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CAN INVOLUTIONS BE USED AS PALAEOTEMPERATURE INDICATORS?

Abstract

Over the last decades Quaternary periglacial successions and related periglacial involutions, often called cryoturbations, have been studied with respect to their genesis, sedimentary environment and climatic significance. Later also palaeotemperature estimations have been made derived from various types of involutions. In this paper I will comment on and criticize the use of these involutions as palaeotemperature indicators. It is demonstrated that involutions occur in both periglacial and in interglacial sequences and the amplitude of involutions can be very variable. Palaeoclimatic inferences and conclusions based on the presence and amplitude of involutions are only valuable if used in combination with other proxy evidence.

INTRODUCTION

Involutions are a common feature in sedimentary sequences. They are generally attributed to loading due to liquifaction and density differences of sediment (e.g. LEEDER, 1999). KUENEN (1965) produced load casts in the laboratory by depositing a sand layer on an unconsolidated clay layer. In periglacial sequences of the Quaternary involutions are very common. The paper of EDELMAN *et al.* (1936) on the Late Pleistocene and Early Holocene cryoturbated deposits in the eastern Netherlands is one of the earliest reports on cold-climate deformations in the Netherlands. They interpreted these involutions as cryoturbations caused by cryostatic pressure or melting of ground ice.

In the 50ties involutions were described from Early Pleistocene deposits in the southern Netherlands (KORTENBOUT VAN DER SLUIJS, 1956; VAN STRAATEN, 1956). Both authors described the same involutions of clay in sand in the so-called "Papzand" formation of Early Pleistocene age, but their interpretations were different. The title of KORTENBOUT VAN DER SLUIJS' paper "The cryoturbations in the Tegelen region" shows that he interpreted these features as cryoturbations related to cold-climate conditions. VAN STRAATEN, however, being more cautious and objective, described the involutions as "Structural features of the Papzand Formation". He

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concluded: "Since a periglacial climate is well established by the presence of fossil ice wedges, the bulk of the corrugations .... may perhaps ... be ascribed to freezing and thawing processes. Meanwhile, it should be kept in mind that the primary condition for most of the corrugations must have been the semi-fluid state of the sediment and this can have resulted not only from the presence of an impermeable layer of frozen ground, but also from the fact that the Papzand rests immediately upon the impermeable Tiglian clay". In other words VAN STRAATEN stated that the involutions are due to fluidization; the causes can be diverse.

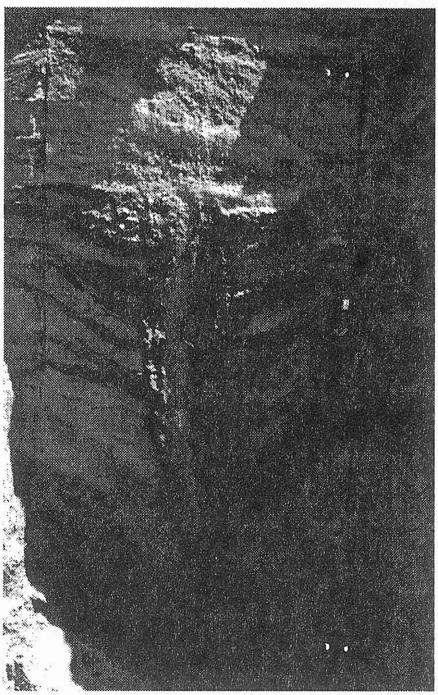
In the decades following VAN STRAATEN'S article our work revealed that the involutions are often connected and related to other periglacial features such as frost cracks and ice-wedge casts (VANDENBERGHE, 1983, 1985, 1988; VANDENBERGHE and KASSE, 1989; KASSE, 1988, 1993). Because of this relationship periglacial involutions have been used as indicators of past permafrost or deep seasonal frost conditions and palaeotemperatures of discrete periods have been inferred from the presence of periglacial involutions. VANDENBERGHE (1988) concluded that "the large involutions .... can be taken as evidence of the former existence of continuous permafrost and .... they allow an estimation of the mean annual temperature of at most −6°C". In the years following this publication we adopted this approach in our research group (ISARIN, 1997; HUIJZER and VANDENBERGHE, 1998; KASSE *et al*., 1998). ISARIN (1997) investigated the climate of the Younger Dryas period based on the presence of specific periglacial phenomena in NW Europe. Specific phenomena like ice-wedge casts have been translated to palaeotemperature by comparison with the recent analogues in (sub)arctic regions (Tab. I). Also relict periglacial involutions have been transferred in this way. Large-scale involutions of more than 0.6 m have been attributed to permafrost and a mean annual air temperature (MAAT) lower than −4 to −8°C depending on the lithology. Similarly, small-scale involutions have been assigned a MAAT lower than −1°C.

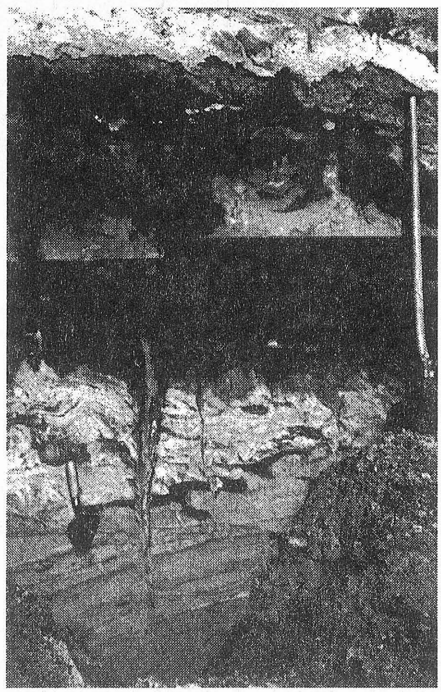
The aim of this paper is to discuss the supposed correlation of involutions (cryoturbations) and involution amplitude with palaeotemperature regimes. In the following sections it will be demonstrated that involutions can occur in both periglacial and interglacial sequences. Also the amplitude or depth of the involutions associated with a former land surface can be very variable and therefore inferences of MAAT based on the presence and amplitude of involutions seem to be hazardous.

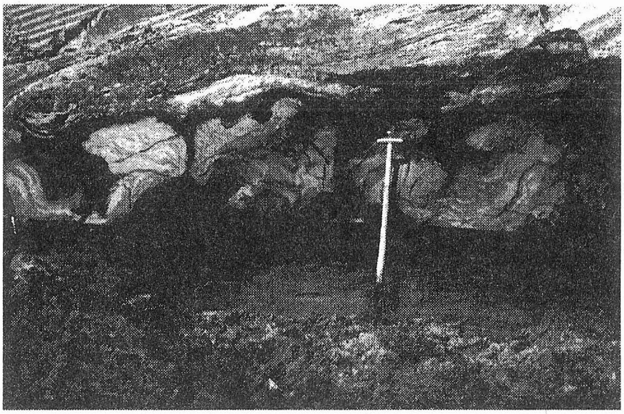
INVOLUTIONS IN PERIGLACIAL SEQUENCES

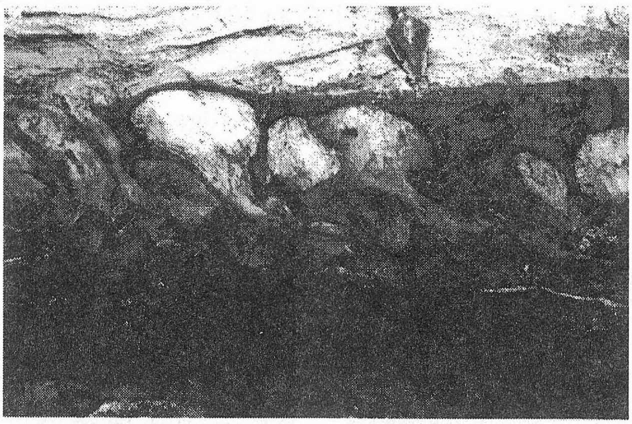
The prove that the sedimentary successions were deposited during a cold phase is normally based on the presence of ice-wedge casts (Pl. 1a). This truncated ice-wedge cast in Weichselian/Vistulian Middle Pleniglacial deposits in eastern Germany (exposure Reichwalde) was formed in sand, and by analogy with modern forms, it is believed to indicate continuous permafrost and a MAAT lower than –6 or –8°C during its formation.

In several cases involutions have been found overlying ice-wedge casts (Pl. 1b). This example from the Early Pleistocene shows two involuted peaty soil layers and, associated with these former land surfaces, frost cracks and small ice-wedge casts occur. From the latter features we reconstructed a mean annual temperature lower than –1 or –4°C during the formation of these Early Pleistocene sediments (KASSE, 1993; KASSE and BOHNCKE, in press). Where involutions overlie ice-wedge casts it can be argued that the involution process was caused by oversaturation due to thawing of ice-rich permafrost. In such cases it can be concluded that the involution is a periglacial involution and because it is related to an ice-wedge cast it can be used for paleotemperature reconstructions. Very often, however, such an unequivocal relation between involutions and ice-wedge casts is not present (Pl. 1c and 1d). On the one hand, the upper involuted part of the former active layer overlying ice-wedge casts may have been eroded (see Pl. 1a); on the other hand involutions may have been formed without the presence of ice-wedge casts. Two examples will illustrate this point.









Pl. 1. Periglacial phenomena in cold-climate successions

(a): Truncated ice-wedge cast in Weichselian/Vistulian Middle Pleniglacial deposits in eastern Germany (exposure Reichwalde); (b): Involuted peaty soils and associated frost cracks and small ice-wedge casts in the Early Pleistocene Beerse Member in northern Belgium (exposure Beerse Ossenweg); (c): Large-scale involutions (c. 1 m) in the Early Pleistocene Beerse Member in northern Belgium (exposure Merksplas Strafinrichting); (d): Medium-scale involutions of Weichselian Middle Pleniglacial age in eastern Germany (exposure Scheibe)

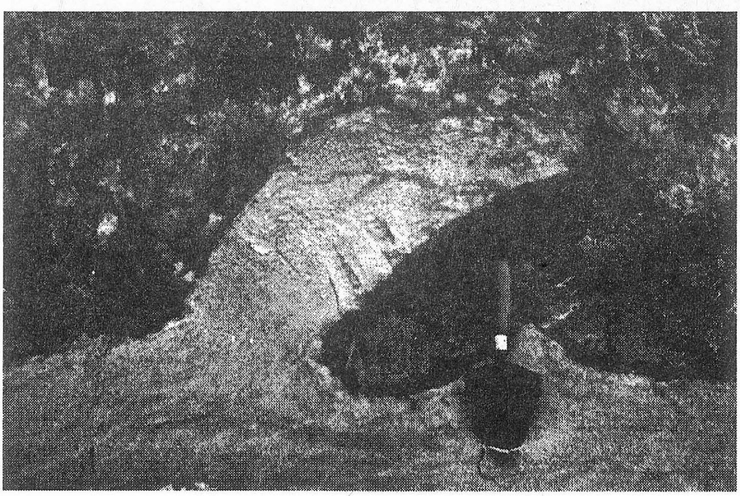
Photo 1c is an example of large-scale involutions (c. 1m) in the Beerse Member that was formed during the Early Pleistocene Tiglian C4 stage c. 1.9 milj. y. ago. Peat has sunk down and sand has moved upwards in diaper-like structures. Normally peat has a lower density than sand, so the involution of peat in sand means that the sand must have been oversaturated with water resulting in a lower specific density than peat. This oversaturation and involution process has been attributed to the melting of permafrost (VANDENBERGHE and KASSE, 1989), but large ice-wedge casts, being the proof of relict permafrost, have not been found.

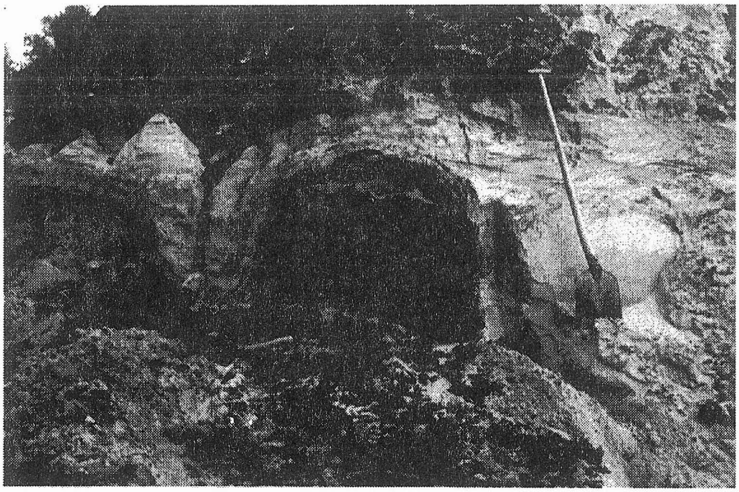
Photo 1d shows medium-scale involutions of Weichselian Middle Pleniglacial age in eastern Germany (exposure Scheibe). The sedimentary sequence is coarsening upward from peat via loam into fluvial sand. This is very typical for Middle Pleniglacial river systems that are characterized by avulsion events (KASSE, 1998; VAN HUISSTEDEN and KASSE, in press). The loading process can be explained by autocyclic processes of river migration and permafrost development and degradation on a river floodplain (KASSE *et al.*, 1995a). During peat formation river activity was outside the point of observation. In this stable land surface permafrost could penetrate into the ground and ground ice was formed. Then, by means of an avulsion event upstream, the river entered this site again and first loams and later sand was deposited. Because of the increased flooding intensity the ground ice melted by thermal erosion which caused an oversaturation of the sediment accompanied by involution of the loamy and sandy deposits. Finally, permafrost disappeared completely and fluvial deposition of sand and gravel continued.

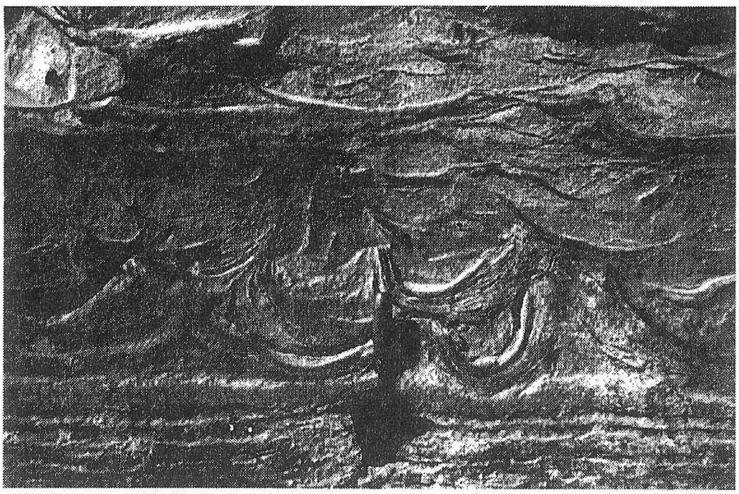
INVOLUTIONS IN INTERGLACIAL SEQUENCES

Involutions and fluidization features not related to cold-climate environments are mostly related to consolidation processes associated with burial or seismic activity (LEEDER, 1999). Some examples from Late Pleistocene sequences can demonstrate this (Pl. 2).

Photo 2a shows medium-scale rather local involutions of sand that has moved upwards in loamy sediments. These loadings occur in the upper part of a fluvial channel-fill sequence in eastern Germany that was probably formed in the Holocene. In general sand has a higher density than loam, so these involutions can only be explained by liquefaction of the sand layer underlying the loams, perhaps due to lateral groundwater flow or seepage to the river channel..







Pl. 2. Involutions in interglacial successions

(a): Medium-scale involutions in the upper part of a Holocene fluvial channel-fill in eastern Germany (exposure Reichwalde); (b): Large-scale involutions of wind-blown sands overlying a Holocene peat of Subboreal age (exposure Boudewijn, Ossendrecht); (c): Involutions in Holocene wind-blown sand (exposure Boudewijn, Ossendrecht).

Besides small-scale involutions, also large-scale forms have been found in interglacial successions. Photo 2b shows Holocene wind blown sands overlying a Holocene peat dated by pollen analysis and ^{14}C-dating (SCHWAN, 1991). The peat top dates from the Subboreal. Clearly because of the weight of the windblown sand, filling in the waterlogged peat depression, the sand has sunk down and the peat migrated upward as diapers.

The contrast in lithology and specific density are not always so evident as in photo 2a/2b. Photo 2c shows involutions of sand in sand with similar grain size. Both sands are of windblown origin (so-called drift sand) and overlie a Holocene humic podzol, so the involutions date from the Holocene interglacial (SCHWAN, 1991, p. 165) (see discussion below).

INVOLUTION AMPLITUDE AND PALAEOCLIMATE RECONSTRUCTION

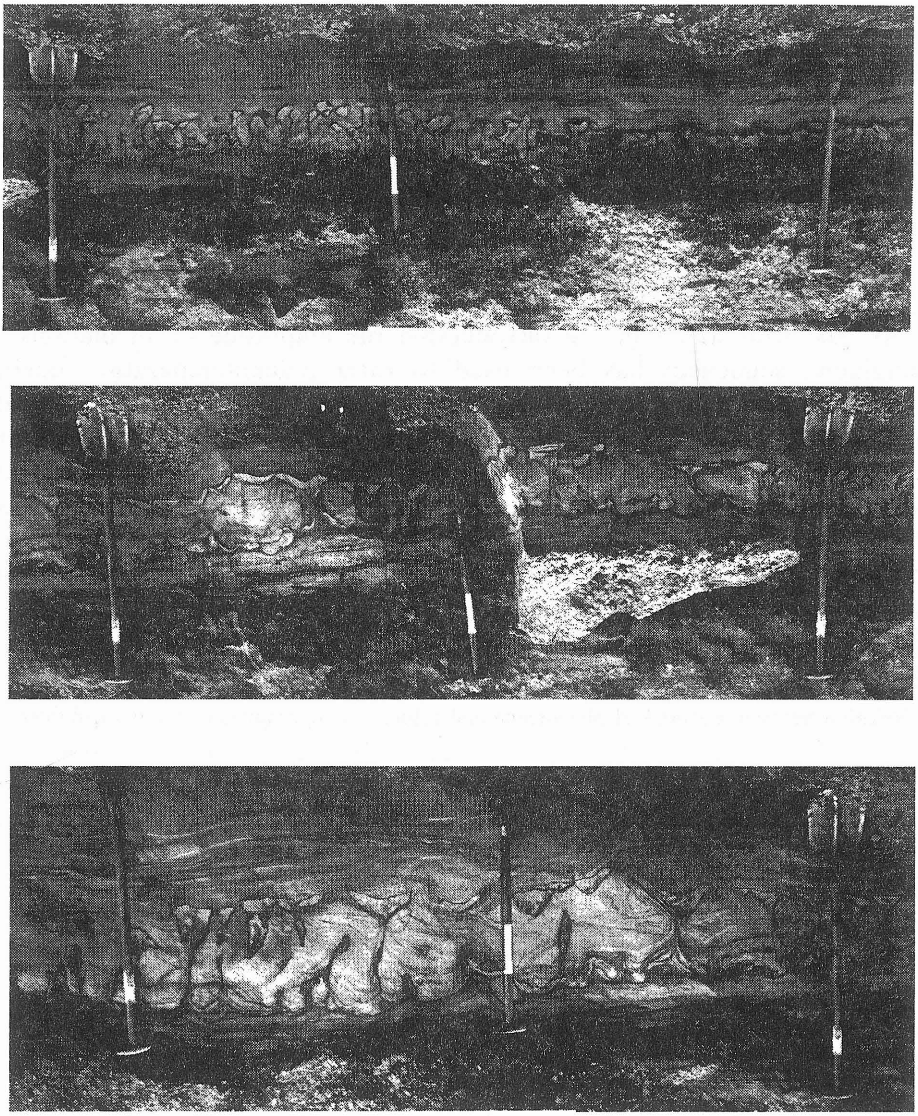
As has been stated in the introduction the amplitude of involutions in periglacial sequences has been used to infer palaeotemperature during their formation (Tab. I) (VANDENBERGHE, 1988; ISARIN, 1997). Large-scale involutions would be related to degradation of permafrost and therefore indicate a MAAT lower than −4 or −8°C. Small-scale involutions would indicate melting of seasonal ground ice, implying a MAAT lower than −1°C. Photos 3 and 4 demonstrate that this correlation of involution depth and palaeotemperature is not so straightforward and can lead to completely erroneous conclusions.

Table I

Relation between periglacial phenomena and inferred temperatutes (after ISARIN, 1997)

PERIGLACIAL PHENOMENA	−MAAT(°C)[a]	MTC(°C)[b]	REFERENCES
THERMAL CONTRACTION CRACS ice-wedge cast, fossil sand-wedge, composite-wedge cast	≤−4[(c], ≤−8[(d]	≤−20	LACHENBRUCH (1962), PÉWÉ (1962, 1966), ROMANOVSKIJ (1976, 1985), WASHBURN (1979), BURN (1990),
seasonal frost crack with primary (or secondary) infiling	≤−1	≤−8(?)	MAARLEVELD (1976), KARTE (1983), (*cf.* ROMANOVSKIJ, 1985)
PERIGLACIAL INVOLUTIONS large-scale (amplitude ≤0.6 m) down-sinking or updoming forms	≤−4[(c], ≤−8[(d]		VANDENBERGHE (1988), VANDERBERGHE & PISSART (1993)
small-scale (amplitude <0.6 m down-sinking or updoming forms, solitary forms	≤−1		VANDENBERGHE (1988)
PERENNIAL FROST MOUNDS open-system pingo	≤−4		WASHBURN (1979), MACKAY (1988)
closed-system pingo	≤−6		MACKAY (1978, 1988), WASHBURN (1979,
organic palsa	≤−1		WASHBURN (1979)
mineral palsa	≤ 5		DEWEZ et al. (1985)

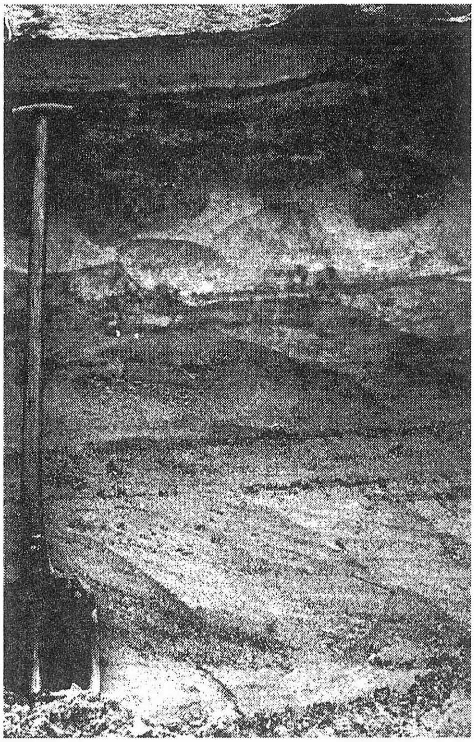
a): Mean Annual Air Temperature; (b): Mean air Temperature of the Coldest Month; (c): fine-grained substrate; (d): coarse-grained substrate

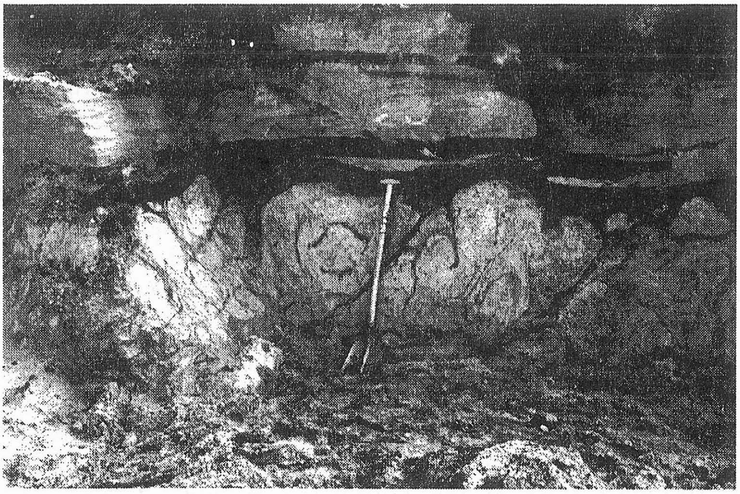


Pl. 3. Involutions with variable amplitude in the Early Pleistocene Kedichem Formation in the southeastern Netherlands (pit Laumans). The composite photo shows the increase in involutions amplitude from the upper left to the lower right side

The involutions in photo 3 are part of the Early Pleistocene Kedichem Formation in the southeastern Netherlands (pit Laumans) (VAN STRAATEN, 1956; KASSE and BOHNCKE, in press). The Kedichem Formation is a generally fine-sandy unit with thin loam beds intercalated. It is underlain by a clay bed of the Tiglian interglacial and overlain by coarse gravelly sands of the Middle Pleistocene Sterksel Formation of Cromerian age. The Kedichem Formation has been formed during the Eburonian glacial, Waalian interglacial and Menapian glacial. The involutions described here occur in the lower part of the Kedichem Formation and most probably are of Eburonian age. Photo 3 shows a strong variability in involution depth of the loam that sunk in the sand. The involution depth increases from 0 cm at the upper left side of the composite photo to 25 cm in the middle part and to c. 50 cm in the lower right hand part. The latter value almost approaches the critical value of 60 cm.

The involutions in photo 4 date from the Younger Dryas period of the Weichselian Late Glacial exposed at Bosscherheide (Bohncke *et al.*, 1993; Kasse *et al.*, 1995b). Photos 4a–d are from the same pit taken during successive years. The sediment succession contains the top of a Late Glacial fluvial terrace, that was covered by Younger Dryas aeolian dunes. The four photos reveal the strong variability of the involution depth. In photo 4a the fine-grained top of the Late Glacial fluvial sediments is affected by weak soil formation as is clear from the brownification and destruction of sedimentary structures. The uppermost sands are the Younger Dryas age dunes. Periglacial involutions are totally absent. Photo 4b contains the same sequence of fluvial sand and fines overlain by aeolian sediments. The fluvial loams are slightly involuted into the underlying fluvial sands. In photo 4c the fluvial sediments and aeolian sand is separated by organic material that has been dated to the Alleröd and early Younger Dryas (Bohncke *et al.*, 1993). From these dates an early Younger Dryas age for the involution phase and a late Younger Dryas age of the dunes has been





Pl. 4. Weichselian Late Glacial fluvial sand and loam overlain by Younger Dryas aeolian dunes at Bosscherheide. Photos 4a–d are from the same pit taken during successive years. Note the strong variability of the involution amplitude.

inferred. The involutions in photo 4b and 4c are small to medium scale and, following the transfer method of Table I, a MAAT lower than û1oC during the Younger Dryas could be inferred. Photo 4d, however, shows the same sequence of fluvial sediment overlain by aeolian sand, but now the amplitude of the involuted level has increased strongly to more than a meter. Such large-scale involutions, following the transfer method of table I, would imply a much lower MAAT of –6°C or lower (see discussion below).

DISCUSSION

Quaternary periglacial successions have been studied for a long time with respect to their age, sedimentary environment, vegetation and periglacial phenomena (e.g. ZAGWIJN, 1974; VANDENBERGHE, 1983; VAN HUISSTEDEN, 1990). Climate reconstructions have been based on vegetation changes (VAN DER HAMMEN, 1951; RAN, 1990; HOEK, 1997) and periglacial phenomena (Vandenberghe, 1983, 1988). Periglacial involutions, often called cryoturbations, have been used also to reconstruct former mean annual air temperatures. Large-scale involutions of more than 0.6 m have been attributed to permafrost and a mean annual air temperature (MAAT) lower than –4 to –8°C depending on the lithology. Similarly, small-scale involutions have been assigned a MAAT lower than –1°C (VANDENBERGHE, 1988; ISARIN, 1997).

In the previous paragraph it has been demonstrated that cold-climate sedimentary sequences in low-land settings in north-western Europe are often characterized by involutions (Pl. 1). Such involutions, in direct association with thermal contraction features as ice-wedge casts can be considered diagnostic for former permafrost (Pl. 1a, b). Involutions as such are not necessarily diagnostic for cold-climate conditions. The causes for the involution process can be diverse as has been stressed by VAN STRAATEN (1956). Melting of seasonal ground ice or ice-rich permafrost is one possibility (Pl. 1c, d). It is very well possible that many of the involutions from cold-climate successions were formed by the degradation of ground ice or permafrost. However, the absolute proof for the former presence of permafrost, i.e. involutions overlying ice-wedge casts, is relatively rare. In addition, in such cases the presence of large-scale involutions as permafrost indicator is superfluous, while the ice-wedge casts as such are the best evidence for former permafrost occurrence. It should be kept in mind that the primary condition for most of the involutions must have been the semi-fluid state of the sediment and this can have resulted not only from the presence of an impermeable layer of frozen ground, but also from the presence of an underlying impermeable clay (VAN STRAATEN, 1956).

Involutions and fluidization features not related to cold-climate environments are mostly related to consolidation processes associated with burial or seismic activity (KUENEN, 1965; NICHOLS *et al.*, 1994). Involution occurred when higher density sediment (e.g. sand) was deposited on lower density material such as peat (Pl. 2b). However, also loading of similarly textured sediment can occur (Pl. 2c). The reason for the involution process of sand in sand seems to be that the lower sand was deposited in a waterlogged depression (SCHWAN, 1991). The wetness of the depositional environment was established from the presence of adhesion ripple lamination in lacquer peels. The upper sand is more dry-aeolian in origin as indicated by plane horizontal and low-angle bedding. Its deposition on the waterlogged lower sediment caused a certain consolidation and liquefaction of the lower unit and consequently, the excess pore water moved upward to the surface causing involutions. The lower boundary of the involutions is rather regular and horizontal, a feature that in cold-climate involutions has often been used as an argument to establish the depth of the top of the frozen ground or top of the permafrost table (VANDEN-BERGHE, 1988). This Holocene example shows that such relations between involution depth and permafrost depth and related palaeoclimatic interpretations might be incorrect.

Involution amplitude or depth in sedimentary successions has been used as a parameter to infer the former MAAT during their formation (Tab. I) (VANDENBERGHE, 1988; ISARIN, 1997). Photos 3 and 4, however, reveal the strong lateral variability of the involution amplitude. Involutions of the same stratigraphic level may range between 0 and more than 1 m. Therefore, inferences related to palaeotemperature estimations are tricky. The small-scale forms, following the transfer method of table I, would indicate deep seasonal frost with mean annual air temperatures lower than –1°C. The large-scale structures would imply permafrost and mean annual air temperatures lower than –4 to –8°C. In the presented cases (Pl. 3 and 4) it seems that the presence and depth of the involutions is related to the palaeotopography. Higher-lying, well-drained sites appear to have evidence of soil formation and involutions are absent because the pore water pressure was too low to generate involutions (Pl. 4a, b). The lower-lying, poorly-drained sites have evidence of peat formation and involutions are often present (Pl. 4c, d). These low-lying areas (pools, former river branches or backswamp areas) were water logged and perhaps, because of lateral water flow, the pore water pressure may have been high leading to liquefaction and loading. Permafrost or deep seasonal frost does not seem to be a necessity to generate such water-logged conditions in a river plain.

It is questionable whether palaeotemperature reconstructions can be based on the presence of involutions of different size. Involutions are most frequently found in low-lying, water-logged areas. Oversaturation and sediment density differences seem to be the controlling factors in determining the involution process.

CONCLUSIONS

1. Involutions are very common and typical in periglacial successions.
2. However, involutions also occur in interglacial successions and therefore, they are not diagnostic for cold-climate deposits. Involution amplitude can vary strongly within one stratigraphic level. Therefore, palaeotemperature estimations based on involution amplitude are questionable.
3. Involutions indicate water-logged over-saturated sediment conditions, frequently but not exclusively present in cold environments.
4. Involutions as such cannot be used to reconstruct palaeotemperature. Only in association with other periglacial phenomena (e.g. ice-wedge casts) their presence is helpful for environmental reconstruction.

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