus 1991). However, the magnetostratigraphy of the Late Pleistocene relies mainly on the secular variation of the direction and intensity of the field and on the occurrence of large directional deviations called palaeomagnetic 'excursions'. The former has a regional character and must be established for different parts of the world, while some of the latter are still a matter of dispute because of a lack of spatial and time consistency. The amplitude of the secular variation of the palaeofield and the occurrence of 'excursions' are also of great importance for our knowledge of processes taking place in the earth's core and core-mantle interface.

Valid information about the fine structure of the ancient earth-magnetic field can only be obtained if it was faithfully recorded and by examining non-

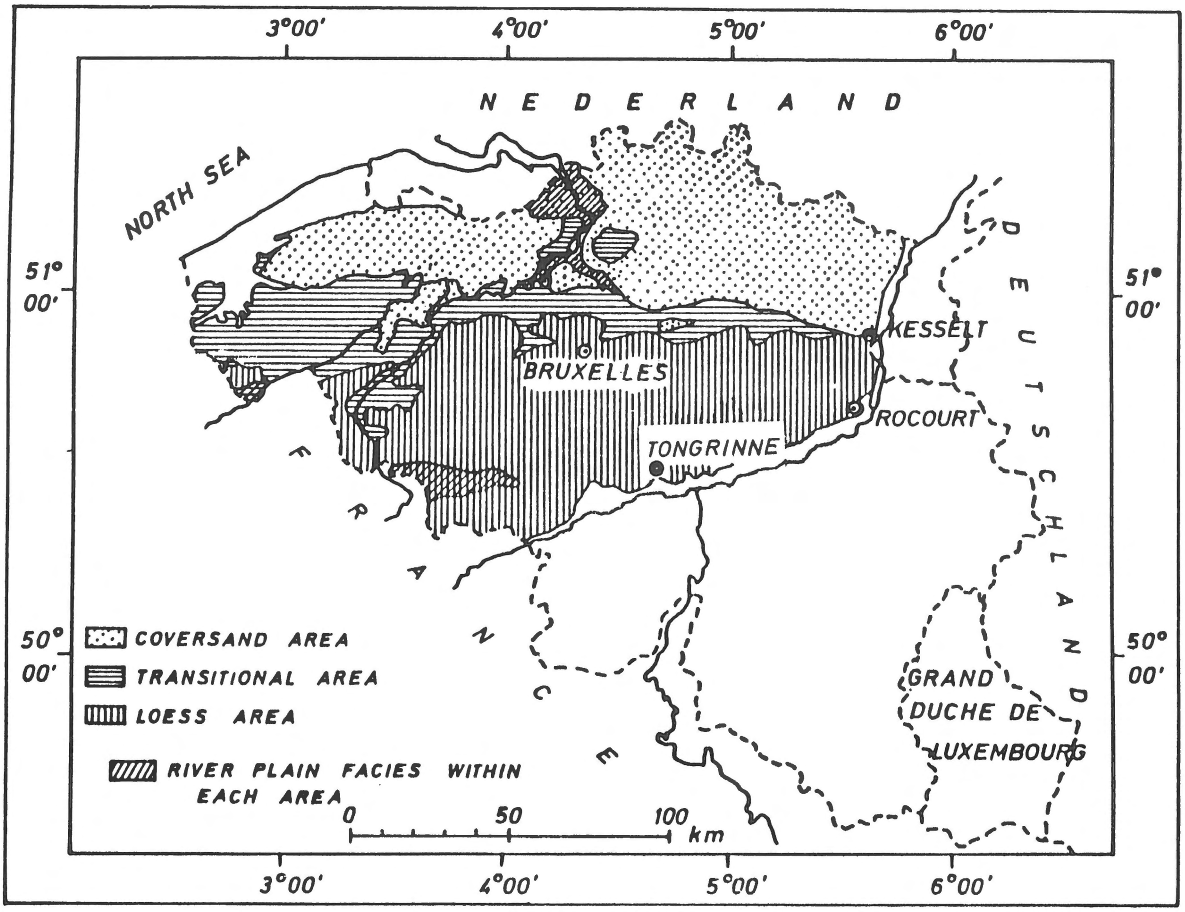


Fig. 1. Map of the sedimentation areas of the Late Pleistocene in Belgium (after Paepe 1967) with localities mentioned in the text.

disturbed rock samples which have retained at least part of their initial remanent magnetization. The aim of this research was to investigate the influence of periglacial activity on the remanent magnetization of sediments, and to demonstrate that at least some of the large directional magnetization changes found in periglacial sediments are not induced by the earth-magnetic field but caused by mechanical disturbances.

Frost action gives rise to different kinds of physical mechanisms in sediments such as thermal contraction, the appearance of segregation ice and an increase of the water volume which transforms into ice (Pissart 1970, Washburn 1973). These mechanisms may result in different structures, like frost cracks, ice wedges, involutions, etc. (Dylik & Maarleveld 1967, Flint 1971, Washburn 1973, Vandenberghe 1988). When a humid soil starts freezing, the volume may increase by as much as 9%, but once transformed into ice the volume decreases with a lowering of the temperature. A sudden drop of the temperature to very low values will contract the frozen ground and internal tensions appear due to the difference in thermal contraction coëfficient between pure ice and the rock constituents. Finally, the soil will fissurate when the horizontal tensions exceed the tensile strength near the surface. The theories of elasticity show that frost exerts three kinds of pressures, resulting in three kinds of fractures each with a different shape: horizontal cracks, 'septiform' cracks and vertical V-shaped cracks (Bertouille 1971).

We only consider vertical V-shaped cracks, assumed to be the result of horizontal tensions. In early spring when defreezing starts, the melting water enters the cracks and freezes when it comes into contact with the frozen soil, producing a vertical vein of ice that penetrates the permafrost. Horizontal compression caused by the re-expansion of the permafrost during the following summer results in the upturning of the permafrost strata by plastic deformation. During the cooling period of the next winter the thermal tensions may create new fissures and will generally reopen the already-existing ice-cemented cracks which are zones of weakness (Lachenbruch 1962). Another increment of ice will be added when the spring meltwater enters the reopened crack and freezes, resulting in the growing of a wedge-shaped vein of ice. In the following we will examine the influence of permafrost and of a relatively large ice wedge, revealed near the southern border of the Late Pleistocene loess in Belgium, on the palaeomagnetic properties of the strata affected.

Stratigraphy

Oriented samples were taken across a fossil ice-wedge cast of the Weichselian, periglacial loess deposits in a brickyard at Tongrinne (Belgium), situated between the basins of the rivers Meuse and Scheldt (Fig. 1). The thickness of the Pleistocene deposits in this small plateau (altitude about 163 m) attains roughly 15 m. The top six metres, visible in the pit, belong to the Late Pleistocene. From bottom to top (Figs 2, 3), we first recognize a Saalian loess deposit, in the top of which a reddish-coloured, textural B horizon occurs as a relict of a Luvisol (FAO soil classification). This soil developed in the Saalian loess during the Eemian interglacial (Paepe & Vanhoorne 1967, Zagwijn & Paepe 1968). It was described from Rocourt, together with the overlying humic horizon, as the Rocourt soil by Gullentops (1954). The Eemian soil is overlain by an aeolian deposit containing an interstadial humic (steppic) soil, called Warneton soil (Paepe 1968) and most often attributed to the Amersfoort and/or Brörup interstadials of Early Weichselian age. Radiocarbon dates of 35 900 (± 1000) BP (GrN-9081) and 47 800 (± 2100) (GrN-9080) were obtained on humates and 38 550 (± 700) (GrN-9186) on the organic residue of GrN-9081 in Rocourt (Haesaerts & Van Vliet 1981, Haesaerts et al. 1981, Gilot 1984) and hence must be considered as minimum ages. Another interstadial soil, called Kesselt soil (Gullentops 1954) occurs on top of a series of faintly stratified loess of Middle Pleniglacial age (61 000 BP–26 000 BP). This soil is followed by a cryoturbated horizon called the 'tongue horizon of Nagelbeek'. The Nagelbeek horizon has been radiocarbon-dated at Kesselt and Lixhe (near Rocourt) respectively at 22 2700 (± 380) (LV-1172) and 22 190 (± 130) BP (GrN-10328) (Gullentops 1981). Thermoluminescence dating yielded much younger dates of 13.5 (± 1.1) ka in Rocourt and 15.2 (± 0.9) ka in Lixhe (Juvigné & Wintle 1988). Finally, pure aeolian loess covers the whole aforementioned series.

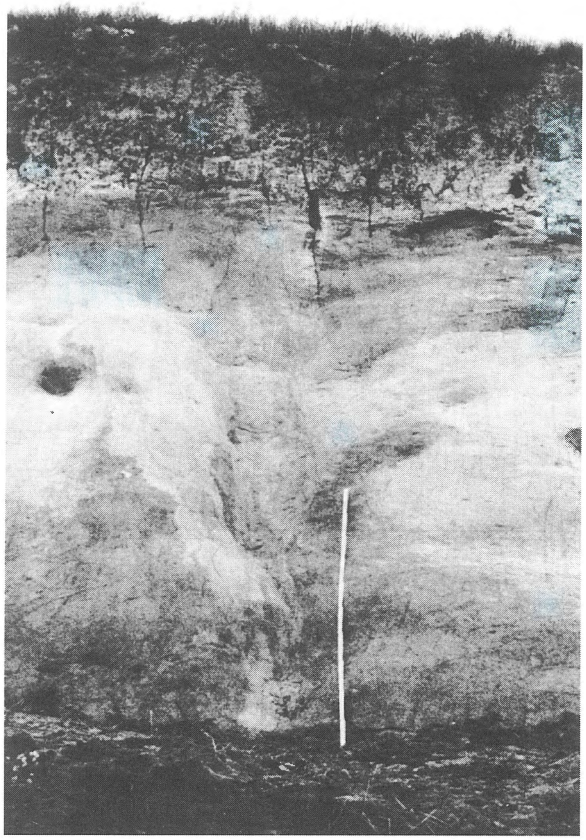


Fig. 2. Ice-wedge cast in Late Pleistocene loess deposits in Tongrinne (Belgium) (see also Fig. 3).

The studied ice-wedge cast, which starts somewhere in the Upper Silt Loam, penetrates all the other mentioned stratigraphical units (Fig. 2). Ac-

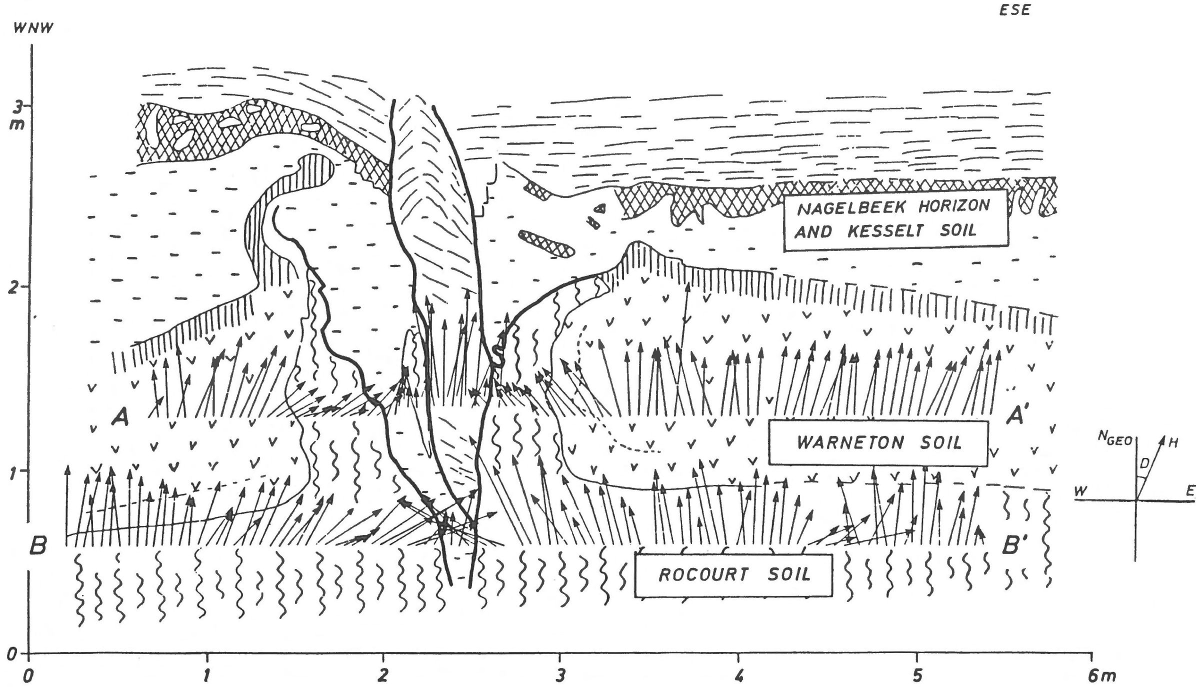


Fig. 3. Horizontal magnetization components (H), after alternating field treatment at 30 millitesla, across ice-wedge cast at the level of the Warneton soil (level AA′) and Rocourt soil (level BB′) at Tongrinne. Geographical north is taken upwards. The limit of the ice-wedge cast is outlined by a solid line.

tually, at its outer rims the ice-wedge cast is filled up with sediments belonging to the Middle Pleniglacial sequence. From field observation, by tracing the boundaries of the upturned Rocourt soil and Warneton soil, we could observe that the wedge opened a first time during the Middle Pleniglacial. During the intensive cooling off during the polar desert phase in the middle of the Late Pleniglacial, about 18 000 BP, the soil reopened preferentially at places where fossil frost wedges occurred in the subsoil. Therefore, we find a younger bronze-coloured wedge of Late Pleniglacial age penetrating into the underlying Middle Pleniglacial one.

Experimental data

Non-disturbed, oriented 2.5 cm samples were obtained by gently hammering 15 cm-long thin-walled plastic tubes for about 8 cm into the cleaned wall of the pit, with the aid of a hollow brass cylinder and piston. The dip and geographical or true azimuth of the protruding plastic tubes were determined with a precision of about 1–2°. A first series of 109 samples was taken at the level of the humic Warneton soil (level AA′) and a second series of 101 samples in the reddish Rocourt soil (level BB′) (Fig. 3). These horizons can easily be followed across the exposure. The filled tubes were sliced and sealed immediately with a cold-setting epoxy and their natural remanent magnetization (NRM) measured with a high-sensitivity JR-3 spinner magnetometer.

Alternating field demagnetization curves of some pilot samples of both levels have nearly the same shape, pointing to similar coercive force spectra and magnetization components (Fig. 4). The median destructive field (MDF), which is the alternating field value necessary to randomize half of the initial remanence, is relatively high and varies between about 25 and 75 millitesla. Although the exact magnetization mechanism of the loess and interbedded palaeosols is still not known with certainty, the high stability against the action of alternating fields and the shape of the demagnetization curves support the presence of a depositional or post-depositional remanent magnetization (DRM

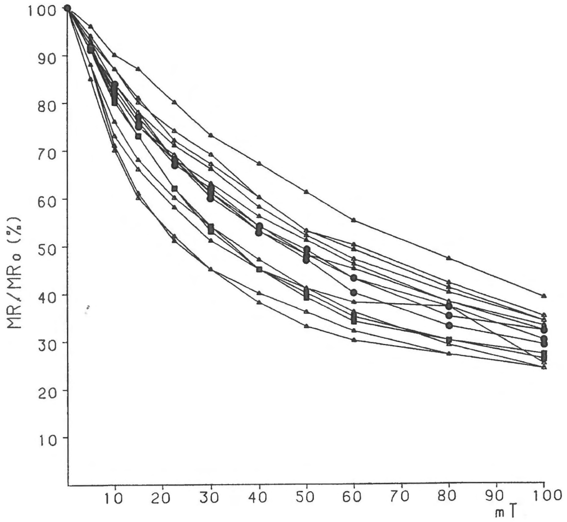


Fig. 4. Alternating field demagnetization curves or ratio of residual remanence to original remanence (MR/MRo) versus alternating field, Tongrinne (■: non-disturbed, △: disturbed, ●: wedge filling).

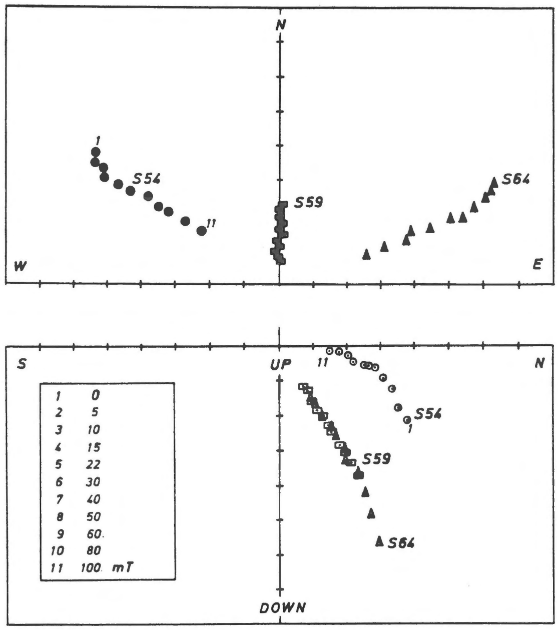
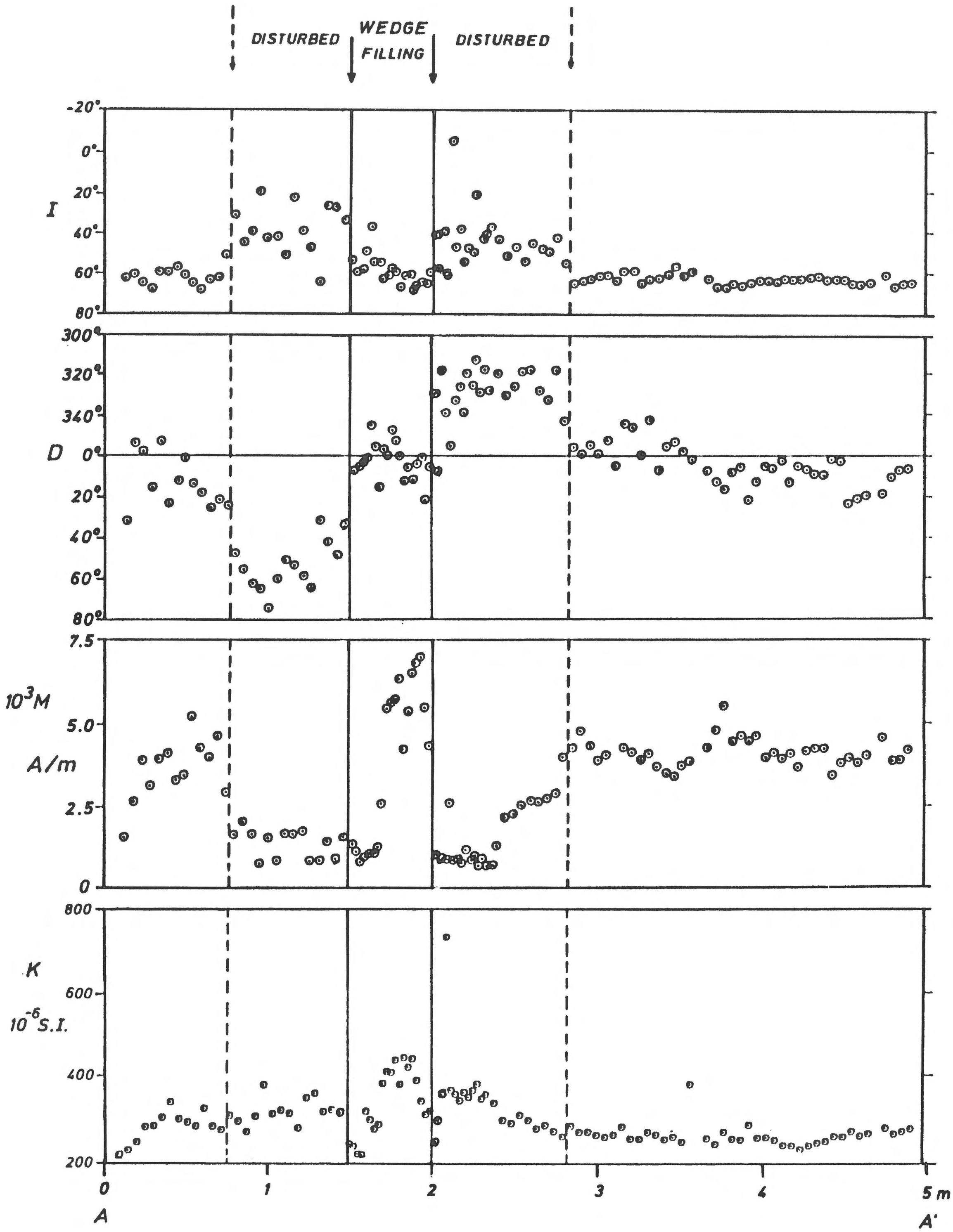


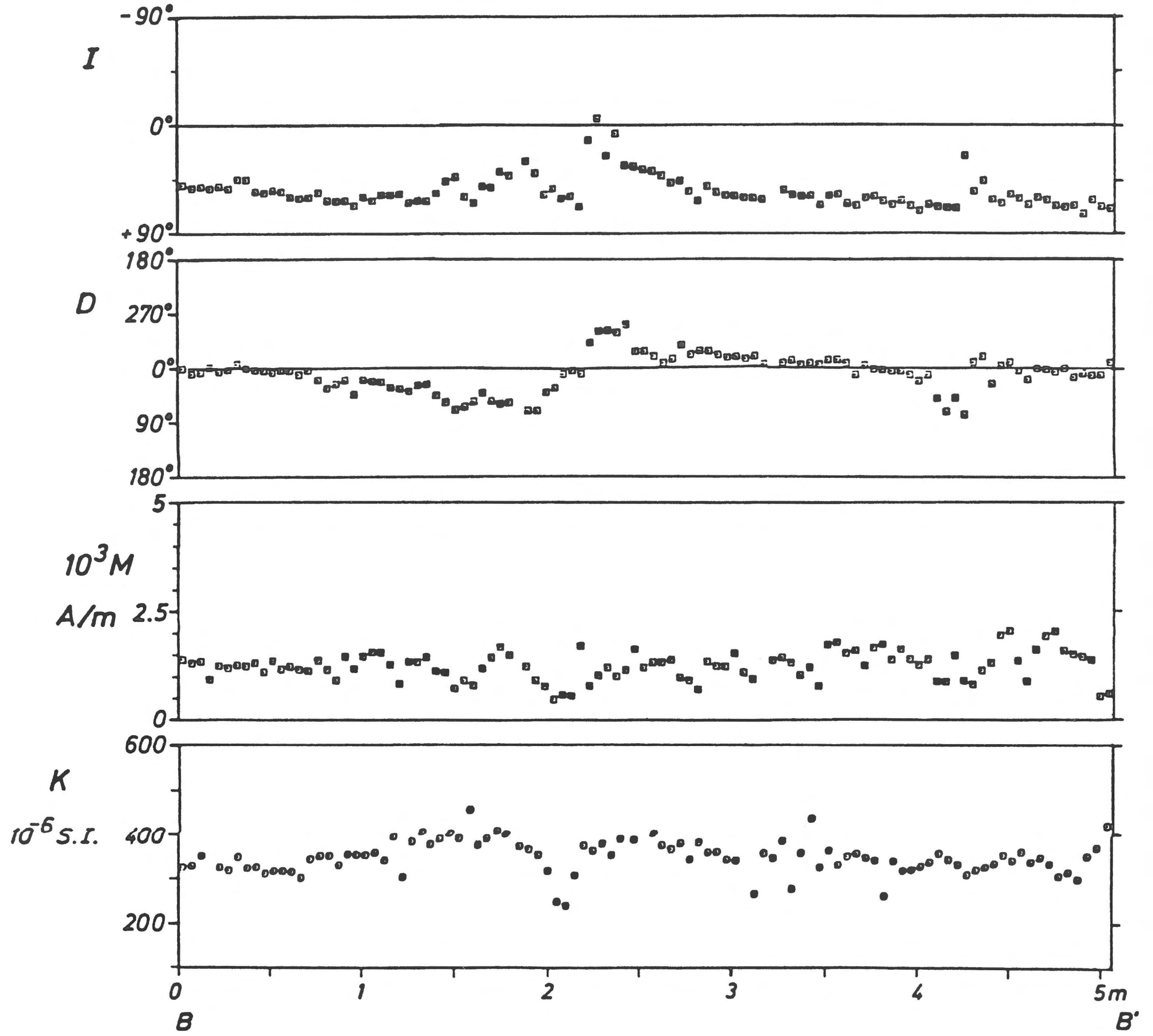
Fig. 5. Orthogonal vector diagrams showing directional behaviour of remanent magnetization during stepwise alternating field demagnetization, Tongrinne. (59 = wedge filling, 54, 64 = deformed strata, closed symbols denote orthogonal projection on horizontal plane, open symbols orthogonal projection on vertical plane containing NS direction.)

or PDRM). From the directional behaviour of the NRM during stepwise alternating field demagnetization it is, however, clear that two magnetization components are present. The orthogonal vector diagrams of three samples are given in Fig. 5 to illustrate this: sample 59 from the wedge filling and samples 54 and 64 from the deformed strata. In these diagrams the dots represent the orthogonal projections of the north-seeking end-points of the magnetization vector, respectively on the horizontal plane (closed symbols) and on the vertical plane through the N-S direction (open symbols) after each demagnetization step. In the samples from the deformed strata, a stable end-direction is only attained after removal of a soft magnetization component in alternating fields of about 20 millitesla. Assuming that the soft component is of viscous origin, acquired in the present field or a field not very different from the actual field, it is possible to estimate the viscous remanent magnetization (VRM) which occurred after deformation (after the last glaciation in our case). The amount varies from sample to sample between about 30 to 60% of the total magnetization. As the direction of the Late Quaternary magnetic field was not very different from the present field direction, it is often difficult to distinguish the VRM from the NRM in these deposits. In deformed strata it may be possible to separate the two components as outlined above. When stored during one month in the laboratory's magnetic field (about 47 microtesla), a VRM builds up spontaneously in the previously demagnetized samples, which amounts to about 5 to 15% of the NRM. Laboratory tests showed that the mean destructive field of a VRM, acquired during two months in the present earth-magnetic field, was very much less than that of the NRM.

The vectors in Fig. 3 represent the horizontal components of the NRM of the samples, taken at the two different levels across the fossil wedge, after partial demagnetization in an alternating magnetic field of 30 millitesla. Inclination, declination, total magnetization intensity after alternating field demagnetization at 30 millitesla and magnetic susceptibility of the samples are plotted in Figs 6a, b. The bulk magnetic susceptibility was obtained after measurement along three perpendicular sample directions in a field of 80 Am^{-1}, at a frequency of 970 Hz, using a Kappabridge KLY-1. From Figs 3


DISTURBED
WEDGE FILLING
DISTURBED
I
-20°
0°
20°
40°
60°
80°
D
300°
320°
340°
0°
20°
40°
60°
80°
10^3M
A/m
7.5
5.0
2.5
0
K
10^{-6} S.I.
800
600
400
200
0
1
2
3
4
5 m
A
A'

(a)



(b)

Fig. 6. Magnetic inclination (I), declination (D), total magnetization intensity (M; in Am^{-1}) and magnetic susceptibility (K; in SI units) across the ice-wedge cast at the level of a) the Warneton soil (level AA′ in Fig. 3) and b) the Rocourt soil (level BB′).

and 6a and b, one can notice that at a large distance from the wedge, the 'cleaned' NRM vectors point nearly in the same direction. The direction is northerly and the average inclination not very different from that corresponding with an axial dipole field. On the contrary, large directional changes occur near the wedge, indicating that the strata have been deformed. In the deformed zones, the inclination is more shallow by about 20 to 25° compared to the inclination in non-disturbed samples. Deviations in declination, as large as 50°, are observed especially in the upturned Rocourt soil. Inside the wedge, the magnetization vectors point again in the same direction and two fillings can be easily recognized on the basis of their magnetization intensity. Indeed, the large contrast in remanence intensity by a factor 2.7 can hardly be attributed solely to geomagnetic field changes but is merely linked to differences in lithology. These wedge fillings have probably acquired their magnetization during melting of the permafrost. The mean inclination and declination, obtained by Fisher's statistic (Fisher 1953), of samples of the less disturbed zones, the wedge fillings and the highly disturbed zones, taken at level AA′, are given in Table 1. Assuming that the sediments were magnetized initially in a uniform direction, the dispersion of the directions of the deformed zones is related to the degree of movement, if the forces acting during the deformation were insufficient to change the magnetization itself. Indeed, deflections of the magnetization vectors may also have occurred by stresses and shearing associated with the deformation. Even a new magnetization, called a shear remanent magnetization, may have appeared, caused by shear strain and squeezing (Games 1977). In the deformed zones, the scatter of the individual magnetization directions is much higher, as can be clearly seen for the inclination in Figs 6a and b, and the magnetization intensity is lower, compared to the non-disturbed samples. This can be rather well explained by small relative movements of the sediment particles during deformation, resulting in an increase of the dispersion of the magnetization directions and, consequently, a decrease of the bulk magnetization intensity. Comparison of the mean directions and the dispersions about the mean directions of samples taken in the upturned Rocourt soil, WNW of the fossil wedge, with samples of the ESE side, leads to the conclusion that the former have been subjected to greater movements than the latter. This result is equally supported by field observations.

Table 1. Declination (D) and inclination (I) of the average magnetization directions in the less disturbed and highly deformed strata at level AA′ in Tongrinne, obtained by Fisher's analyses (Fisher 1953). (Declination is given in degrees of geographical north, inclination is given in degrees and reckoned positive when the magnetization is downward, α 95 is the circle of confidence in degrees at a probability level of 95%, k is Fisher's estimate of precision and N the total number of vectors or samples.)

	N	D	I	α 95	k
Less disturbed					
Warneton soil ESE	39	5.7	63.7	1.0	271
Warneton soil WNW	13	13.3	62.2	2.8	111
Wedge fillings	20	0.3	58.8	3.0	61
Disturbed					
ESE	22	329.3	45.2	4.8	22
WNW	14	54.0	38.3	5.5	28

Two wedge fillings can be differentiated, not only on the basis of their remanence intensity, but also because of their different weak-field response or weak-field magnetic susceptibility. Both these structure-sensitive, rock-magnetic properties depend on the chemical composition, grain size and shape of the magnetic minerals present. In contrast to the second parameter, the first one is also field-dependent in case of a DRM. The high remanence and susceptibility values of one of the fillings (Figs 6a, b) are not significantly different from the values found in a previous study for the Late Pleniglacial loess (Hus & Geeraerts 1986). The same can be noticed for the NRM of a series of 134 samples recovered along a vertical profile passing more or less through the middle of the fossil wedge (Fig. 7). The other filling has a much lower remanence by a factor of about 2.7 (Figs 6a, b and bottom part of Fig. 7) and also a lower magnetic susceptibility (Figs 6a, b) by a factor 1.5. Comparison with the values found for a vertical profile which was sampled in 1986 at a few metres distant from the wedge supports the idea that the second filling is of Middle Pleniglacial age (Hus & Geeraerts 1986).

Implications and conclusions

The palaeomagnetic investigation, and in particular the magnetic stability tests, indicate that the deformed strata near the fossil ice wedge possess at least part of a magnetization acquired prior to deformations, that has remained stable subsequent to deformation (see also Graham 1949). An important VRM has probably been acquired afterwards. The retention of directional anomalies in the deformed strata suggests that the sediments are capable of maintaining at least part of their original magnetization for a relatively long period of time, in this case at least 50 000 years.

Not only ice-wedging but also other periglacial features like involutions, creep, solifluction, etc., may have influenced greatly the initial remanence recorded in sediments. Maps of the distribution of

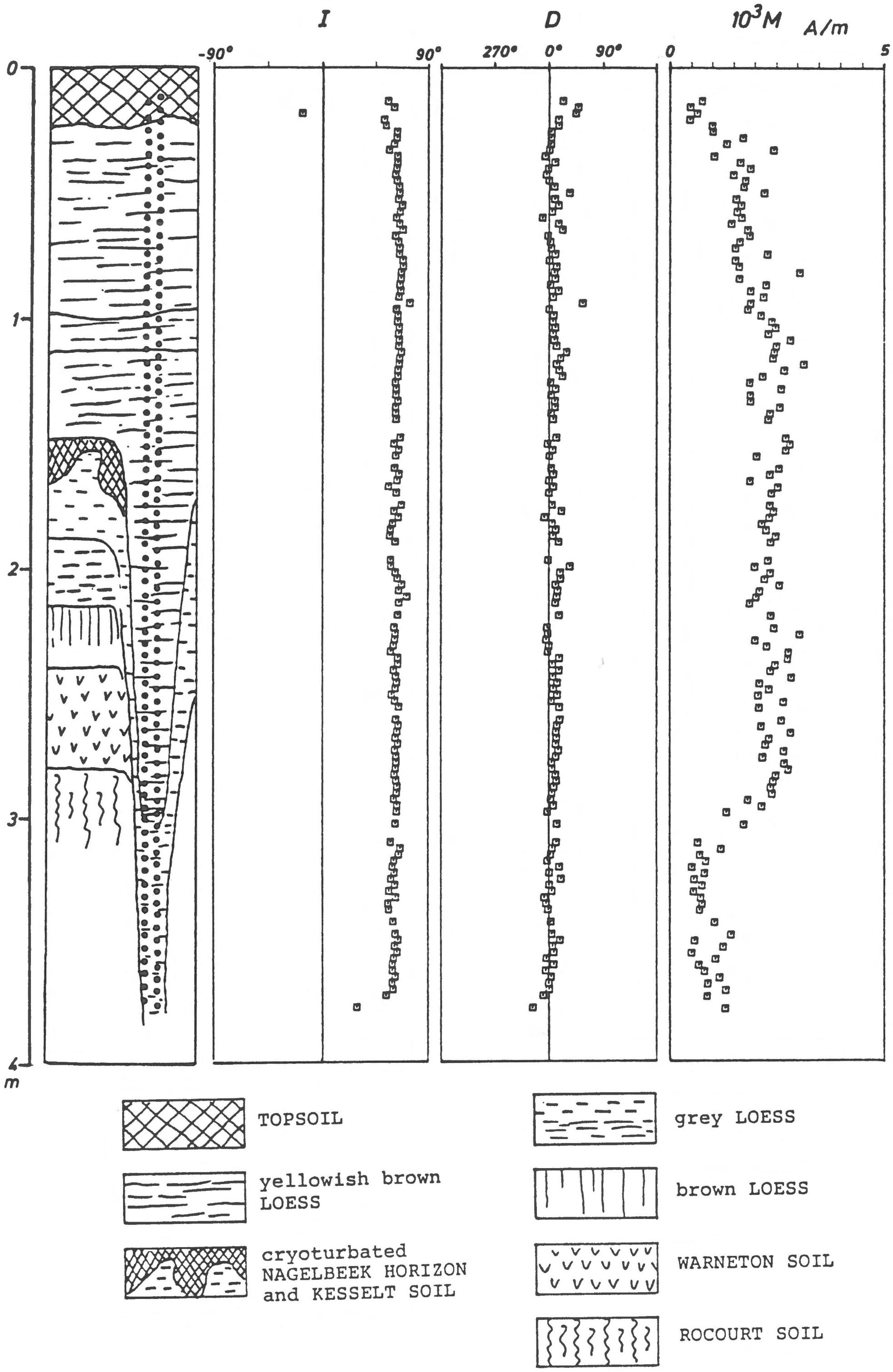


Fig. 7. Inclination (I), declination (D) and magnetization (M) intensity of the Late Pleistocene loess deposits at Tongrinne along a vertical profile passing more or less through the middle of the ice-wedge cast of Fig. 2.

Last Glacial, periglacial features in Europe illustrate well the extent of their occurrence (Poser 1948, Kaiser 1960, Velichko 1972, Eissmann 1981). Therefore, great care should be exercised when taking samples for palaeomagnetic purposes in order to avoid disturbed regions. Deformation due to periglacial activity may not be recognized when the sediment is sampled by coring, and anomalous direction changes found might be erroneously interpreted as 'excursions' of the geomagnetic field (cf. Verosub 1977). It may be impossible to determine the short-term behaviour of the geomagnetic field from magnetization measurements in these sediments and magnetostratigraphical correlations based on the short-term field fluctuations and 'excursions' observed should be regarded with caution.

The wedge fillings which could be recognized in the field, can also be differentiated on the basis of their remanent magnetization intensity and weak field response or magnetic susceptibility.

Although the directional anomalies observed in the deformed strata cannot be used to determine the exact stress history, they enable us to evaluate the strain, and they are an easy aid to visualize relationships of the various fabric elements of a deformed zone.

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References

Bertouille, H. 1971 Théories physiques appliquées à quelques phénomènes de cryergie – Colloque Internat. Géomorphologie. Liège-Caen, Communication à Caen 7: 132–155

Dylik, J. & G.C. Maarleveld 1967 Frost cracks, frost fissures and related polygons – Meded. Geol. Stichting N.S. 18: 7–21

Eissmann, L. 1981 Periglaziäre Prozesse und Permafroststrukturen aus sechs Kaltzeiten des Quartärs – Altenburger Naturwiss. Forsch. 1: 1–171

Fisher, R.A. 1953 Dispersion on a sphere – Proc. R. Soc. (London) A. 217: 295–305

Flint, R.F. 1971 Glacial and Quaternary Geology – Wiley, New York, 802 pp

Games, K.P. 1977 The magnitude of the palaeomagnetic field a new non-thermal non-detrital method using sun-dried bricks – Geophys. J.R. Astr. Soc. 48: 315–330

Gilot, E. 1984 Datations radiométriques. In: D. Cahen & P. Haesaerts (eds): Peuples chasseurs de la Belgique préhistorique dans leur cadre naturel – Inst. Roy. Sci. nat. Belgique, Bruxelles: 115–125

Graham, J.W. 1949 The stability and significance of magnetism in sedimentary rocks – Journal Geophys Res 54, 2: 133–167

Gullentops, F. 1954 Contributions à la chronologie du Pleistocene et des formes du relief en Belgique – Mém. Inst. Géol. Louvain XVIII: 125–252

Gullentops, F. 1981 About the climate of the last glaciation in NW Europe – Reprint of Conference of 2nd June 1981, Symposium on Quaternary Climatic Variations, Univ. Cathol. Louvain

Gullentops, F., E. Paulissen & J. Vandenberghe 1981 Fossil periglacial phenomena in NE-Belgium – Biuletyn Peryglacjalny 28: 345–365

Haesaerts, P. & B. van Vliet-Lanoë 1981 Phénomènes periglaciaires et sols fossiles observés à Maisières-Canal, à Harmignies et à Rocourt – Biuletyn Peryglacjalny 28: 291–325

Haesaerts, P., E. Juvigné, O. Kuyl, H. Mucher & W. Roebroeks 1981 Compte rendu de l'excursion du 13 juin 1981, en Hesbaye et au Limbourg néérlandais, consacrée à la chronostratigraphie des loess du Pléistocène supérieur – Ann. Soc. Géol. Belg. 104: 223–240

Haesaerts, P. 1984 Aspects de l'évolution du paysage et de l'environnement en Belgique au Quaternaire. In: D. Cahen & P. Haesaerts (eds): Peuples chasseurs de la Belgique préhistorique dans leur cadre natural – Inst. Roy. Sci. nat. Belgique, Bruxelles: 27–39

Hus, J., R. Paepe, R. Geeraerts & J. Sommé 1976 Preliminary magnetostratigraphical results of Pleistocene sequences in Belgium and Northwest France – I.G.C.P. Project: Quaternary glaciations in the Northern Hemisphere, Bellingham (U.S.A.) 3: 99–128

Hus, J.J. & R. Geeraerts 1986 Palaeomagnetic and rock magnetic investigation of Late Pleistocene loess deposits in Belgium – Phys. Earth Planet. Inter. 44: 21–40

Hus, J.J. 1991 Polarity magnetostratigraphy in Quaternary Research – Geobound 2: 100–113

Juvigné, E.H. & A.G. Wintle 1988 A new chronostratigraphy of the Late Weichselian loess units in Middle Europe based on thermoluminescence dating – Eiszeitalter und Gegenwart 38: 94–105

Kaiser, K.H. 1960 Klimazeugen des periglazialen Dauerfrost-boden in Mittel und Westeuropa – Eiszeitalter und Gegenwart 11: 121–141

Lachenbruch, A.H. 1962 Mechanisms of thermal contraction cracks and ice-wedge polygons in permafrost – Geol. Soc. America Special Papers 70: 1–69

Maarleveld, G. 1960 Les phénomènes périglaciaires au Pleistocène ancien et moyen aux Pays-Bas – Biuletyn Peryglacjalny 9: 135–141

Paepe, R. 1968 Les sols fossiles pléistocènes de la Belgique – Pédologie 18: 176–188

Paepe, R. & R. Vanhoorne 1967 The stratigraphy and palaeobotany of the Late Pleistocene in Belgium – Cartes Géol. Min. Belgique, Mem. 8: 1–96

Paepe, R. & W. Zagwijn 1972 Possibilités de corrélation des dépôts weichséliens de la Belgique et des Pays-Bas – Assoc. Franç. Étude du Quaternaire Bull. 9: 64–69

Pissart, A. 1970 Les phénomènes physiques essentiels liés au gel. Les structures périglaciaires qui en résultent et leur signification climatique – Ann. Soc. Géol. Belg. 93: 7–49

Poser, H. 1948 Boden und Klimaverhältnisse in Mittel und Westeuropa während der Würmeiszeit – Erdkunde 2: 53–68

Vandenberghe, J. 1985 Paleoenvironment and stratigraphy during the Last Glacial in the Belgian-Dutch border region – Quat. Research 24: 23–38

Vandenberghe, J. 1988 Cryoturbations. In: M.J. Clark (ed.): Advances in Periglacial Geomorphology. John Wiley & Sons Ltd: 179–198

Vandenberghe, J. & P. Van den Broek 1982 Weichselian convolution phenomena and processes in fine sediments – Boreas 11: 299–315

Vandenberghe, J. & C. Kasse 1989 Periglacial environments during the Early-Pleistocene in the southern Netherlands and northern Belgium – Palaeogeogr., Palaeoclimat., Palaeoecol. 72: 133–139

Van der Hammen, T., G. Maarleveld, J. Vogel & W. Zagwijn 1967 Stratigraphy, climatic succession and radiocarbon dating of the last glacial in The Netherlands – Geol. Mijnbouw 46: 79–95

Velichko, A.A. 1972 La morphologie cryogène relicte: caractères fondamentaux et cartographie – Zeitschr. Geomorphologie, Supplementband 13: 59–72

Verosub, K.L. 1977 Geomagnetic excursions and their paleomagnetic record – Revs. Geophys. Space Phys. 15: 145–155

Washburn, A.L. 1973 Periglacial Processes and Environments – Edward Arnold Publ., London, 320 pp

Zagwijn, W.H. 1957 Vegetation, climate and time-correlations in the Early Pleistocene of Europe – Geol. Mijnbouw N.S. 19: 233–244

Zagwijn, W.H. 1961 Vegetation, climate and radiocarbon datings in the Late Pleistocene of the Netherlands. Part 1: Eemian and Early Weichselian – Meded. Geol. Stichting N.S. 14: 15–45

Zagwijn, W.H. 1974 Vegetation, climate and radiocarbon datings in the Late Pleistocene of the Netherlands. Part 2: Middle Weichselian – Meded. Rijks Geol. Dienst N.S. 25: 101–110

Zagwijn, W.H. & R. Paepe 1968 Die Stratigraphie der weichselzeitlichen Ablagerungen der Niederlände und Belgiens – Eiszeitalter und Gegenwart 19: 129–146