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Channelized subglacial drainage under soft-bedded ice sheets: evidence from small N-channels in Central European Lowland

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Examples of small (m-scale) subglacial meltwater channels of Nye-type from central Europe coupled with the occurrence of large tunnel valleys suggest a significant role of non-distributed drainage system during major Pleistocene glaciations in this area. Hydraulic transmissivity of unconsolidated sediments overridden by the ice sheets was not sufficient to drain all basal meltwater as groundwater flow, so that the excess water volume was evacuated in hydraulically efficient channels incised into the bed, well preserved in the geological record. The channels are steep-sided, surrounded by undisturbed sediments and filled mainly with till, and they are bound by sharp, undulating erosional contacts. Their occurrence in sub-marginal areas of past ice sheets is consistent with the glaciological theory.

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INTRODUCTION

Hydrology of glaciers and ice sheets is of fundamental importance for glacial mass balance but also for the dynamic behaviour of the ice body. It has been demonstrated that ice movement velocity and glacier stability largely depend on the ability of the drainage system to evacuate the meltwater to the foreground (J. Menzies, 1995; D. I. Benn, D. J. A. Evans, 1998; R. LeB. Hooke, 1998). It can be generalised that under efficient drainage conditions capable of rapid meltwater transfer, glaciers remain stable being coupled to their beds. Conversely, if water excess exists at the ice base, hydraulic lifting can occur leading to an unstable behaviour of the glacier, orders-of-magnitude increase in movement velocity and ultimately to glacier collapse.

Impact of water pressure increase in the subglacial environment on glacier dynamics is two-fold. Firstly, if a glacier rests on unconsolidated permeable sediments, water pressure increase will reduce shear strength of this sediment which can initiate deformations of the substratum contributing to the forward movement of the glacier (G. S. Boulton, A. S. Jones, 1979). Many researchers believe that bed deformation is an important if not major component of the total movement of soft-bedded ice sheets both in some modern (R. B. Alley *et al.*, 1986; G. S. Boulton, R. C. A. Hindmarsh, 1987) and past (R. B. Alley, 1991; P. U. Clark, 1994; J. K. Hart, 1995; G. S. Boulton, 1996) environments. Secondly, if the subglacial water pressure approaches the ice overburden pressure, the glacier will be lifted from the bed by a pressurised water layer and go afloat. Rapid increase in advance speed will follow, because the glacier weight can be no longer supported by the substratum. Surges of some glaciers are attributed to widespread basal separation (B. Kamb *et al.*, 1985).

In recent years numerous papers picked up the issue of interrelationships between different subglacial drainage systems in the context of ice sheet behaviour both as conceptual and numerical models (see review in A. G. Fountain, J. S. Walder, 1998). Accurate determination of these drainage systems is difficult due to inaccessibility of modern glacier beds, and due to interpretation uncertainties with regard to past glaciations. There is a broad consensus that soft-bedded, temperate glaciers which this paper refers to, drain subglacial meltwater through conduits incised into the substratum (J. F. Nye, 1973; J. S. Walder, A. Fowler, 1994), through channels carved in basal ice (H. Röthlisberger, 1972), through a distri-

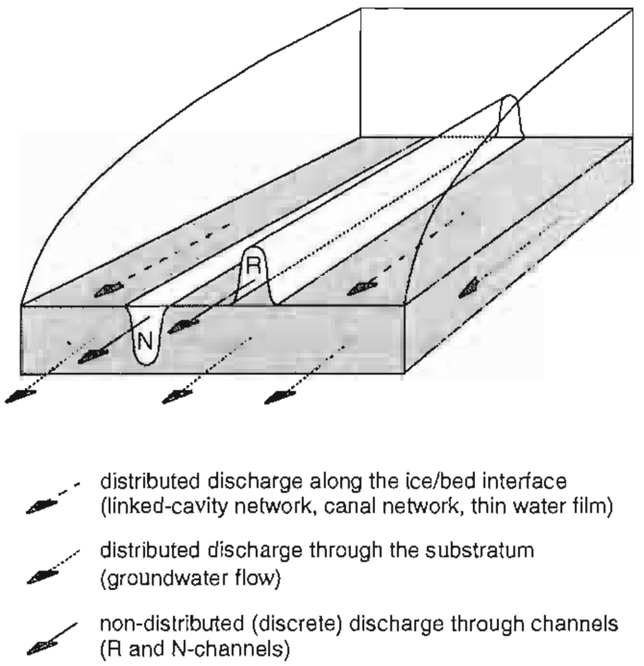

Fig. 1. Schematic representation of subglacial meltwater drainage systems under a warm-based glacier resting on permeable substratum; those systems may or may not operate simultaneously

buted system of linked cavities at the ice/bed interface (L. Lliboutry, 1968; B. Kamb, 1987), through a thin water film at the ice base (J. Weertman, 1972) and through the permeable substratum as groundwater flow (G. S. Boulton, A. S. Jones, 1979). Relative importance and interactions of these drainage systems can vary greatly being controlled by climatic (ablation rates), glaciologic (ice temperature) and geologic (substratum permeability) conditions.

One important aspect of reconstructing drainage systems of past ice sheets is validation using genuine geological data. This refers primarily to physical and numerical models, which must be constrained by the framework of field evidence. After a brief review of subglacial drainage systems, this paper gives examples of small (m-scale) buried ice-bed channels that originated during three major Pleistocene glaciations across the Central European Lowland, which were investigated in several outcrops in Germany and Poland. Together with well-known large-scale meltwater conduits (tunnel valleys) from the same area, these channels are interpreted as evidence that hydraulic transmissivity of the substratum did not suffice to drain all basal meltwater as groundwater flow. One possible consequence was temporary instability of these ice sheets during phases of water pressure increase, which could have led to rapid advances coupled with increased glaciotectonic activity.

SUBGLACIAL DRAINAGE SYSTEMS

Meltwater beneath a warm-based glacier (temperature above the pressure melting point) originates from melting of ice due to trapping of geothermal heat flux at the glacier sole (recharge usually estimated as about 6 mm/yr ice column equivalent; W. S. B. Paterson, 1993) and due to frictional heat at the ice/bed interface (another 6 mm/yr at basal sliding velocities of 20 m/yr; D. E. Sugden, B. S. John, 1976). The meltwater volume produced due to these mechanisms can vary in accordance with glaciologic parameters such as ice temperature and flow velocity, and with geologic parameters such as thermal conductivity and mechanical properties of the substratum. For parts of northern Germany during the last glaciation J. A. Piotrowski (1997*a*) estimated the basal melting rate as 36 mm/yr, which is similar to the inferred maximum groundwater recharge at the ice sheet base of 30 mm/yr postulated by G. S. Boulton *et al.* (1995). Subglacial environment can be also supplied with meltwater reaching the bed through englacial conduits such as moulins and crevasses draining water from the iee surface and its interior (R. L. Shreve, 1985). In the ice margin proximity this is the major meltwater source altogether, whereas under a thicker ice cover its importance diminishes to probably negligible values far under the ice sheet.

Subglacial meltwater is pressurised by ice overburden and its potentiometric surface follows the ice surface slope, so that a hydraulic gradient occurs which drives the water towards the ice margin where it discharges into subaerial water collectors such as rivers, lakes and the sea. Drainage systems at the ice base are largely known now due to numerous investigations under modern glaciers and reconstruction for past ice sheets based on sedimentary and geomorphic record (see reviews in D. I. Benn, D. J. A. Evans, 1998, and A. G. Fountain, J. S. Walder, 1998), but the relationships between the particular components are still debatable. In general, subglacial meltwater can be evacuated to the ice margin (1) through a low-energy **distributed system** in which drainage occurs in a thin water layer along much portion of the ice/bed interface and within the bed as groundwater flow, and (2) through a **non-distributed (discrete) system** of channels and conduits capable of discharging large water volumes in a short time (Fig. 1). Both systems are hydraulically connected, although the interaction degree is rather limited. It should also be mentioned that in the 1980's yet another discharge mechanism was postulated by J. Shaw (e.g. 1983), in which large volumes of previously stored meltwater are released and drain catastrophically under the ice sheet in a several-metres-thick water layer within few days. These large-scale subglacial floods are believed to have influenced global ocean level and possibly climate through a rapid input of large quantities of meltwater into oceans during the late Pleistocene (J. Shaw, 1989).

DISTRIBUTED SYSTEM

Groundwater flow. If a glacier or an ice sheet moves over permeable sediments, basal meltwater would first enter the sediment and be drained as groundwater flow. Because the system is pressurised by ice overburden, the drainage occurs analogue to water flow though a confined porous aquifer and the drainage capacity is governed by the Darcy law:

$$v = -K\frac{dh}{dl}$$

in which v is the specific discharge, K is the hydraulic conductivity [L/T] and dh/dl is the hydraulic gradient [1]. Although this basic principle of groundwater flow is well established, it has not been applied to subglacial aquifers until recently (G. S. Boulton, A. S. Jones, 1979; E. M. Shoemaker, 1986; N. E. Brown *et al.*, 1987; C. S. Lingle, T. J. Brown, 1987; G. S. Boulton *et al.*, 1995; J. A. Piotrowski, 1997*a, b*). The reason for this is probably that calculating meltwater discharge through the glacier bed requires good knowledge of spatial distribution of hydraulic conductivity as well as the hydraulic gradient, which is particularly difficult when reconstructions for past ice sheets are attempted. It is therefore not surprising that such studies lead to controversies, well illustrated by the on-going debate as to whether the unconsolidated sediments overridden by Pleistocene ice sheets had sufficient capacity to drain all subglacial meltwater or not. This is a question reaching beyond the issue of the drainage systems only, as it pertains to the general problem of ice sheet stability, which will be dealt with further in the text.

When more meltwater appears at the ice bed than can be evacuated through the substratum as groundwater flow, the system is forced to develop additional storage and drainage modes as a linked-cavity network or channels.

Linked-cavity network. Subglacial water-filled cavities separate the ice sole from the bed in a network consisting of numerous, broad and shallow water lenses linked by narrow connections referred to as orfices. These networks have been originally postulated for hard bedrock beneath glaciers by L. Lliboutry (1976) and B. Kamb (1987), but similar drainage system can also be envisaged for soft subglacial beds when elevated water pressure lifts the glacier from its bed in places. Water throughflow is limited by the narrow geometry of the orfices, so that the cavity system serves primarily as a storage reservoir of nearly stagnant meltwater whilst only a part of it is linked to subglacial channels. Cavity network configuration varies in time and space according to changes in water in and output. Stability of the entire system, however, is secured by the fact that there is no tendency for larger cavities to capture water from smaller ones (A. G. Fountain, J. S. Walder, 1998, equation 10), which prevents formation of an arborescent (branching) network typical for channels. This situation changes under high discharge conditions when, due to increased melting rates, pressure drops in larger cavities causing drainage of water from smaller ones and initiation of channels (B. Kamb, 1987).

Canal network. J. S. Walder and A. Fowler (1994) and P. U. Clark and J. S. Walder (1994) have proposed a slightly different system of distributed drainage on soft, deformable subglacial beds. This is a network of broad, shallow canals interconnected in a braided system in which pressure/discharge relations are the same as in the linked-cavity network, so that here too, larger conduits do not grow at the expense of smaller ones. This system, however, should be capable of transmitting larger water fluxes due to the absence of orfices. To-date, this theoretically conceived discharge mechanism has not been observed in any modern glacial environment yet.

Subglacial water film. It is widely recognised that glaciers, whose soles are at the melting point, rest on a thin film of meltwater (J. Weertman, 1972) with a thickness of typically well under ca. 1 mm (B. Hallet, 1979). This water originates from pressure melting on stoss sides of bed obstacles and flows then to pressure shadow zones where it refreezes; for this reason it is referred to as regelation water film. Although contributing to the forward ice movement, this water film is obviously a rather inefficient drainage mechanism because of its small thickness. Should the water film increase in thickness, it will become unstable and tend to develop a cavity or a proto-channel (J. F. Nye, 1976).

NON-DISTRIBUTED SYSTEM

R-channels. Subglacial meltwater channels incised upwards into basal ice have been often observed at ice margins and some have been investigated directly during low-discharge times. Hydraulics of these channels was first analysed quantitatively by H. Röthlisberger (1972) and hence they are referred to as R-channels. Under steady state conditions water pressure in R-channels is slightly lower than pressure in the surrounding ice, so that melting of ice along the channel walls by frictional heat is compensated by ice creep into the channel (R. L. Shreve, 1972). Increase in water pressure results in enlarging of channel cross-sectional area, and pressure drop causes enhanced creep of ice into the channel which may lead to its complete closure. One conclusion from the theoretical analysis of H. Röthlisberger (1972) is that water pressure in larger channels is lower than in smaller ones, so that a hydraulic gradient occurs between such channels if they communicate. This leads to water capture by large channels and their further enlargement resulting in the development of arborescent drainage system similar to a subaerial catchment area where smaller creeks drain into progressively larger ones. It is therefore understandable that along ice margins only few large channel portals occur which carry meltwater collected from smaller channels further under the glacier. Lateral pressure gradients between interconnected channels is perhaps the most important difference to the linked-cavity and canal drainage systems. When R-channels are filled with sediment, which is not destroyed by subsequent ice movement, eskers will be preserved after the deglaciation. Coarse-grained material found in most eskers indicate high flow and transport energy in R-channels, which make them efficient means of rapid meltwater evacuation. It is likely that many R-channels do not leave any recognisable topographic expression because of the sensitivity of the in-fill sediment to glacial erosion.

N-channels. In areas where basal meltwater can erode the substratum easier than it can carve upward into the ice as in areas of soft, unconsolidated sediments, N-channels develop (J. F. Nye, 1973). Their dimensions vary through several orders of magnitude between just few centimetres and several hundreds of metres. N-channels can be studied on erosional surfaces exposed after deglaciation as well as they can be reconstructed from borehole data if filled with sediment. Most spectacular channels of this type are known as tunnel valleys, which occur throughout the Central European Lowland stret-

Fig. 2. Location of sites discussed in the text (dots)

ching for many tens of kilometres and reaching over 500 m depth in places (J. Ehlers *et al.*, 1984). N-channels occur as isolated features or they can create a network of arborescent or non-arborescent drainage systems. Such drainage systems develop from former distributed flow networks whose capacity was exceeded by meltwater surplus which could not have been accommodated by other, more static drainage modes anymore. As opposed to R-channels, the N-channels are not affected by glacier movement directly and can develop through down-cutting at one place even under highly mobile ice sheets. Discharge rates in N-channels can be occasionally extremely high, as indicated by reconstruction of some Pleistocene tunnel valleys where meltwater fluxes could have been in the range of few thousands m^3/s during short-lasting outburst phases (e.g. J. A. Piotrowski, 1994).

Several studies of subglacial drainage systems indicate a possible chain reaction and switching to successively more efficient drainage modes as the meltwater volume at the ice base increases. At first, the meltwater is drained through the permeable substratum (I exclude the regelation film from further considerations due to its negligible importance for the total water transfer). As soon as the maximum hydraulic transmissivity of the bed under Darcian flow conditions is reached, the pressurised water would accumulate at the ice/bed interface and drain through the linked-cavity/canal system. Further increase of the water volume imposes evolution into a non-distributed drainage, in which R and N-channels efficiently evacuate meltwater to the foreground and secure glacier stability. Because these drainage systems leave different signatures in the geologic record, it is often possible, by studying them, to reconstruct the history of the subglacial hydrology for a given ice sheet.

FIELD EVIDENCE OF SMALL N-CHANNELS

Large-scale N-channels preserved as tunnel valleys are extensively documented in the Central European Lowland (e.g. F. Grube, 1983; J. Ehlers *et al.*, 1984; G. Schwab, 1996; S. Kozarski, 1966/1967; M. Pasierbski, 1979; W. Niewiarowski, 1995), but much smaller channels of possibly the same origin have largely escaped attention of researchers thus far. In this section I give some examples of such buried channel exposed in outcrops in Germany and Poland. Location of the outcrops is shown in Figure 2.

BRÜGGE

In a gravel pit at Brügge, some 20 km south of Kiel in north-west Germany a series of m-scale buried channels of the Weichselian Glaciation are exposed. The channels are incised into outwash sediments and filled with till. Example given in Plate I, Figure 1 shows a bifurcated channel of about 3 m depth and 5 m width at the top cut into parallel-bedded outwash. The channel bottom is undulating due to bifurcation, with the deepest part occurring in the middle of the incision. The steep-sided flanks dip at the angle of up to 80°, and a 15-cm-long overhanging wall occurs in one place. The outwash into which the channel in incised is entirely undisturbed, so that an impression is given of "razor-blade" erosion process during channel formation. The channel is filled with coarse-grained till showing ductile deformation structures (flame structures with minor folding) at the bottom. In the central part the till exhibits few, attenuated subhorizontal stringers of fine-grained sorted material up to 3 cm thick. Outside the channel, this till continuously merges into a 1–2 m thick sheet of regional extent. The maximum extent of the ice sheet that created the channel was probably only a few kilometres away (J. A. Piotrowski, 1996); thus the channel can be considered an ice-marginal feature. Its origin was clearly due to channelized meltwater erosion at the ice base, either in a single conduit that wandered laterally or by two conduits that later merged into one. Subsequently, the channel was filled with basal till which was accompanied by minor gravity deformations and washing.

DRANSKE

Another small channel of similar origin occurs at Dranske on the Isle of Rügen, at the base of a Weichselian till (Pl. I, Fig. 2). The 1.5-m-deep channel is eroded into largely undisturbed, parallel-stratified outwash. The channel has an overall V-shape and its flanks undulate strongly with overhanging sections in places. As in-fill material a massive, rather coarse-grained till occurs, which continues outside the channel as an up-to-2-m-thick till sheet. To the right of the channel, the till exhibits deformed pockets and stringers of silt and fine sand, apparently derived from the local substratum. The till in and outside the channel is evidently one and the same sedimentologic unit since no boundary occurs in between. Contact between the channel fill and the underlying outwash is extremely sharp, which suggests focused erosion by fast flowing meltwater stream. As in Brügge, no sorted sediments occur at the channel base. Ice limit of this advance is within few kilometres to the south-west.

NIEDERSTEINBACH

A strikingly similar fossil channel is exposed in Niedersteinbach, central Germany (Pl. II, Fig. 1). This about 0.8 m deep and 1.5 m wide channel derives from the Elsterian Glaciation which reached its limit about 10 km further to the south. The channel is carved into cross-bedded, coarse-grained outwash, underlain in turn by another till. Within 20 cm from the channel bottom, the outwash is slightly disturbed with ductile deformations and step-like normal faults dipping towards the channel. The channel is found at the base of a several-m-thick till, being itself filled with this till. The till both inside and outside the channel is massive and stone rich. In some places along the till base, undeformed stringers and lenses of sand, occur. There is no glaciofluvial material at the channel bottom, and till rests directly on a sharp erosional plane carved into the underlying sediment.

WELZOW-SÜD

In the Welzow-Süd open cast lignite mine in eastern Germany several buried channels of the Saalian age are exposed. Most of them are tens of metres deep and would fall into a tunnel valley category. Here I focus on one smaller channel, whose detailed sedimentology and genesis is subject of another paper (J. A. Piotrowski *et al.*, in print).

The channel is 5 m deep, distinctly U-shaped and carved into almost completely undisturbed, parallel-bedded outwash sediments (Pl. II, Fig. 2). As it is the case with other channels described in this paper, the Welzow-Süd channel is bounded from the surrounding deposits by a distinct erosional surface. Its flanks are very steep and overhanging in few places, and its width varies between 3 m at the bottom and 4.5 m at the top. Right beneath the channel there is a silty-clayey diapir contorted towards the channel axis, which suggests that the water pressure in the channel was lower than the pressure around it. This in turn indicates that the channel served as drainage pathway for the groundwater from the surrounding aquifer (J. A. Piotrowski *et al.*, in print).

The channel fill consists of three sediment units, that is cross-bedded meltwater sand and gravel at the bottom, fine-grained, largely massive till in the middle, and crudely stratified to massive outwash sand at the top. At the uppermost part of the in-fill a boulder lag with well-rounded stones occurs. This heterogeneous in-fill indicates a non-uniform channel formation, with meltwater erosion phase succeeded by till deposition, which possibly led to a temporary channel closure. A second erosion phase followed, which removed a part of the till before the channel was ultimately closed by outwash deposition at the top. Occurrence of outwash in the channel together with lack of glaciotectonic disturbances in the surrounding sediments provides a convincing evidence of meltwater erosion as the formation mechanism. The limit of this ice advance was 25 km further south.

NIETĄŻKOWO

At Nietążkowo, about 20 km south of Poznań (Poland), a set of subglacial bedforms occurs at the base of the Weichselian till (L. Kaczmarek, 1992). Plate III, Figure 1 depicts a bifurcate incision at the till base similar to the channel at Brügge, although smaller. The incision is interpreted as a small N-channel. Its depth is at maximum about 50 cm, and the width reaches its maximum of 1.2 m in the central part of the channel. Further up, an overhanging flank on the left reduces the channel cross-section. The in-fill consists of a massive, occasionally fractured sandy till which extends outside the channel as a 2–3 m thick sheet, interpreted by L. Kaczmarek (1992) as lodgement till. The underlying outwash is undisturbed around the channel, and it is separated from the channel fill by sharp erosional surface. This surface exhibits cm-scale undulations, particularly in the vicinity of the overhanging flank. The ice sheet under which the channel originated reached its outermost position about 15 km further to the south.

The buried N-channels described above seem to have several common features, which suggest their origin under similar boundary conditions. All of them are steep-sided with partly overhanging flanks, the contacts to the surrounding material is well defined and sharp, sediments around the channels are typically undisturbed, the channels are filled mainly with till which conformably merges with till sheets around the channels, they are incised into outwash sediments typically at least several metres thick, and they are found in sub-marginal zones of past ice sheets.

DISCUSSION AND CONCLUSIONS

It seems now widely accepted that a casual relationship exists between hydraulic characteristics of bed sediments and channel formation such as that channels develop when not all basal meltwater can be evacuated as groundwater flow (E. M. Shoemaker, 1986; G. S. Boulton, R. C. A. Hindmarsh, 1987; J. A. Piotrowski, 1997*a*). If this is correct, then a key factor is the transmissivity of the substratum, determined by the thickness of the unconsolidated layer and its hydraulic conductivity (K in the equation above), both of which can vary over several orders of magnitude. Restricting these considerations to the Central European Lowland, it can be stated that because the thickness of the unconsolidated sediments varies typically between few tens to few hundreds of metres, the factor controlling the bulk transmissivity are the K-values which range between $<10^{-9}$ for clays and 1 m/s for gravels (R. A. Freeze, J. Cherry, 1979). In a series of papers, G. S. Boulton and co-workers (e.g. G. S. Boulton *et al.*, 1995, 1996) postulated that outside the Scandinavian shield all the basal meltwater discharge could have been drained as groundwater flow. This was based on a generalisation of the unconsolidated sediments to just one hydrogeologic unit with conductivity of about 10^{-3} to 10^{-4} m/s, which corresponds to medium sand. More realistic, however, is a sandwich-like substratum including layers with much lower conductivity (clay, silt, till). Accordingly, J. A. Piotrowski (1997*a*, *b*) concluded that in north-west Germany only about 1/4 of the basal meltwater volume could drain as groundwater, and the rest was evacuated through channels. This suggestion based on geostatistical regionalisation of hydrogeologic parameters in the substratum (J. A. Piotrowski *et al.*, 1996, 1997) is supported by abundant occurrence of tunnel valleys in the area. The current paper, documenting also small-scale fossil channels gives further support to the idea that subglacial sediments were insufficient to drain all basal meltwater in central Europe. This seems to hold for all three major glaciations in this area (Elsterian, Saalian and Weichselian Glaciations).

Assuming validity of this conclusion, it is tempting to speculate on the stability of past ice sheets, which is among other factors influenced also by the subglacial hydraulics. Initiation of channelized drainage must have been preceded by porewater pressure increase in the substratum, which could have facilitated pervasive bed deformation, as postulated by many recently (see reviews in J. Menzies, 1996, and D. I. Benn, D. J. A. Evans, 1998). Other studies, however (e.g. J. A. Piotrowski, A. Kraus, 1997; J. A. Piotrowski, S. Tulaczyk, in print) suggest that water pressure increase resulted in widespread separation of ice from the bed by a thin meltwater layer which prevented transformation of glacier-induced shear stresses to the bed. It follows that in those times the ice sheet was possibly unstable due to enhanced basal sliding, which could have resulted in rapid movement velocity increase and surges.

It is worthwhile to note that the steep-sided geometry of all channels presented here speaks against bed deformation, because in such a system rather wide and shallow canals would form (J. S. Walder, A. Fowler, 1994; P. U. Clark, J. S. Walder, 1994).

It is difficult to say how long did the small channels operate and how far under the ice were they, but the distance to the limit of the relevant ice advance gives a maximum constraint for the latter. All channels given here can be considered sub-marginal features at the scale of the ice sheet, which is consistent with the idea of water capture into single conduits in the proximity to the ice margin as discussed earlier.

Although much work has been recently done on subglacial hydraulic systems in the context of mass transfer and ice sheet behaviour, further studies are badly needed which would incorporate both theoretical models and the sedimentologic work, because mainly cross-checked interdisciplinary research can contribute to a real progress in this field.

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REFERENCES

ALLEY R. B. (1991) — Deforming-bed origin for southern Laurentide till sheets? J. Glaciol., 37: 67–76.

ALLEY R. B., BLANKENSHIP D. D., BENTLEY C. R., ROONEY S. T. (1986) — Deformation of till beneath ice stream B, West Antarctica. Nature, **322**: 57–59.

BENN D. I., EVANS D. J. A. (1998) — Glaciers and glaciation. Edward Arnold. London.

BOULTON G. S. (1996) — The origin of till sequences by subglacial sediment deformation beneath mid-latitude ice sheets. Ann. Glaciol., **22**: 75–84.

BOULTON G. S., CABAN P. E., VAN GIJSSEL K. (1995) — Groundwater flow beneath ice sheets: part I — large scale patterns. Quatern. Sc. Rev., **14**: 545–562.

BOULTON G. S., CABAN P. E., VAN GIJSSEL K., LEIJNSE A., PUNKARI M., VAN WEERT F. H. A. (1996) — The impact of glaciation on the groundwater regime of Northwest Europe. Glob. Planet. Change, **12**: 397–413.

BOULTON G. S., HINDMARSH R. C. A. (1987) — Sediment deformation beneath glaciers: rheology and sedimentological consequences. J. Geophys. Res., **92**: 9059–9082.

BOULTON G. S., JONES A. S. (1979) — Stability of temperate ice caps and ice sheets resting on beds of deformable sediment. J. Glaciol., **24**: 29–43.

BROWN N. E., HALLET B., BOOTH D. B. (1987) — Rapid soft-bed sliding of the Puget glacial lobe. J. Geophys. Res., **92**: 8985–8997.

CLARK P. U. (1994) — Unstable behaviour of the Laurentide Ice Sheet over deforming sediment and its implications for climate change. Quatern. Res., **41**: 19–25.

CLARK P. U., WALDER J. S. (1994) — Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. Geol. Soc. Am. Bull., **106**: 304–314.

EHLERS J., MEYER K.-D., STEPHAN H.-J. (1984) — Pre-Weichselian glaciations of North-West Europe. Quatern. Sc. Rev., 3: 1–40.

FOUNTAIN A. G., WALDER J. S. (1998) — Water flow through temperate glaciers. Rev. Geophys., **36**: 299–328.

FREEZE R. A., CHERRY J. (1979) — Groundwater. Prentice-Hall. New Jersey.

GRUBE F. (1983) — Tunnel valleys. In: Glacial deposits in north-west Europe (ed. J. Ehlers): 257–258. A. A. Balkema. Rotterdam.

HALLET B. (1979) — Subglacial regelation water film. J. Glaciol., **23**: 321–334.

HART J. K. (1995) — Subglacial erosion, deposition and deformation associated with deformable beds. Progress Phys. Geogr., **19**: 173–191.

HOOKE R. LeB. (1998) — Principles of glacier mechanics. Prentice Hall. New Jersey.

KACZMAREK L. (1992) — Glaciodynamic implication of the Vistulian lodgement till in Nietążkowo, Leszno phase. In: Last ice sheet dynamics and deglaciation in the North European Plain. Excursion guide, Peribaltic Group Meeting (eds. M. Böse *et al.*): 28–33.

KAMB B. (1987) — Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. J. Geophys. Res., **92**: 9083–9100.

KAMB B., RAYMOND C., HARRISON W., ENGELHARDT K., ECHELMEYER K., HUMPHREY N., BRUGMAN M., PFEFFER T. (1985) — Glacier surge mechanism: 1982–1983 surge of Variegated Glacier, Alaska. Science, **227**: 469–479.

KOZARSKI S. (1966/1967) — On the origin of subglacial channels in the North Polish and North German plain. Bull. Soc. Amis Sc. Lett. Poznań, Ser. B, **20**: 21–36, .

LINGLE C. S., BROWN T. J. (1987) — A subglacial aquifer bed model and water pressure dependent basal sliding relationship for a West Antarctic ice stream. In: The dynamics of the West Antarctic Ice Sheet (eds. C. J. van der Veen, J. Oerlemans): 249–285.

LLIBOUTRY L. (1968) — General theory of subglacial cavitation and sliding of temperate glaciers. J. Glaciol., **7**: 21–58.

LLIBOUTRY L. (1976) — Physical processes in temperate glaciers. J. Glaciol., 16: 151–158.

MENZIES J. ed. (1995) — Modern glacial environments. Butterworth-Heinemann. Oxford.

MENZIES J. ed. (1996) — Past glacial environments. Butterworth-Heinemann. Oxford.

NIEWIAROWSKI W. (1995) — Diagnostic features of subglacial channels of glacial and glacio-glaciofluvial origin, exampled by channels of the Chełmno–Dobrzyń and the eastern Gniczno Lakelands. Quest. Geogr., 4: 225–231.

NYE J. F. (1973) — Water at the bed of a glacier. Symposium on the Hydrology of Glaciers, 95: 189–194. IAHS Publ.

NYE J. F. (1976) — Water flow in glaciers; jökulhlaups, tunnels and veins. J. Glaciol., 17: 181–207.

PASIERBSKI M. (1979) — Remarks on the genesis of subglacial channels in Northern Poland. Eiszeit. u. Gegenw., 29: 189–200.

PATERSON W. S. B. (1993) — The physics of glaciers. Pergamon Press. Oxford.

PIOTROWSKI J. A. (1994) — Tunnel-valley formation in northwest Germany — geology, mechanisms of formation and subglacial bed conditions for the Bornhöved tunnel valley. Sed. Geol., 89: 107–141.

PIOTROWSKI J. A. (1996) — Dynamik und subglaziale Paläohydrogeologie der weichselzeitlichen Eiskappe in Zentral-Schleswig-Holstein. Geol.-Paläont. Inst. Univ. Kiel, Reports, 79: 1–188.

PIOTROWSKI J. A. (1997*a*) — Subglacial hydrology in northwestern Germany during the last glaciation: groundwater flow, tunnel valleys, and hydrological cycles. Quatern. Sc. Rev., 16: 169–185.

PIOTROWSKI J. A. (1997*b*) — Subglacial groundwater flow during the last glaciation in northwestern Germany. Sed. Geol., 111: 217–224.

PIOTROWSKI J. A., BARTELS F., SALSKI A., SCHMIDT G. (1996) — Geostatistical regionalization of glacial aquitard thickness in northwestern Germany, based on fuzzy kriging. Math. Geol., 28: 437–452.

PIOTROWSKI J. A., BARTELS F., SALSKI A., SCHMIDT G. (1997) — Regionalisierung der Durchlässigkeitsbeiwerte mit unscharfen (fuzzy) Zahlen: Der Natur näher? Grundwasser, 1: 3–10.

PIOTROWSKI J. A., GELETNEKY J., VATER R. (in print) — Soft-bedded subglacial meltwater channel from the Welzow-Süd open-cast lignite mine, Lower Lusatia, eastern Germany. Boreas.

PIOTROWSKI J. A., KRAUS A. (1997) — Response of sediment to ice sheet loading in northwestern Germany: effective stresses and glacier bed stability. J. Glaciol., 43: 495–502.

PIOTROWSKI J. A., TULACZYK S. (in print) — Ice-bed separation and enhanced basal sliding under the last ice sheet in northwest Germany? Quatern. Se. Rev.

RÖTHLISBERGER H. (1972) — Water pressure in intra- and subglacial channels. J. Glaciol., 11: 177–203.

SCHWAB G. (1996) — Zum Relief der Quartärbasis in Norddeutschland. Bemerkungen zu einer neuen Karte. Z. Geol. Wiss., 24: 343–349.

SHAW J. (1983) — Drumlin formation related to inverted meltwater erosional marks. J. Glaciol., 29: 461–479.

SHAW J. (1989) — Drumlins, subglacial meltwater floods, and ocean responses. Geology, 17: 853–856.

SHOEMAKER E. M. (1986) — Subglacial hydrology for an ice sheet resting on a deformable aquifer. J. Glaciol., 32: 20–30.

SHREVE R. L. (1972) — Movement of water in glaciers. J. Glaciol., 11: 205–214.

SHREVE R. L. (1985) — Esker characteristics in terms of glacier physics, Katahdin esker system, Maine. Geol. Soc. Am. Bull., 96: 639–646.

SUGDEN D. E., JOHN B. S. (1976) — Glaciers and landscape. A geomorphological approach. Edward Arnold. London.

WALDER J. S., FOWLER A. (1994) — Channelized subglacial drainage over a deformable bed. J. Glaciol., 40: 3–15.

WEERTMAN J. (1972) — General theory of water flow at the base of a glacier or ice sheet. Rev. Geophys. Space Phys., 10: 287–333.

SYSTEMY KANAŁOWE DRENAŻU PODLODOWCOWEGO: PRZYKŁADY TUNELI TYPU *N* Z EUROPY ŚRODKOWEJ

Streszczenie

Podane przykłady niewielkich (rząd wielkości w metrach) subglacjalnych tuneli wód roztopowych typu *N* z obszaru środkowej Europy oraz znane wielkoskalowe rynny tego samego typu wskazują na istotną rolę drenażu kanałowego podczas głównych zlodowaceń plejstoceńskich na tym terenie (fig. 1, 2). Przewodność hydrauliczna osadów podlodowcowych pozwalała na drenaż jedynie części wód subglacjalnych przez podłoże w postaci wody gruntowej. Pozostała część była drenowana tunelami o znacznej wydajności hydraulicznej, wciętymi w podłoże i zachowanymi do dziś w zapisie geologicznym. Tunele te mają strome ściany, są wypełnione głównie gliną zwałową i są ostro oddzielone od niezaburzonych osadów otoczenia pofalowaną powierzchnią erozyjną (tabl. I–III). Ich położenie w strefach submarginalnych dawnych zlodowaceń jest zgodne z teorią glacjologiczną.

EXPLANATIONS OF PLATES

PLATE I

Fig. 1. Buried subglacial meltwater channel of Weichselian age at Brügge, Schleswig-Holstein, north-west Germany. Note undisturbed character of outwash sediments in the bed and channel bifurcation. The channel is filled with till. Flow direction into the exposure face

Fig. 2. Buried subglacial meltwater channel of Weichselian age at Dranske, Isle of Rügen, north-east Germany. Note the largely undisturbed character of outwash sediments in the bed, partly overhanging channel flanks and massive till as in-fill sediment. Flow direction roughly into the exposure face

PLATE II

Fig. 1. Buried subglacial meltwater channel at the base of thick Elsterian till at Niedersteinbach, Saxony, eastern Germany (arrow). Ellipsoid feature beneath the channel is due to secondary iron oxidation. Flow direction roughly into the exposure face

Fig. 2. Buried subglacial meltwater channel of Saalian age at Welzow-Süd, Saxony, eastern Germany. Note the undisturbed character of outwash surrounding the channel and very steep channel flanks. The channel is filled with outwash (bottom), till (middle) and outwash (top). Flow direction out of the exposure face. Detailed account in J. A. Piotrowski *et al.* (in print)

PLATE III

Fig. 1. Buried subglacial meltwater channel of Weichselian age at Nieciążkowo, west-central Poland. Note the undisturbed character of outwash surrounding the channel, its steep, partly overhanging flanks and the trough bifurcation. The channel is filled with massive, partly fissured till

 Geol. Quart., 1999, 43 (2)

Fig. 1

Fig. 2

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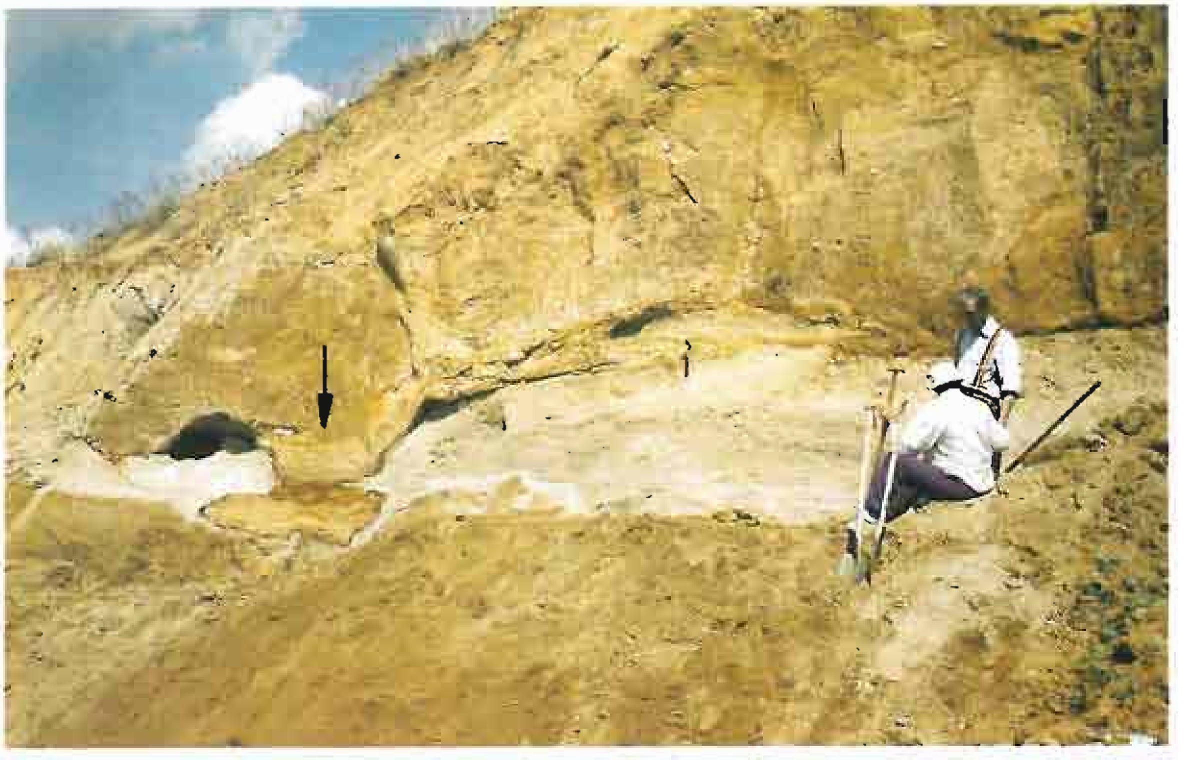

Fig. 1

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