Géographie physique et Quaternaire

Middle Wisconsinan Climate Fluctuations Recorded in Central Alaskan Loess

Les fluctuations climatiques du Wisconsinien moyen identifiées dans les loess du centre de l'Alaska

Klimatische Fluktuationen im mittleren Wiskonsinium, aufgezeichnet im Löss von Zentral-Alaska

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Volume 44, numéro 1, 1990

URI : https://id.erudit.org/iderudit/032793ar
DOI : https://doi.org/10.7202/032793ar

Éditeur(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (imprimé)
1492-143X (numérique)

Citer cet article

Begét, J. (1990). Middle Wisconsinan Climate Fluctuations Recorded in Central Alaskan Loess. *Géographie physique et Quaternaire*, *44*(1), 3–13. https://doi.org/10.7202/032793ar

Résumé de l'article

Les courbes climatiques très précises tracées à partir des profils de susceptibilité magnétique faites sur le loess du centre de l'Alaska ont montré des fluctuations au Wisconsinien moyen. Deux intervalles de vents de faible intensité et de réchauffement climatique, séparés par une période de vents plus forts, ont pu être reconstitués à partir de plusieurs inventaires loessiques du Wisconsinien moyen. Les dates au radiocarbone recueillies sur le loess du Fox Permafrost Tunnel montre que l'optimum de la dernière période de vents faibles a eu lieu vers 30-32 ka BP, et qu'il était associé à une régression du pergélisol. Une période plus ancienne de vents faibles au début du Wisconsinien moyen (vers 50-60 ka BP) correspond à un horizon de bois fossile du Permafrost Tunnel et à un paléosol d'une grande superficie dans les régions de loess. Des intervalles datant de la même époque ont été observés à partir des données polliniques de Grande Pile, provenant de carottes marines et de glace. Les périodes chaudes de 30-32 ka et de 50-60 ka BP relevées dans les séquences de loess de l'Alaska ont peut-être été provoquées par l'effet de serre en raison de l'augmentation du CO2 atmosphérique comme l'a enregistrée la carotte de glace de Vostok. L'intervalle de vents plus intenses associé au développement de coins de glace reflète peut-être un refroidissement climatique lié aux faibles valeurs de CO2 atmosphérique, vers 42 ka BP.

Géographie physique et Quaternaire, 1990, vol. 44, n° 1, p. 3-13, 8 fig.

MIDDLE WISCONSINAN CLIMATE FLUCTUATIONS RECORDED IN CENTRAL ALASKAN LOESS

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ABSTRACT Fluctuations in Middle Wisconsinan environments are recorded in high resolution proxy climatic curves derived from magnetic susceptibility profiling of central Alaskan loess. Two intervals of low wind intensity and climatic amelioration, separated by a period of somewhat higher wind intensity, can be recognized in several loess records of the Middle Wisconsinan. Radiocarbon dates from loess in the Fox Permafrost Tunnel indicate that the culmination of the later period of low wind intensity occurred *ca.* 30-32,000 yr BP, and was associated with thermal degradation of permafrost. An older period of low wind intensity early in the Middle Wisconsinan, *ca.* 50-60,000 yr BP, is correlative with a fossil wood horizon in the permafrost tunnel and a widespread paleosol in loess sections. Warm intervals of similar age are recorded in the Grande Pile pollen record, in ice cores and in marines cores. The 30-32,000 yr BP and the 50-60,000 yr BP warm events recorded in Alaskan loess sequences may have been caused by "greenhouse" warming produced by transient increases in atmospheric CO_2 as recorded in the Vostok ice core. A Middle Wisconsinan interval of higher wind intensity, associated with the development of ice wedges, may reflect climatic cooling due to low atmospheric CO_2 values *ca.* 42,000 yr BP.

RÉSUMÉ *Les fluctuations climatiques du Wisconsinien moyen identifiées dans les loess du centre de l'Alaska.* Les courbes climatiques très précises tracées à partir des profils de susceptibilité magnétique faites sur le loess du centre de l'Alaska ont montré des fluctuations au Wisconsinien moyen. Deux intervalles de vents de faible intensité et de réchauffement climatique, séparés par une période de vents plus forts, ont pu être reconstitués à partir de plusieurs inventaires loessiques du Wisconsinien moyen. Les dates au radiocarbone recueillies sur le loess du Fox Permafrost Tunnel montre que l'optimum de la dernière période de vents faibles a eu lieu vers 30-32 ka BP, et qu'il était associé à une régression du pergélisol. Une période plus ancienne de vents faibles au début du Wisconsinien moyen (vers 50-60 ka BP) correspond à un horizon de bois fossile du Permafrost Tunnel et à un paléosol d'une grande superficie dans les régions de loess. Des intervalles datant de la même époque ont été observés à partir des données polliniques de Grande Pile, provenant de carottes marines et de glace. Les périodes chaudes de 30-32 ka et de 50-60 ka BP relevées dans les séquences de loess de l'Alaska ont peut-être été provoquées par l'effet de serre en raison de l'augmentation du CO_2 atmosphérique comme l'a enregistrée la carotte de glace de Vostok. L'intervalle de vents plus intenses associé au développement de coins de glace reflète peut-être un refroidissement climatique lié aux faibles valeurs de CO_2 atmosphérique, vers 42 ka BP.

ZUSAMMENFASSUNG *Klimatische Fluktuationen im mittleren Wiskonsinium, aufgezeichnet im Löss von Zentral-Alaska.* Die Fluktuationen in der Umwelt des mittleren Wiskonsiniums sind in sehr präzisen Klimakurven abgebildet, die mittels Magnet-Empfindlichkeitsprofilen auf dem Löss von Zentral-Alaska aufgezeichnet wurden. Zwei Intervalle niedriger Windintensität und klimatischer Verbesserung, die durch eine Periode relativ höherer Windintensität unterbrochen wurden, können in einigen Lössaufzeichnungen aus dem mittleren Wiskonsinium erkannt werden. Radiokarbondatierungen von Löss in dem Fox-Permafrost-Tunnel zeigen, dass der Höhepunkt der späteren Periode mit geringer Windintensität um *ca.* 30-32 000 Jahre v.u.Z. eintrat und mit der thermischen Abtragung des Permafrostbodens verbunden war. Eine ältere Periode geringer Windintensität zu Beginn des mittleren Wiskonsiniums, *ca.* 50-60 000 Jahre v.u.Z. korreliert mit einem fossilen Holz-Horizont im Permafrost-Tunnel und einem ausgedehnten Paläoboden in den Lössabschnitten. Warme Intervalle ähnlichen Alters sind in dem Pollen-Zeugnis von Grande-Pile aufgezeichnet, in den Eis und in den marinen Kernen. Die warmen Perioden um 30-32 000 Jahre v.u.Z. und 50-50 000 Jahre v.u.Z., die in Lösssequenzen von Alaska aufgezeichnet sind, könnten durch "Treibhaus-Effekt" wegen der Erhöhung des CO_2 in der Atmosphäre hervorgerufen worden sein, wie im Eisbohrkern von Vostok nachweisbar. Ein Intervall höherer Windintensität im mittleren Wiskonsinium verbunden mit der Entwicklung von Eiskeilen mag eine klimatische Abkühlung als Folge von niedrigen CO_2-Werten in der Atmosphäre um *ca*, 42 000 Jahre v.u.Z. spiegeln.

Manuscrit reçu le 10 mai 1989; manuscrit révisé accepté le 23 octobre 1989

INTRODUCTION

Magnetic susceptibility profiling of Quaternary loess can, in some cases, produce proxy climate curves which closely resemble marine isotope curves (Kukla *et al.*, 1988; Begét and Hawkins, 1989; Begét *et al.,* 1990). This suggests that proxy climate records from loess have the potential to complement Quaternary proxy climatic data sets obtained by coring marine and lacustrine sediments and ice sheets, and may shed new light on the history of climate change in terrestrial areas.

This paper presents the results of detailed magnetic susceptibility studies of Late Pleistocene loess sections in central Alaska (Fig. 1). These studies were undertaken to determine (1) if radiocarbon dating would support apparent correlations between marine isotope curves and proxy climate curves produced by magnetic susceptibility studies of loess sections; (2) if higher sampling frequencies during stratigraphic studies of loess can produce detailed proxy climatic curves, particularly in areas where loess sedimentation rates are high; and (3) if such high resolution proxy climate curves from central Alaskan loess can be correlated with other detailed proxy climate curves from around the world.

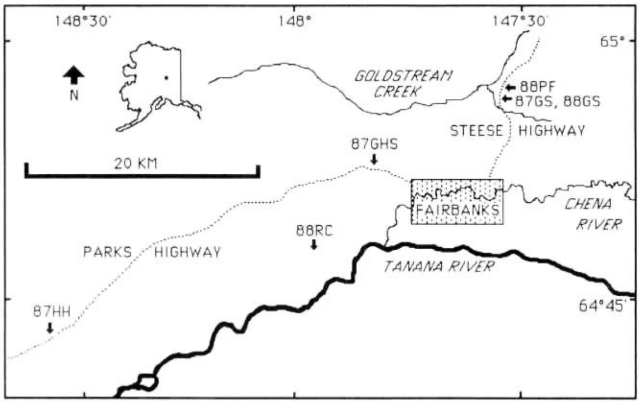

FIGURE 1. Location of selected loess sections in central Alaska near Fairbanks, Alaska. 88PF: Fox Permafrost Tunnel; 87GS and 88GS: Goldstream Valley; 87GHS: Gold Hill Steps locality; 88RC: Rosie Creek; 88HH: Halfway House.

Localisation des sites loessiques choisis, à proximité de Fairbanks, au centre de l'Alaska. 88PF: Fox Permafrost Tunnel; 87GS et 88GS: Goldstream Valley; 87GHS: Gold Hill Steps; 88RC: Rosie Creek; 88HH: Halfway House.

HIGH RESOLUTION MAGNETIC SUSCEPTIBILITY PROFILING OF LOESS

Several published reports on magnetic susceptibility profiling of loess in China (Tungsheng *et al.*, 1985; Kukla, 1987; Kukla *et al.*, 1988) first showed that the patterns of susceptibility variations measured through loess sections mirror the record of marine isotope stages. Statistical tests of the similarity between magnetic susceptibility profiles from Alaskan loess and marine isotope curves are highly significant, and confirm the proxy climatic character of the susceptibility signal (Begét and Hawkins, 1989).

The magnetic susceptibility of sediments is strongly related to the content of magnetite, and to a much lesser degree to the content of other iron-bearing minerals (Nettleton, 1971; Sharma, 1986). The content of magnetite in sediments can change as sedimentation is affected by variations in climate and environment. In marine cores, susceptibility variations are linked to changes in influx of eolian sediment due to changes in wind intensity and competence, so that interglacial sediments deposited during times of low atmospheric circulation intensity have lower susceptibilities than sediments deposited during full-glacial conditions. The discovery that, "the susceptibility signal... may be directly related to wind direction and intensity" (Leg 117 Scientific Drilling Party, 1988, p. 14) in marine sediments provides a model for interpreting the significance of susceptibility variations in some loess sequences. In central Alaska, eolian sediments deposited during full glacial conditions have high susceptibilities, while Holocene and past interglacial sediments are relatively depleted in ferromagnetic minerals and are characterized by low susceptibility (Begét and Hawkins, 1989). This is quite consistent with abundant field data and global climate models indicating that wind intensity in Alaska during full glacial conditions was significantly greater than in postglacial time (Thorson and Bender, 1985; Kutzbach, 1987).

Independent evidence confirming the link between paleowind intensity and magnetic susceptibility of Alaskan loess comes from studies of loess granulometry. While Alaskan loess is very well sorted, variations as large as 2 phi in the maximum grain size of loess in the Fox Permafrost Tunnel of central Alaska have previously been reported by Hamilton *et al.*, (1988). Such variations in loess grain size probably reflect changes in wind intensity, with somewhat coarser loess being deposited during times of higher wind intensity (Pye, 1987).

Multiple grain size analyses of loess from Goldstream Valley in central Alaska show systematic variations in the granulometry of deposits of different ages, with Holocene and Middle Wisconsinan loess being somewhat finer than loess deposited during the Late Wisconsinan (Fig. 2). A significant relationship exists between the grain size of a loess horizon and its magnetic susceptibility (Fig. 3). We suggest that during times of low wind intensity, loess deposits in central Alaska are relatively depleted in magnetite and large particles by density fractionation during eolian transport. Magnetic susceptibility fluctuations in Alaskan loess are largely proxy measures of wind intensity, although other factors may also influence susceptibility.

Nettleton (1971) and Sharma (1986) have suggested that magnetite, because of its very high susceptibility and common occurrence, is by far the most important mineral controlling magnetic susceptibility in sediments. From Floyd and Trench (1988) and Nettleton (1971) the amount of magnetite in sediment samples is given by:

$$26.55M = P \qquad (1)$$

where M is magnetic susceptibility in SI units, and P is percent magnetite content (by volume). Susceptibility values in central Alaskan loess range from approximately 200×10^{-5} to 10

$\times 10^{-5}$ SI units, corresponding to changes in magnetite content from 0.05% to 0.003%. Because wind intensities can change rapidly in response to environmental changes, eolian deposits in some cases may contain especially sensitive records of past climate changes.

Previous studies of magnetic susceptibility in China and Alaska have been based upon sampling of loess at 10 cm intervals, resulting in a sample frequency and resolution on the order of 10^3 years. However, it is possible to accurately measure loess susceptibilities at higher frequencies, so that sample resolution is improved by an order of magnitude. We suggest that increasing sampling frequency will, in some cases, result in the production of detailed paleoclimatic reconstructions with resolution of 10^2 years from terrestrial areas.

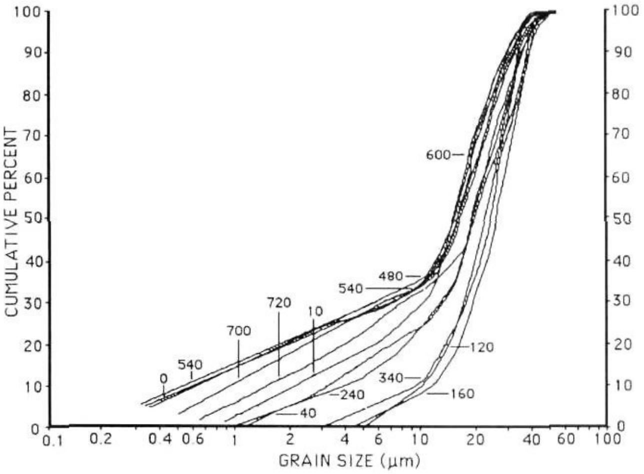

FIGURE 2. Multiple X-ray sedigraph grain size analyses of loess at the Goldstream Valley site. Depths of samples correspond to measured section 87GS-1. Significant amount of fine-grained (<10μm) loess in Holocene and Middle Wisconsinan samples may reflect lower wind speeds or significant contribution from distal loess sources (Pye, 1987).

Analyses granulométriques par rayons x des loess au site de Goldstream Valley. La profondeur des échantillons correspond à celle de la coupe 87GS-1. Une quantité importante des loess fins (<10 μm) recueillie dans les échantillons datant de l'Holocène et du Wisconsinien moyen est liée soit à des vents de faible intensité, soit à des apports considérables de sources éloignées de loess (Pye, 1987).

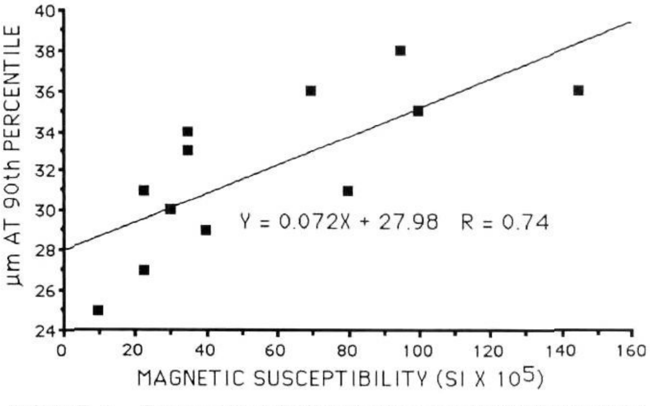

FIGURE 3. Regression plot of magnetic susceptibility versus loess grain size at 90th percentile as determined by sedigraph analyses. Higher susceptibilities are found at horizons of coarser loess, indicating susceptibilities are related to changes in wind intensity and competence during loess deposition.

Courbe de régression de la granulométrie au 90e percentile sur la susceptibilité magnétique, telle que déterminée par les analyses au sédigraphe. Les horizons de loess plus grossiers ont une susceptibilité plus élevée, démontrant ainsi que les susceptibilités sont liées aux changements d'intensité et de compétence des vents au cours de la mise en place du loess.

This report presents the results of analysis at 2 cm intervals through several central Alaskan loess sections, using a Bartington© magnetic susceptibility meter and field probe MS2F. The field probe has a diameter of about 1.5 cm. When measuring a cleaned, flat surface, the sensitivity of the probe falls off logarithmically with distance, so that at a 2 cm spacing there is minimal overlap between the sediments analyzed at successive horizons (Fig. 4). It is advantageous to measure magnetic susceptibility variations of loess in the field, because undisturbed sections should best record the primary variability of the loess, and hence be most sensitive to depositional evidence of past environmental changes.

At several sections magnetic susceptibility values were measured in the field for 3-5 discrete samples at each level, and then averaged. The field measurements are generally in excellent agreement with laboratory measurements of magnetic susceptibility. The accuracy of the MS2F probe is estimated at ± 5%, and in practice successive measurements result in a precision of approximately ± 10%. In the few cases where larger variations were observed, there was often some visible evidence of structural disruption or slumping within the section. Such variability was most often found in zones of paleosols or buried forest beds, and in some cases may reflect the presence of local concentrations of significant amounts of organic material in the loess. Sediment disruption and mixing by melting of ground ice during warm intervals, reworking of

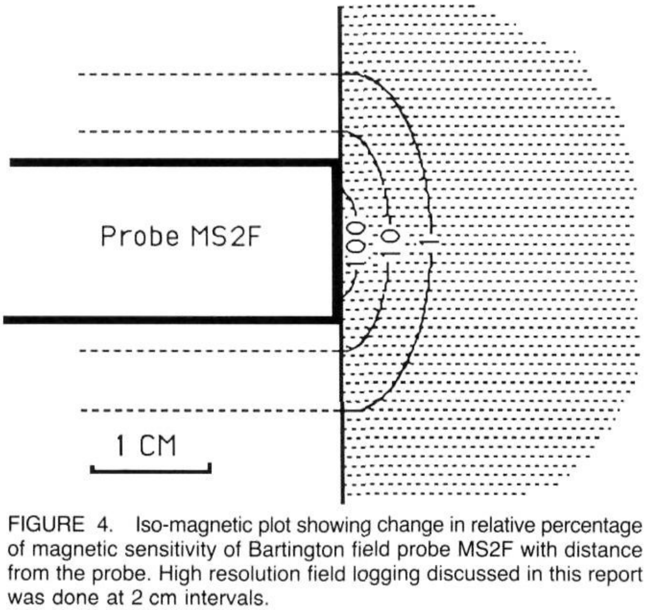

FIGURE 4. Iso-magnetic plot showing change in relative percentage of magnetic sensitivity of Bartington field probe MS2F with distance from the probe. High resolution field logging discussed in this report was done at 2 cm intervals.

Courbes isomagnétiques illustrant le changement du pourcentage relatif de sensibilité magnétique de la sonde Bartington MS2F selon la distance de la sonde. L'analyse du sol a été faite à intervalle de 2 cm.

loess by slopewash or other processes, or significant disruption of the loess by tree-throw or growth and decay of roots during times of forest cover and paleosol formation may also be responsible for some of the inter-sample variability found near paleosols.

MAGNETIC SUSCEPTIBILITY PROFILES OF LOESS FROM GOLDSTREAM VALLEY, ALASKA

Much of the Pleistocene loess which accumulated in low-lying valleys near Fairbanks, Alaska, has been removed by hydraulic mining. However, relict high cliffs of loess left by mining provide exposures tens of meters thick. In Goldstream Valley mining exposures more than 20 m high are found approximately 1 km south of the Fox Permafrost Tunnel, near the intersection of the Steese Highway and the Goldstream Valley Road. At this site a buried peat layer and a forest bed occur near the top of the section, sandwiched by buff and yellow loess (Fig. 1, 3).

Two magnetic susceptibility profiles have been measured through the loess and forest bed at this locality, at sites where the sedimentology of the loess indicated it was a primary eolian deposit (Begét, 1988). The first, 87GS-1, was measured in the laboratory on samples collected at 10 cm intervals, while the second, 88GS-1, was measured in the field at 2 cm intervals approximately 1-2 m north of the first. There is good agreement between the two profiles (Fig. 5). Both sections crossed the peat layer and buried forest bed, which facilitates correlations between the upper parts of the two sections. Radiocarbon dates indicate that the peat layer was formed 3950 ± 60 yr BP (B-24229) and the forest bed was formed between 6300 ± 60 yr BP (B-28543) and 7290 ± 60 yr BP (B-28544). The Holocene sequence is underlain by a zone of massive, buff loess without organic material (zone A, Fig. 5) that has much higher susceptibilities (zone B) and by oxidized loess which shows considerable variability in susceptibility (zone C). The pattern of susceptibility changes allows correlation by curve-fitting between the two profiles (Fig. 5).

Although there is little organic material preserved in most loess exposures, frozen loess in the Fox Permafrost Tunnel has preserved abundant Middle Wisconsinan wood and plant fossils. The tunnel lies about 1.0 km north of sections 87GS-1 and 88GS-1 (Fig. 1), and is excavated into the continuation of the same loess deposit. An important study by Hamilton *et al.* (1988) described the stratigraphy and paleoecology of the sediments within the Fox Permafrost Tunnel, identified the silts as primary eolian deposits, and developed a chronology based on radiocarbon dates from organic material preserved in the loess.

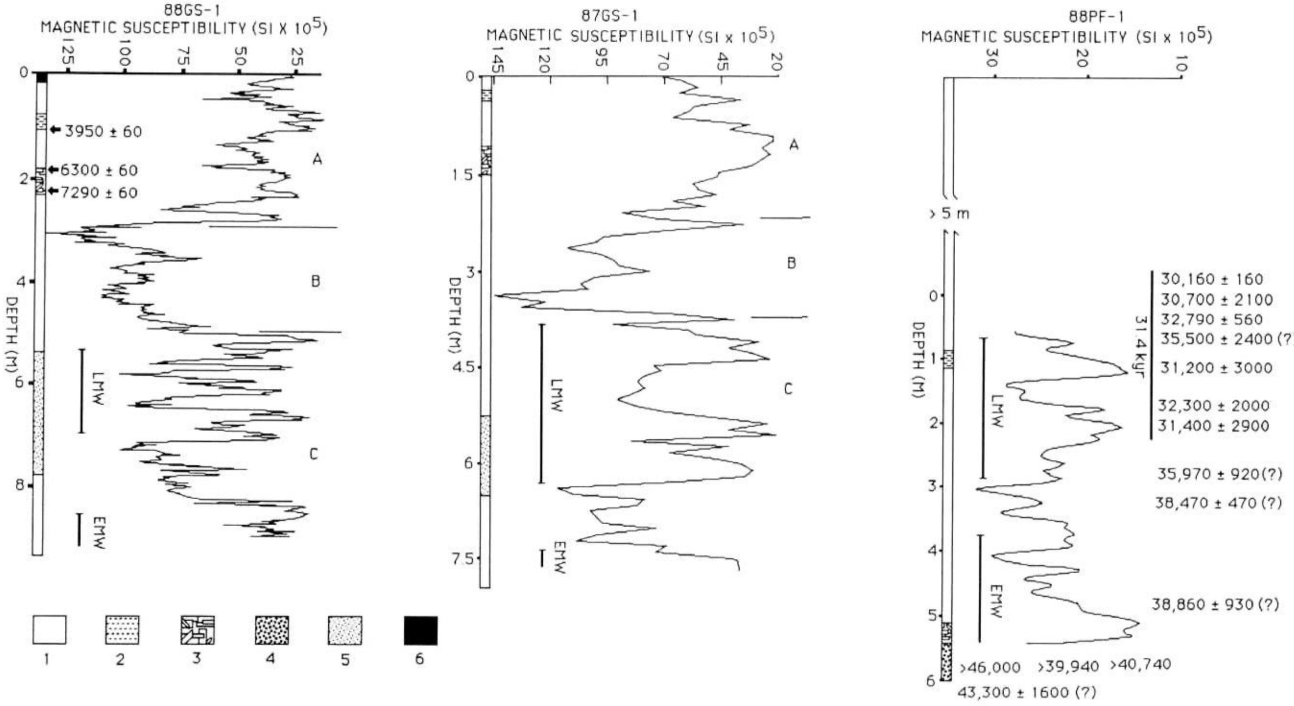

FIGURE 5. Magnetic susceptibility profiles, radiocarbon dates, and simplified lithostratigraphic logs through loess sections in Goldstream Valley. Alternating low and high susceptibility zones in 87GS-1 and 88GS-1 are designated, from youngest to oldest, A (Holocene), B (Late Wisconsinan) and C (Middle Wisconsinan). The radiocarbon dated sequence 88PF-1 from the Fox Permafrost Tunnel is correlated with zone C. Low susceptibility zones dating from the early Middle Wisconsinan (EMW) and late Middle Wisconsinan (LMW) are designated on profiles in zone C. Possibly suspect radiocarbon dates are followed by a question mark.

Courbes de susceptibilité magnétique, dates au radiocarbone et stratigraphie simplifiée des coupes de loess de Goldstream Valley. Les zones de susceptibilité faible et élevée en alternance dans les échantillons 87GS-1 et 88GS-1 sont identifiées, de la plus récente à la plus ancienne: A (Holocène); B (Wisconsinien supérieur); C (Wisconsinien moyen). La séquence 88PF-1 du Fox Permafrost Tunnel datée au radiocarbone correspond à la zone C. Les zones de faible susceptibilité datant du début du Wisconsinien moyen (EMW) et de la fin du Wisconsinien moyen (LMW) sont identifiées dans la zone C. Les datations au radiocarbone incertaines sont suivies d'un point d'interrogation.

Vegetation and slumps cover the surface exposures of loess near the tunnel, so that the closest exposures through the top of the loess sequence in the vicinity of the tunnel are at 87GS-1 and 88GS-1. A stratigraphic log and radiocarbon dates from a ventilation shaft at the permafrost tunnel are quite similar to the upper parts of 87GS-1 and 88GS-1 (Hamilton *et al.*, 1988). Based on the radiocarbon chronology from both sites, stratigraphy, and wiggle matching between susceptibility profiles, the Middle Wisconsinan loess in the permafrost tunnel is correlated with zone C of interior Alaskan loess profiles (Fig. 5).

The loess section tested for magnetic susceptibility variations at the permafrost tunnel lies in a narrow adit that connects the basal tunnel to the upper horizontal tunnel, found approximately 15 m past the point of divergence of the two tunnels. Magnetic susceptibilities were measured at 2-cm intervals through a continuous section which extended from the basal Fox Gravel to near the roof of the upper tunnel through the small connecting adit. The radiocarbon dates reported by Hamilton *et al.* (1988) were collected from different areas of the tunnel complex, and compiled in a composite section. The measured section is tied to this composite section at a prominent thaw horizon above multiple ice wedges, dated by Hamilton *et al.* (1988) at *ca.* 30,000-32,000 yr BP, and easily recognized and traced along the length of the upper tunnel (Fig. 5).

The radiocarbon dates at 87GS-1 and 88GS-1 and those reported by Hamilton *et al.* (1988) can be used to calibrate the age of climate events recorded by prominent peaks in Late Quaternary magnetic susceptibility profiles from central Alaskan loess. The sediments in zone A of sections 87GS-1 and 88GS-1 are characterized by abundant organic material and low susceptibilities, and radiocarbon dates indicate they are Holocene in age. Radiocarbon dates from the ventilation tunnel indicate that loess of similar age overlies the permafrost tunnel, but is now inaccessible (Hamilton *et al.*, 1988). No radiocarbon dates are available from the massive loess in zone B, characterized by high magnetic susceptibilities, which underlies the Holocene sediments at 87GS-1 and 88GS-1, but limiting ages suggest these sediments were deposited sometime before 7500 yr BP, and so were probably deposited mainly during the Late Wisconsinan. The lowermost zone C is then thought to correlate with the radiocarbon-dated Middle Wisconsinan section of frozen loess in the Fox Permafrost Tunnel, deposited more than 30,000 yr BP.

These apparent correlations, based on stratigraphy and radiocarbon dates, are supported by similarities between the magnetic susceptibility profiles of loess in zone C in surface sections and in the permafrost tunnel. The sediments in the permafrost tunnel and zone C of the loess sections are characterized by generally low susceptibilities, but rapid changes between deposition of high and low susceptibility loess are also recorded. Two broad zones of low susceptibility are present in all these sections, one occurring at the base of Zone C and one near the top. The horizon of buried willow trees at the base of the Fox Permafrost Tunnel and an interval of melting of ice wedges recorded near the top of the section in the tunnel are associated with low susceptibility horizons in the eolian silts, and appear to be broadly correlative with these two intervals of low susceptibility within zone C. The low susceptibility measurements, as discussed above, record weak wind intensities, which may have been associated with times of relative warming.

The correlation by curve-fitting between section 88PF-1 measured in the Fox Permafrost Tunnel and other loess sections indicate that these sections overlap, and that zone C contains a record of events as old and older than *ca.* 30,000 yr BP, and corresponds to the Middle Wisconsinan. The general agreement between the pattern of variations in the susceptibility record at multiple sites indicates these changes reflect regional environmental change, including variations in atmospheric circulation intensity and wind competence.

Hamilton *et al.* (1988, Fig. 8) have previously shown that 30,000-32,000 year-old loess in the Fox Permafrost Tunnel is unusually fine-grained, suggesting it records an interval of very low wind intensity during the time of degradation of permafrost. Mesic taxa also increase at this level (Hamilton *et al.*, 1988, Fig. 15). This period appears to constitute an important climatic event in central Alaska which T. D. Hamilton (1989, pers. comm.) suggests be named the Fox thermal interval. The recognition of this event in susceptibility profiles through loess at the Fox Permafrost Tunnel and other loess sites is consistent with this suggestion.

Correlations and chronology of the susceptibility profiles are less clearly defined for the older parts of zone C. The pattern of susceptibility changes in zone C is complex, and shows rapid fluctuations. It is not clear if the rapid fluctuations reflect environmental change, such as the multiple climate jumps known to have occurred at about this time (Broecker *et al.*, 1988), or if they reflect inherent problems of sample resolution and analytical precision. Nonetheless, we suggest that broad similarities exist between 88PF-1 and the pattern of loess susceptibility profiles for zone C at other sites, and that these reflect the general pattern of environmental change during the Middle Wisconsinan. In zone C, recording the Middle Wisconsinan, the 30,000-32,000 yr BP Fox thermal event is preceded by an earlier sequence of loess with higher susceptibilities which appears to record a time of somewhat higher wind intensity before about 36,000 yr BP. Early in zone C low susceptibility measurements record another broad interval of low wind intensities during the early Middle Wisconsinan, which is associated with the buried willow tree layer in the permafrost tunnel (Fig. 5). The age of this older low susceptibility zone is not well defined. Hamilton *et al.* (1988) have suggested that some of the oldest radiocarbon dates in the Fox Permafrost Tunnel are contaminated by younger organic material. Such contamination is common in loess (Goh *et al.*, 1977). If it is conservatively assumed that dates >38,000 yr BP may be minimum ages (Fig. 5), then the oldest part of zone C, correlative with the lower half of 88PF-1 and including the low susceptibility loess found at the boundary between the basal gravel and frozen loess in the permafrost tunnel, lies beyond the limit of conventional radiocarbon dating. The low magnetic susceptibility of loess, presence of tree roots, small willow logs and a weak paleosol, and the absence of ice wedges in the lowermost loess (Hamilton *et al.*, 1988) may reflect low wind speeds and mild environmental conditions during deposition of the oldest loess preserved in the Fox Permafrost Tunnel, at a time early in the Middle Wisconsinan.

THE RECORD OF THE MIDDLE WISCONSINAN OTHER LOESS LOCALITIES

Magnetic susceptibility profiles from several other loess localities in central Alaska can be correlated by curve-fitting with the radiocarbon-dated sections discussed above, and help to provide additional stratigraphic context for the Middle Wisconsinan susceptibility variations recorded in the loess. The magnetic susceptibility profiles in loess from the Fox Permafrost Tunnel and other sites in Goldstream Valley may have been somewhat disrupted by the presence of ice wedges. In addition, it is likely that sections 87GS-1 and 88GS-1 were further disturbed during the melting of ice wedges visible after their exposure (T. D. Hamilton, 1989, pers. comm.) Permafrost at these sites has helped to preserve organic material for radiocarbon dating, but may be responsible for some of the variation in susceptibility observed between curves collected within the same area.

South-facing slopes in central Alaska are largely free of permafrost. Successive buried paleosols and tephras in some loess sections demonstrate that loess deposition has caused slow aggradation of ground surfaces, and the lack of disruption of such marker horizons shows that no large significant erosion or slumping due to permafrost melting has occurred (Begét, 1988). Such undisrupted sections constitute ideal localities to document the effect of environmental changes on the susceptibility of loess.

A long, continuous susceptibility proxy climate record has been measured through loess at the Halfway House locality (Begét and Hawkins, 1989). A high resolution susceptibility profile of the upper part of the Halfway House section (Fig. 6), like those at 88PF-1, 87GS-1, and 88GS-1, shows an upper low susceptibility zone (A) correlated with the Holocene, overlying a Late Wisconsinan low susceptibility zone (B), which in turn overlies a zone of generally low susceptibility marked by significant variability (C). The *ca.* 30,000-32,000 yr BP low susceptibility horizon found in the loess in the Middle Wisconsinan sequence in the permafrost tunnel can be recognized in Halfway House sequence 88HH-1 (Fig. 6), as can the low susceptibility interval thought to have formed early in the Middle Wisconsinan. Interestingly, a weak paleosol designated Sa, and consisting of a 5-15 cm thick Ah horizon over a weak Cox horizon, occurs at approximately 4 m depth at Halfway House. This paleosol may be correlative with the wood-rich loess layer and weak paleosol found at the base of the loess in the permafrost tunnel (Fig. 5). Loess with low susceptibility occurs at Sa, and appears to be correlative with low susceptibility horizons identified in early Middle Wisconsinan loess at the permafrost tunnel and at other sites.

Paleosol Sa occurs just above a high susceptibility zone D in 88HH-1, which appears to be correlative with the Early Wisconsinan, and which in turn precedes zone E, which appears to be correlated with the last interglaciation. A strong

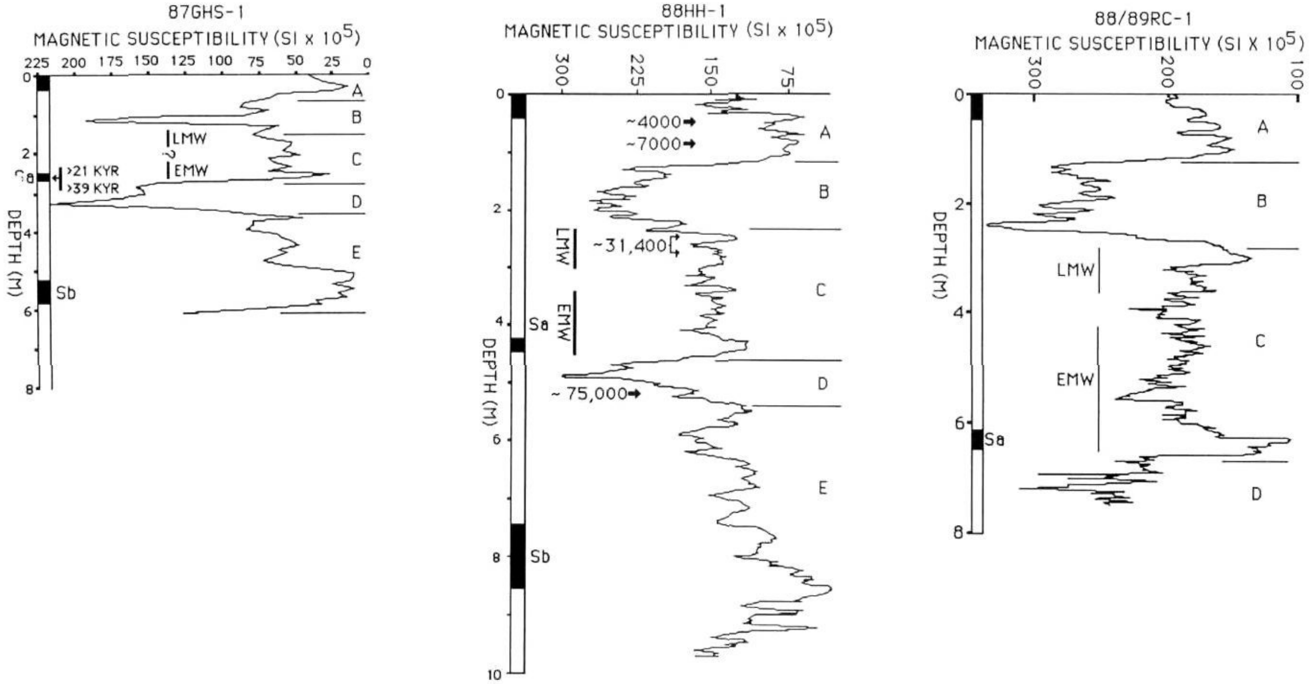

FIGURE 6. Magnetic susceptibility profiles, radiocarbon dates, and simplified lithostratigraphic logs from loess profiles west of Fairbanks, Alaska. A thin paleosol designated Sa which lies beyond the limits of radiocarbon dating, is found at the beginning of zone C at sites 88HH-1, 87GHS-1, and 88/89RC-1. A deeper and thicker paleosol designated Sb is found at sites 88HH-1 and 87GHS-1 and is correlated with the last interglaciation.

Courbes de susceptibilité magnétique, dates au radiocarbone et stratigraphie simplifiée des coupes dans le loess à l'ouest de Faibanks, Alaska. Un paléosol mince, désigné par les lettres Sa, ne pouvant être daté par la méthode au radiocarbone, se situe au début de la zone C aux sites 88HH-1, 87GHS-1 et 88/89RC-1. Un paléosol plus profond et plus épais, appelé Sb, a été trouvé aux sites 88HH-1 et 87GHS-1 et a été mis en corrélation avec le dernier interglaciaire.

paleosol designated Sb occurs at *ca.* 8.0-8.5 m depth in zone E, and probably formed during the last interglacial (Begét and Hawkins, 1989; Begét *et al.,* 1990). These results are consistent with new fission track dates on glass of the Old Crow tephra, found lower in the Halfway House section, which indicate it was deposited prior to the last interglaciation (Westgate, 1988).

A magnetic susceptibility profile measured through loess at the Gold Hill steps locality, named 87GHS-1, also appears to show two low susceptibility zones within loess zone C (Fig. 6). Paleosols Sa and Sb can also be recognized at this locality, and radiocarbon dates on material from the Ah (?) horizon indicate Sa was formed >37,800 yr BP (I-14,960) and >20,200 yr BP (I-14,936). These dates are consistent with the radiocarbon limiting ages from loess and wood from the base of the Fox Permafrost Tunnel, and support the apparent correlation between Sa and wood-bearing loess from the base of the permafrost tunnel.

A susceptibility profile measured through loess exposed in roadcuts along Rosie Creek Road (88/89RC-1) also reveals a similar pattern (Fig. 6). This locality lies within a few kilometers of the Tanana River, the source of most of the loess found in the Fairbanks area. The range of magnetic susceptibilities of the loess are higher at the Rosie Creek site than at any other site yet examined, reflecting its proximity to the source of the loess in the Tanana River.

Sedimentation rates, based on available radiocarbon dates and curve fitting, appear to be highest at sites which lie near fluvial silt sources such as that at Rosie Creek or the sites in Goldstream Valley and lower at sites found at greater distances (Fig. 7). These findings are also consistent with the eolian fractionation model for the variations in grain size and magnetic susceptibility in central Alaskan loess sections. Variations in loess sedimentation rates through time at individual sites are thought to reflect changes in wind sediment capacity and loess supply, but probably are also strongly influenced by longterm changes in surface vegetation and effective surface roughness heights and changes in the length of the summer season during which loess is principally transported (Begét, 1988). Apparent sedimentation rate changes may also reflect postdepositional effects including the progressive compaction of loess downsection or thawing of interstitial ice and ice wedges.

Low susceptibility loess zone A is recognized at the top of profile 88/89RC-1. This is underlain by zone B reflecting deposition of higher susceptibility loess, which in turn is underlain by zone C of loess with generally low susceptibilities, but showing significant variation in susceptibility values. Although no radiocarbon dates are available at 88RC-1, correlation of paleosol Sa and by curve fitting suggests that zone A reflects the Holocene, the next lower zone B with high susceptibilities was deposited during a time of higher wind intensity best correlated with the Late Wisconsinan, and zone C records the Middle Wisconsinan. The upper part of zone C at 88/89RC-1 reflects an interval of low wind intensities and deposition of low susceptibility loess. Paleosol Sa, consisting of a 20-cm-thick Ah and Bh paleosol complex, is associated with a low susceptibility interval correlated with the beginning of the Middle Wisconsinan.

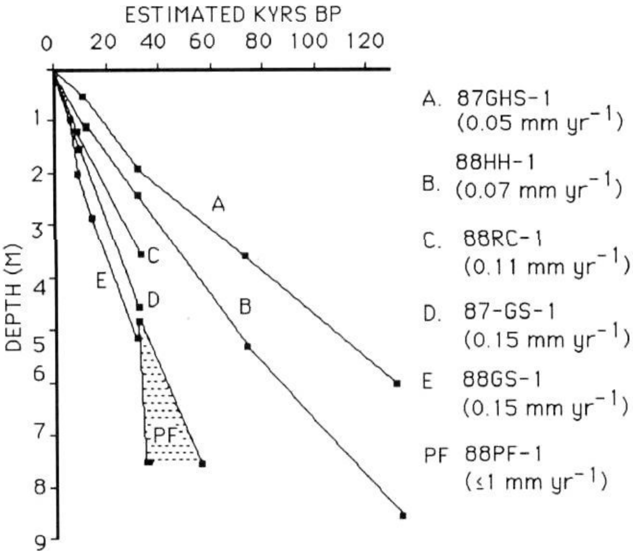

FIGURE 7. Estimated sedimentation rates at loess sites in central Alaska. Chronology from radiocarbon dates and correlation by curve fits at *ca.* 10,000, 31,000, 75,000 and 125,000 yr BP in long loess profiles. High sedimentation rate estimate at Fox Permafrost Tunnel reflects assumption that old radiocarbon dates from basal loess and gravel are accurate; alternatively, extrapolation of regional sedimentation rates suggest basal sediments are approximately 55,000-60,000 years old (early Middle Wisconsinan).

Estimation des taux de sédimentation aux sites loessiques du centre de l'Alaska. La chronologie établie à partir des dates au radiocarbone et la corrélation par les courbes coïncident, dans les longs profils loessiques, vers 10, 31, 75 et 125 ka BP. Les taux de sédimentation élevés estimés au Fox Permafrost Tunnel semble confirmer l'hypothèse selon laquelle les anciennes dates au radiocarbone obtenues sur le loess de la base et des graviers sont justes; l'extrapolation des taux de sédimentation à l'échelle régionale montre que les sédiments de la base datent d'à peu près 55-60 ka (début du Wisconsinien moyen).

Taken together, there is good agreement between magnetic susceptibility profiles from several different sites separated by tens of kilometers in central Alaska. This indicates that magnetic susceptibility profiling can produce reproducible and reliable records of environmental change. The good agreement between profiles measured in the laboratory on samples collected at 10 cm intervals, and field profiling at 2 cm intervals, suggests that field measurements can produce reliable data sets, and that high resolution stratigraphic studies can provide detailed information about the pattern of environmental changes in interior Alaska.

In general, these loess profiles show that Middle Wisconsinan climates were characterized by systematic fluctuations between higher and lower windspeeds. Associated paleosols and other features indicate that the lowest susceptibility loess horizons mark times of mild climate. Atmospheric circulation intensity in Alaska should decrease as climate ameliorates (Kutzbach, 1987), so it is reasonable that times of low wind speed which result in low susceptibility loess deposits in central Alaska were probably generally associated with warmer intervals. Low susceptibility sediments were deposited *ca.* 30,000-32,000 yr BP, at the same time as warm conditions are recorded in the Fox Permafrost Tunnel and other sites in Alaska (Hamilton *et al.*, 1988; Hamilton and Robinson, 1988). A widespread paleosol, informally named Sa (Begét and Hawkins, 1989) and wood fossils found in low susceptibility loess at the base of the Fox Permafrost Tunnel appear to record a period of climatic amelioration in the beginning of the Middle Wisconsinan, beyond the limits of radiocarbon dating.

CORRELATIONS WITH OTHER PROXY CLIMATIC RECORDS OF THE MIDDLE WISCONSINAN

The agreement between the proxy climatic records of the Middle Wisconsinan obtained at several loess sites in central Alaska by magnetic susceptibility profiling suggests that they record regional environmental changes. A crossplot of selected loess susceptibility profiles with other well-known proxy climate curves (Fig. 8) was made to test for correlations between the Alaskan record and other Middle Wisconsinan climate records.

If the radiocarbon chronology from the 88PF-1 site is treated conservatively to reflect probable contamination of the oldest finite dates (Hamilton *et al.*, 1988), good agreement is apparent between the pattern of climate change recorded by the loess record from central Alaska and several other detailed proxy climate records. Particularly good agreement seems to occur between the loess record and the Grande Pile pollen record of environmental changes in northern Europe. In particular, the age of the warming at *ca.* 30,000-32,000 yr BP in central Alaska is quite close to that of the Denekamp warm event of the Grande Pile core (Woillard and Mook, 1982) bracketed by ages of *ca.* 31,000 yr BP and 29,000 yr BP. The average of six radiocarbon dates on the Denekamp interval in the Grande Pile pollen core is 29,700 yr BP (Broecker *et al.*, 1988), more than a millenium later than the 31,400 yr BP average of six dates associated with a thaw zone above ice wedges in the permafrost tunnel, but the range and standard errors of the dates from Alaska and the Grande Pile core include broad overlap. A warm event is also recorded in high resolution studies of north Atlantic marine core V23-82 between 29,000 yr BP and 32,100 yr BP, and forms part of an interstade beginning after 35,200 yr BP (Broecker *et al.*, 1988).

Slightly older low susceptibility sediments identified in late Middle Wisconsinan susceptibility profiles may correlate with the Hengelo warm event identified in the Grande Pile core and dated to 40,000 ± 600 yr (Woillard and Mook, 1982). A possibly correlative warm event predates 35,640 ± 1810 in core V23-82.

A warm interval designated the Moershoofd in the Grande Pile core is dated between ~ 62,000 and 49,800 + 1500 − 1300, and occurred near the beginning of the Middle Wisconsinan. This may be broadly correlative with the early Middle Wisconsinan low susceptibility zone and wood fossils from the basal loess in the permafrost tunnel, and paleosol Sa and low susceptibility sediments found near the base of zone C in other central Alaskan loess sequences. This event may also be recorded in core V23-82.

Several rapid inflections in magnetic susceptibility are recorded within the Middle Wisconsinan loess sequence, par-

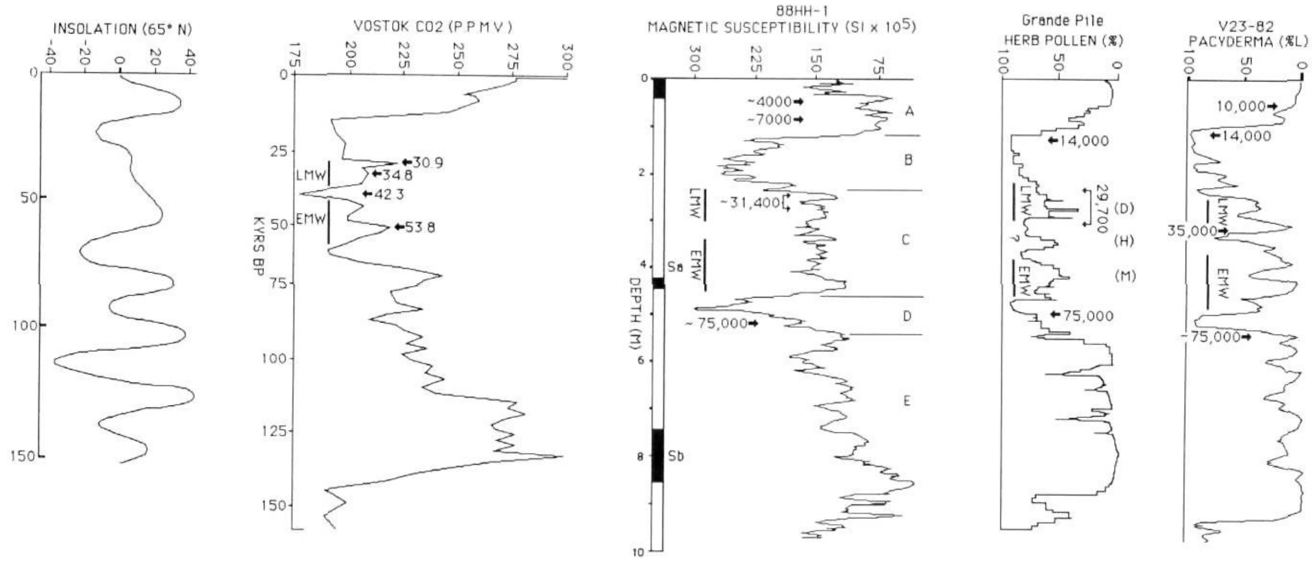

FIGURE 8. Comparison of retrodicted mean annual solar insolation (Berger, 1978), reconstructed atmospheric CO_2 content (Barnola *et al.*, 1987), magnetic susceptibility variations at loess section 88HH-1, the Grande Pile pollen record (Woillard and Mook, 1982), and foraminiferal variations in marine core V23-82 (Broecker *et al.*, 1988). Relatively high atmospheric CO_2 measurements from the early Middle Wisconsinan (EMW) and late Middle Wisconsinan (LMW) appear to correlate with times of low magnetic susceptibility and low wind intensity in Alaska, and warm intervals recorded at Grande Pile and in marine cores in Middle Wisconsinan sediments.

Comparaison entre l'insolation moyenne annuelle reconstituée (Berger, 1978), la teneur reconstituée en CO_2 (Barnola et al., *1987), les variations de la susceptibilité magnétique au site 88HH-1, les données polliniques de Grande Pile (Woillard et Mook, 1982), et les variations de la quantité de foraminifères dans la carotte marine V23-82 (Broecker* et al., *1988). Les mesures du CO_2 atmosphérique élevé du début du Wisconsinien moyen (EMW) et de la fin du Wisconsinien moyen semblent correspondre aux époques de faible susceptibilité magnétique et de vents de faible intensité qu'a connu l'Alaska et des intervalles chauds enregistrés à Grande Pile et dans les carottes marines de sédiments du Wisconsinien moyen.*

ticularly *ca.* 30,000-36,000 yr BP (Fig. 5,6). Similar variability in magnetic susceptibility has not been found in Holocene or Late Wisconsinan loess sequences, suggesting that the rapid changes in Middle Wisconsinan susceptibility are due to actual changes in the characteristics of the loess caused by rapid environmental changes. The abrupt changes in susceptibility may reflect rapid, short-term changes in atmospheric circulation intensity and local wind competence. Numerous rapid changes in atmospheric circulation intensity are independently recorded by short-lived spikes in dust influx to the Greenland Ice Sheet during the Middle Wisconsinan (Patterson and Hammer, 1987; Broecker *et al.*, 1988). Such rapid environmental changes have been called climate "jumps". Recently, Broecker *et al.* (1988) compared proxy climatic records from Greenland ice cores, marine cores, and the Grande Pile pollen site to determine if evidence of synchronous Middle Wisconsinan climate jumps could be established. The marine and pollen record showed 3-4 climate jumps between 40,000-22,000 yr BP while the ice record showed 2-3 times as many. Broecker *et al.* (1988) were unable to make definitive correlations between the timing or even the number of such rapid climate jumps identified in north Atlantic proxy climate records because of inherent problems of resolution and comparative dating. The rapid susceptibility variations in Middle Wisconsinan loess appear to constitute additional evidence for the existence of Middle Wisconsin climate jumps. Unfortunately, the data resolution and the available radiocarbon dates from Alaskan loess do not at this time allow definitive correlations to be made between the climate jumps recorded in loess and those found in the north Atlantic proxy climate records.

The shape and character of the proxy climate records available from Middle Wisconsinan loess appear to be broadly similar to some records from the north Atlantic area. Alaskan loess contains evidence of a warm event occurring *ca.* 30,000-32,000 yr BP, preceded by an interval of cooler climate in the Middle Wisconsinan during which wind intensity was higher and ice wedges developed at the Fox Permafrost Tunnel, which in turn was preceded by a broad complex warm period dating to 50,000-60,000 yr BP.

CAUSES OF MIDDLE WISCONSINAN CLIMATE VARIABILITY

The possible correlations between central Alaskan proxy climate records and those from other areas may have important implications for our understanding of the character and extent of Middle Wisconsinan climate change. The good agreement between the pattern of climate change recorded in the North Atlantic and in Alaskan loess suggests that several climate events during the Middle Wisconsinan affected very large areas of the northern hemisphere, particularly at high latitudes.

Time series analysis has shown that the effects of orbital forcing are recorded both in marine sediments (Martinson *et al.*, 1987; Imbrie and Imbrie, 1980), and in the loess record of central Alaska (Begét and Hawkins, 1989). However, such forcing is inadequate to explain the pattern of Middle Wisconsinan climate changes discussed here. Orbital forcing operates on a time scale of 10^4-10^5 years, and cannot account for climate shifts of shorter duration. Retrodiction of Middle Wisconsinan insolation changes suggests that solar insolation in the northern hemisphere gradually increased starting *ca.* 70,000 yr BP, and then decreased after about 45,000 yr BP during the Middle Wisconsinan (Berger, 1978). The evidence of a period of ice wedge growth at the height of Middle Wisconsinan insolation, and periods of mild climate at the beginning and end of the Middle Wisconsinan, cannot be explained by orbitally controlled insolation changes (Fig. 8).

This paper suggests that some of the climate variability recorded for the Middle Wisconsinan may reflect changes in atmospheric CO_2 content. The well-known "greenhouse effect" suggests that worldwide temperatures are strongly affected by the amount of CO_2 gas in the atmosphere. The recent discovery that the atmospheric CO_2 content varied through the Late Pleistocene suggests that much of the earth's climatic variability may reflect changing atmospheric CO_2 content (Genthon *et al.*, 1987).

The record of atmospheric CO_2 changes from the Vostok ice core shows that there was considerable variability in atmospheric composition during the Middle Wisconsinan (Barnola *et al.*, 1987). Modern values of CO_2 are approximately 340 p.p.m.v., and reflect a significant anthropogenic component. Pre-industrial late Holocene values are estimated to have been about 280 p.p.m.v. At full glacial conditions the Vostok core data suggests CO_2 content was approximately 195 ± 7 p.p.m.v. The highest concentration of atmospheric CO_2 during the Middle Wisconsinan occurred roughly 31,000 years ago, when CO_2 was 223 ± 9 p.p.m.v. A minor peak in CO_2 content occurred approximately 35,000 yr BP, when CO_2 was $210 + 11/-5$ p.p.m.v.. An extremely low concentration of $178.5 + 18/-5$ was determined for *ca.* 42,000 yr BP. Early in the Middle Wisconsinan a prolonged period of relatively high atmospheric CO_2 occurred between 54,000-58,000 yr BP when CO_2 values reached $219.5 + 5/-10$.

Similarities between the pattern of CO_2 changes and loess susceptibility profiles suggest that part of the climatic variability recorded in the Alaskan loess record may reflect environmental shifts forced by atmospheric CO_2 changes (Fig. 8). Good agreement exists between the age of the Middle Wisconsinan peak in atmospheric CO_2 content at *ca.* 31,000 yr BP and the radiocarbon-dated interval of permafrost degradation and the low susceptibility zone found in Alaskan loess at 30,000-32,000 yr BP (Fig. 5), suggesting that these two may be related. Similarly, the CO_2 peak at *ca.* 54,000-58,000 yr BP and the oldest Middle Wisconsinan low susceptibility zone in loess zone C, palesol Sa, and the wood fossil layer in the Fox Permafrost Tunnel may be related.

The times of high atmospheric CO_2 content from the Vostok ice core also agree well with the ages of the Middle Wisconsinan Denekamp and Moershoofd warm events from the Grande Pile pollen core, dated at *ca.* 29,700 and 50,000-62,000 yr BP. The Middle Wisconsinan period of low atmospheric CO_2 content which occurred approximately 42,300 yr BP is therefore thought to be associated with the Middle Wisconsinan interval of high wind intensity recorded by high susceptibilities found in the middle of zone C (Middle Wisconsinan) in the loess profiles, and cold intervals of similar age recorded in other proxy climatic records (Fig. 5,8).

DISCUSSION AND CONCLUSIONS

The first-order variations in magnetic susceptibility measured through loess profiles in central Alaska can be broadly correlated with proxy climatic records from ice sheets, terrestrial records from other areas of the world, and marine isotope stages. Broad shifts in susceptibility allow proxy climatic records from central Alaskan loess to be subdivided into zones corresponding to the Middle Wisconsinan, Late Wisconsinan and Holocene. Radiocarbon dates indicate that the timing and pattern of inflections in the susceptibility curves are broadly consistent with that of Late Pleistocene marine isotope stages and other proxy climatic records of the Late Quaternary. Climatic shifts lasting $\geq 10^4$ years recorded in loess, like those of the marine record, probably reflect the effects of Milankovitch orbital cycles (Begét and Hawkins, 1989). However, high resolution magnetic susceptibility profiling of loess sections has identified a complex proxy record of Middle Wisconsinan climatic events which cannot be explained by the earth's planetary orbital variations.

Two regions of low susceptibility sediments found in early Middle Wisconsinan and late Middle Wisconsinan loess sequences appear to record times of low wind intensity and climatic warming. The youngest warm event occurred *ca.* 30,000-32,000 yr BP., appears to be correlative with the Denekamp warm interval in the Grande Pile pollen core, and is associated with an interval of permafrost degradation recorded in the Fox Permafrost Tunnel (Hamilton *et al.*, 1988). A warm event early in the Middle Wisconsinan is recorded in the loess sequences by a wood-rich horizon in the Fox Permafrost Tunnel and a widespread paleosol in other loess sections, and may be correlative with the Moershoofd warm interval recorded in the Grande Pile pollen core.

The recent documentation of natural variability in CO_2 content in the Pleistocene atmosphere may account for some of the short term climate changes identified in proxy climate data sets. Relative highs in atmospheric CO_2 occurred at *ca.* 31,000 yr BP and 54,000-58,000 yr BP, times thought to be correlative with deposition of low susceptibility loess in central Alaska. These two intervals are separated by a sequence of loess with somewhat higher susceptibility, which may reflect increasing wind intensities during a period of very low atmospheric CO_2 concentration *ca.* 42,300 yr BP. The evidence of permafrost degradation *ca.* 30,000-32,000 yr BP, and the development of paleosols and preservation of fossil wood which appear to date from an interval early in the Middle Wisconsinan characterized by high atmospheric CO_2 contents constitutes strong evidence that, at least on some occasions, Alaskan climates were strongly affected by naturally occurring atmospheric CO_2 changes.

The evidence that some important Pleistocene climate events reflect changes in the efficiency of heat absorption in the terrestrial atmosphere due to changing CO_2 content (*i.e.*, the "greenhouse effect") is relevant to discussions of the possible effects of ongoing climate changes forced by atmospheric CO_2 increases. Pleistocene deposits recording intervals of warming associated with past CO_2 changes constitute powerful evidence which can be used to test global climate models. Better understanding of the linkage and responsiveness of the earth's climate to documented prehistoric CO_2 changes can be used to critically examine and calibrate the predictions of the degree of "greenhouse" warming which will follow the modern anthropogenic perturbation of atmospheric CO_2 content.

ACKNOWLEDGEMENTS

Many thanks for laboratory work and assistance in the field by Nancy Bigelow, Kathy Campbell, Greg Kehoe, DeAnne Pinney, and students in my class on glacial and periglacial geology. Good critical reviews of this manuscript by Dr. Thomas D. Hamilton, Dr. Charles Schweger, Dr. David Hopkins and Dr. Mary Keskinen are gratefully acknowledged. Financial support through grants from the Department of Geology and Geophysics of the University of Alaska, the National Science Foundation Archeometry program, and the American Chemical Society defrayed the costs of data collection and radiocarbon dating.

REFERENCES

Barnola, J. M., Raynaud, D., Korotkevich, Y. S. and Lorius, C., 1987. Vostok ice core provides 160,000 year record of atmospheric CO_2. Nature, 329: 408-414.

Begét, J., 1988. Tephras and sedimentology of frozen loess, p. 672-677. *In* K. Senneset, ed., Fifth International Permafrost Conference, Proceedings, Vol. 1. Tapir, Trondheim, 909 p.

Begét, J. and Hawkins, D., 1989. Influence of orbital parameters on Pleistocene loess deposition in central Alaska. Nature, 337: 151-153.

Begét, J., Stone, D. and Hawkins, D., 1990. Paleoclimatic forcing of magnetic susceptibility variations in Alaskan loess during the late Quaternary. Geology, 18: 40-43.

Berger, A. L., 1978. Long-term variations of caloric insolation resulting from the earth's orbital elements. Quaternary Research, 9: 139-167.

Broecker, W. S., Andree, M., Bonani, G., Wolfli, W., Oeschger, H. and Klas, M., 1988. Can the Greenland climatic jumps be identified in records from ocean and land? Quaternary Research, 30: 1-7.

Floyd, J. D. and Trench, A., 1988. Magnetic susceptibility contrasts in Ordovician greywackes of the southern uplands of Scotland. Journal of the Geological Society of London, 145: 77-83.

Genthon, C., Barnola, J. M., Raynaud, D., Lorius, C., Jouzel, J., Barkov, N. I., Korotkevich, Y. S. and Kotlyakov, V. M., 1987. Vostok ice core: climatic response to CO_2 and orbital forcing changes over the last climatic cycle. Nature, 329: 414-418.

Goh, K., Molloy, B. and Rafter, T., 1977. Radiocarbon dating of Quaternary loess deposits, Banks Peninsula, Canterbury, New Zealand. Quaternary Research, 7: 177-196.

Hamilton, T. D., Craig, J. L. and Sellman, P. V., 1988. The Fox permafrost tunnel: A late Quaternary geologic record in central Alaska. Geological Society of America Bulletin, 100: 948-969.

Hamilton, T. D. and Robinson, S. W., 1988. Middle Wisconsin interstadial interval, central and northwest Alaska. Geological Society of America Bulletin, 20: A208-A209.

Imbrie, J. and Imbrie, J. Z., 1980. Modelling the climatic response to orbital variations. Science, 207: 942-953.

Kukla, G., *1987. Loess stratigraphy in central China. Quaternary* Science Reviews, 6: 811-814.

Kukla, G., Heller, F., Ming, L., Chun, X., Sheng, L. and Sheng, A., 1988. Pleistocene climates in China dated by magnetic susceptibility. Geology, 16: 811-814.

Kutzbach, J. E., 1987. Simulations of climatic patterns during deglaciation, p. 425-446. *In* W. F. Ruddiman and H. E. Wright, eds., North America and Adjacent Oceans During the Last Deglaciation, Geological Society of America, Boulder, 501 p.

Leg 117 Scientific Drilling Party, 1988. Leg 117 finds mountains, monsoons. Geotimes, 33: 13-16.

Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, T. C. and Shackleton, N., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quaternary Research, 27: 1-30.

Nettleton, L. L., 1971. Elementary Gravity and Magnetics for Geologists and Seismologists. Society of Exploration Geophysicists, Tulsa, 120 p.

Patterson, W. S. B. and Hammer, C. U., 1987. Ice core and other glaciological data, p. 91-109. *In* W. F. Ruddiman and H. E. Wright, eds., North America and Adjacent Oceans During the Last Deglaciation, Geological Society of America, Boulder, 501 p.

Pye, K., 1987. Aeolian Dust and Dust Deposits. Academic Press, London, 334 p.

Sharma, P. V., 1986. Geophysical Methods in Geology. Elsevier, New York, 442 p.

Thorson, R. and Bender, G., 1985. Eolian deflation by ancient katabatic winds: A late Quaternary example from the north Alaska Range. Geological Society of America Bulletin, 96: 702-709.

Tungsheng, L., Zhisheng, A., Baoyin, Y. and Jiamao, H., 1985. The loess paleosol sequence in China and climatic history. Episodes, 8: 21-28.

Westgate, J., 1988. Isothermal plateau fission-track age of the late Pleistocene Old Crow tephra, Alaska. Geophysical Research Letters 15: 376-379.

Woillard, G. and Mook, W., 1982. Carbon-14 dates at Grande Pile: Correlation of land and sea chronologies. Science, 215: 159-161.