Donnerstag 20. Oktober 2011	14:30-15:00

Natural Radioactive Isotopes in Glacier Studies

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Abstract

Arctic glaciers are retreating; studies on their changes and evolution are necessary as they concern not only the arctic but the whole world. We present a new possibility to investigate meltwater supplied by glacierized basins in introducing radioactive isotope measurements in combination with more classical parameters like electrical conductivity. Among the natural radioactive elements the most promising is the noble gas radon, more precisely the isotope ^{222}Rn, with a half life of 3.8 days and the possibility of automated continuous measurements.

Radon levels in glacier meltwater show surprisingly high values up to 33 Bq/L in the accumulation season. Varying radon concentrations can be linked to mixing of meltwater from different origins, roughly supraglacial, englacial and subglacial. Only meltwater in contact with rock or sediments can be charged with radon.

Results from 5 years of sampling on Werenskiold glacier, covering both glaciological seasons, are presented and discussed. The results of continuous measurements gives a supplementary information on drainage footpaths and the style and system of the draining of glaciers.

Our study intends to make a contribution to better understand the behavior of meltwater and the response of glaciers to environmental parameters and also, on a longer term, to climate change.

Introduction

In a period of global glacier retreat, the understanding of the processes whereby meltwater drains from beneath glaciers is a central problem in glaciology (Boulton et al., 2007). To understand changes and evolution of glacier's state, studies based on the meltwater drainage within glacier systems are very important (Wadham 1998). Water plays a dominant role in many glacial processes and the erosional, depositional and environmental significance of meltwaters and associated fluvioglacial processes cannot be overemphasized (Eyles 2006). Different ionic species are acquired from contact during water flow through the glacier drainage system and contribute to the increased electrical conductivity and, in the case of radon, to an uptake of radon escaping from bed rock and sediments. Examination of the isotopic composition of meltwaters is an important tool for judging of fate/history of meltwaters circulating in glaciers (Peter 2006, Bukowska- Jania 2007).

The Radiation Physics Laboratory, University of Luxembourg, is dealing with natural radioactivity, mainly radionuclides of the Uranium and Thorium Decay Series and notably radon. It has been involved in the development of conceptual and numerical models to study the dispersion and transport

of radionuclides in subsoil and groundwater environments (Kies, 2005). A good expertise has been gained in the metrology of radioisotopes, especially those of the natural decay chains (Tosheva 2004).

Methodology

In hydrology, a classic isotopic hydrograph study during rain events leads to a quantitatively portioning of runoff water into contributions from different waters: superficial runoff, interflow water and groundwater (Kraemer 1998, Kies 2005). Based on longtime experience in the use of natural radionuclides as environmental tracers, the present paper relates an attempt to transpose the contribution of natural radionuclides and especially radon to study glacier meltwater. We expect a sort of hydrograph separation of the origin of meltwaters into currently known habitats: surface runoff (supraglacial), within (englacial) and ice basement contact zone (subglacial).

Radon (^{222}Rn) is a radioactive noble gas (T=3.8 d), it originates from the decay of radium (^{226}Ra), member of the natural ^{238}U series. After creation radon has the possibility to join the gaseous or liquid surroundings in contact with the hosting rocks and soils. Soluble in water, radon can be carried over longer distances during its mean life time of 5.5 days (period T = 3.8 days). Thus radon can be used in nature as a suitable tracer for studying short-lived phenomena.

Glacial meltwater acquires solute in a manner that reflects the characteristics of the flow route taken, with factors including transit time, access to atmospheric gases and contact with reactive rock flour (Tranter 1997). The solute content of meltwater should therefore provide a composite picture of the flow contribution of different hydrological reservoirs, so that glaciers with different hydrological systems and bedrock geologies produce contrasting bulk meltwater. Different ionic species are acquired from contact during water flow through the glacier drainage system; temporal variations of ionic concentration (Gordon 1997, Peter 2006) and radon may be interpreted in terms of the water flow pathways. High conductivity, high ionic stable and radioactive element concentrations indicate contact with reactive sediments and rocks, possibly for extended periods of time. High radon concentrations indicate contact with sediments/rocks, this contact happening less than 20 days before sampling. The length of contact is important. In the case of radon a steady equilibrium concentration can be expected whenever uptake of radon is counterbalanced by decay.

Roughly one can distinguish between two subglacial flow systems: canalized and distributed (Swift, 2002):

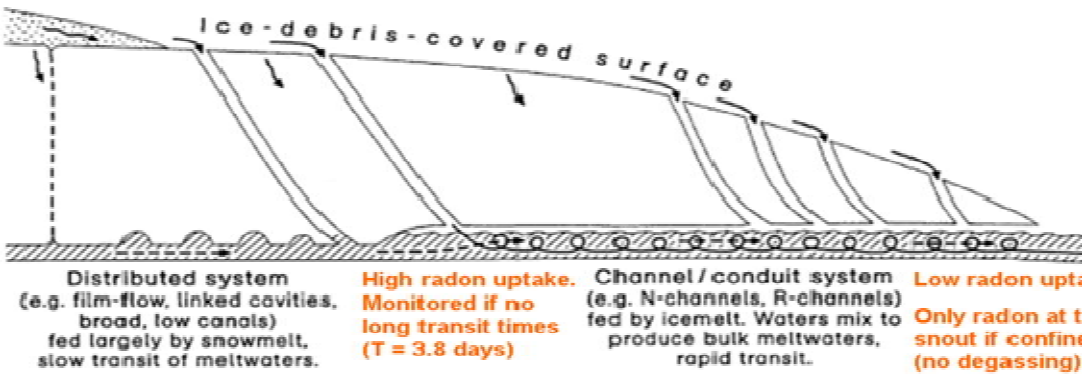


Fig. 1.: *Subglacial flow systems and radon (adapted from Tranter et al., 1994).*

- The canalized flow system has concentrated inputs of meltwater via moulins or crevasses, it has large water fluxes, often strongly turbulent with high velocity, it covers a small proportion of the glacier bed. This system has low probability to uptake large amount of radon. If confined, is likely to transport radon to the outflow without decay as transport is rapid.
- The distributed subglacial drainage system has low flow velocities with sheet, cavity or porous flow at the ice–bed interface. Resistive or restricted flowpaths cover a large proportion of the glacier bed through a network of shallow canals over areas of basal sediment. Direct surface meltwater inputs are absent or scarce; most meltwater derives from basal melting. The distributed system predominates where glacier flow prevents rationalisation into a channelised network and in overdeepenings (Swift, 2002); besides it is the predominant form of drainage during winter. The distributed drainage system is the predominant source of radon, the contribution to the outflow must be no longer than several radon decay periods. An indirect way to track at the outflow the contribution of melwater from the distributed system are increased concentrations in meltwater and transported fine grained sediments of Lead210, with 22.4 year half-life, the quasi stable not direct decay product of radon.

Radon concentrations depend on the radium concentrations of the rocks, the rock/sediment- water contact surface and the contact duration. Meltwater containing radon is secure information that part of this water has been recently in contact with the bedrock, the more radon the higher is the fraction of meltwater in contact with bedrock, the fraction without contact being nearly radon free.

Field site

For our investigation we chose the well studied the Werenskiold glacier (79°40'N;10°40'E) situated in the south-western part of Wedel-Jarlsberg Land in SW Spitsbergen. Its closeness to the Polish Polar Station in Hornsund has made the glaciated catchment well studied in terms of glaciology, climatology, geomorphology and geology (Jania 1988, Pälli 2002, Bukowska-Jania 2007). Werenskioldbreen is a polythermal glacier with terminus on land, a 25 km^2 area and a 200-240 m maximum thickness. The terminus and the lower part of the glacier is divided into two parts by a central moraine, one third to the northern and two third to the southern part. Given the difference in height and the thickness of ice upglacier, the hydraulic head is considerable and powerful artesian-driven water spouts are common at the ice front especially during the melting period.

Before upwelling, water flows relatively independently of icemelt to the terminus via a subglacial drainage system, possibly constituting flow through a sediment layer. Cold basal ice at the terminus forces it to take a subterranean routing in the latter stages. Meltwater drainage from the glacier is dominated by artesian outflows at the south and north ice margins. The existence of spatially discrete flow paths conveying snowmelt and subglacial icemelt to the terminus is the norm for polythermal-based glaciers on Svalbard (Wadham, 1998).

The Werenskiold Glacier basin is located at the meeting point of three tectonic blocks of the Hecla Hoek formation. The southern neighborhood of the glacier is build of the metamorphic groups Isbjørnhamna and Eimfjellet, comprising Proterozoic amphibolites, migmatites, quartzites, chlorites and amphibolite−quartzite schists. The eastern surroundings of the accumulation field consist of the Deilegg formation, build predominantly of thick banks of phyllites, laminated schists and quartzite conglomerates with dolomite and marble precipitations. The Jens Erikfjellet formation, which limits the

glacier basin from the north−west, is build predominantly of greenschists and mica−calcite−quartzite schists. (Czerny, 1993).

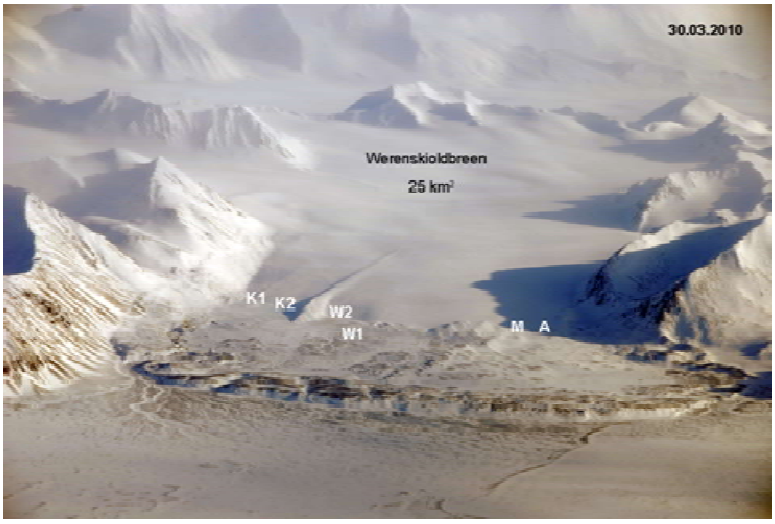


Fig.2: *Werenskioldbreen with the different April sampling locations. At W3, W1 and often W2 important artesian outflows are observed in the ablation period.*

Measurements and results.

Diffferent outflow areas at the terminus of Werenskioldbreen were sampled between September 2006 and April 2011: 2 areas in the northern part called K1 and K2, W1-W2 are important summer outflows to the south of the central moraine and M-A is an area close to the southern end of the glacier front (Fig.2). All areas are situated at the terminus of the glacier at an altitude around 70 - 80 m. The sampling dates covered the different periods of the glacial cycle: end of September 2006; at the end of the ablation period in 2007-2011 for K1-K2 and M-A; during the ablation periods (July – Mid September) for W1-W2 in 2007-2010.

One has to distinguish between measuring campaigns at the end of the accumulation season in April-beginning of May and those during July-Mid September ablation period.

In April part of the forefield is covered by ice, mostly naled ice, especially at the mentioned locations. But only in K1, K2 and M-A running water or water outflows of ice domes could be accessed and sampled, often after breaking the ice cover. Only artesian outflows (summer) or running water (winter) were sampled. They are insofar interesting as they originate from basal meltwater and are not mixed by superficial meltwater. Often winter outflows are not active in the ablation season when the main outflows draining the glacier are reactivated. Only artesian upwelling water was sampled in summer, thus a prior degassing of radon could be avoided, continuous measurements of radon were not possible in April.

To measure radon continuously in the water phase we use the partition coefficient $K_{water/air}$ of radon between water and air. This coefficient depends on temperature, for meltwater around 0°C, $K_{water/air}$ is close to 0.1 (Clever, 1979). A silicon diffusion tube connected to a radon-in-air monitor, put into flowing water, allows the diffusion of radon nuclides until the equilibrium partition is obtained. Each 30 minutes the air in the silicon tube is pumped through a closed radon tight tubing system into a scintillation cell

where radon decays together with radon progeny decays are counted. After passing the radon monitor, the air is directed to a CO_2 monitor based on infrared absorption, tested and calibrated for low concentrations at air temperatures close to 0°C

Besides the continuous measurements of radon performed in September 2009, regularly from 2006 on, water samples are analyzed in the laboratory of the Polish Arctic Base in Hornsund by the liquid scintillation technique. Water is sampled in 120 ml radon tight bottles. At the laboratory 12 ml are replaced by 10 ml of scintillator. Vigorous shaking for 2 minutes allows most of radon to be trapped by the scintillator. After allowing phase separation and equilibrium between radon and his short lived decay products, 8 ml of scintillator are filled into a vial to be measured in a Hidex portable LSC monitor allowing alpha-beta separation. The limit of detection is 10 mBq/L.

In order to understand and model the radioactive information it is absolutely necessary to rely on continuous radon measurements coupled with other crucial parameters. We chose to measure continuously: electrical conductivity, temperature with very high precision, CO_2, pH, total dissolved gas pressure and dissolved oxygen. Atmospheric conditions at the terminus and on different locations of the glacier are obtained by meteorological stations operated by colleagues from the university of Wroclaw and Warsaw. We have further information from the geochemical fingerprints of the water in determining in our radiochemical laboratory the concentrations of all relevant radionuclides. Often chemical analysis is performed at the Polish Base laboratory by ion chromatography. Altogether we expect a better understanding of the pathways of glacier meltwater, crucial for the dynamics of glaciers, the separation of meltwater in different compartments and origins.

In the melting periods 2007, 2008 and 2009, continuously combined recording conductivity-temperature RBR XR-420™ probes (C-T) were installed close to or directly in the outflows of turbid artesian vents situated at or close to the glacier tongue.

The temperature probe is a 24-bit Thermometrics™ thermistor in a sealed unit together with the conductivity probe. It has a resolution of 10^{-5} °C, a range of -5°C to 25°C and an accuracy of ± 0.002 °C, IST-90, guarantied by the manufacturer. The conductivity probe has a resolution of 0.01 µS/cm, a range of 0-2 mS/cm and an accuracy of ± 3 µS/cm.

As a rule, each water sampling is combined with an insitu recording with the C-T probe for some minutes, even in April. Sometimes in April it was possible to monitor temperature and EC continuously at outflows over days before they were refrozen (see Fig. 7).

Ablation period

In September 20th 2006 was sampled the outflow W2. The temperature was low (- 5 °C), it was a sunny day after snowfall the day before; no superficial melting was observed on the glacier. C-T levels were recorded insitu, two water samples were taken in radon tight bottles to the Polish station to be measured by liquid scintillation. Radon and conductivity measurements showed very high values (radon concentration 22 +/- 1 Bq/L) reflecting the subglacial origin. Pulina (Pulina, 1990) refers that, based on the glacial river of the Werenskioldbreen, ablation water in summer is as much as 80–95%

of the total meltwater flow, but, beginning in September, the share of subglacial sources increases, possibly representing the entire flow by the end of that month.

Due to the lack of surface melting in September and the not yet closure of water pathways by freezing and closure due to deformation of ice, one may assume that steady state radon concentrations are approached originating from sub-glacial meltwater.

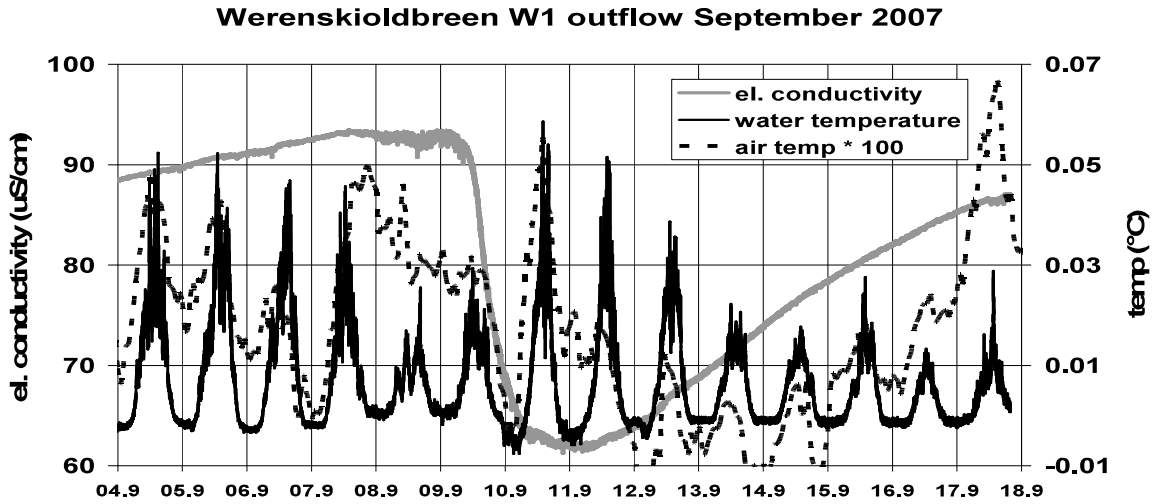


***Fig. 3**: example of continuous recording of temperature and electrical conductivity close to the outflow vent at W2.*

For the whole melting period in one artesian outflow, W1 (2007, 2009, 2010), W2 (2008), a monitoring unit comprising the described C-T probe and a radon-in-water unit were installed close to or into the outflow vent. In 2007 W1 and W2 were active, it was decided to do the installation in W1, the best accessible of them. Unfortunately, two days after installation, a sudden increase of the outflow destroyed the radon and CO_2 measuring unit therefore only data from the C-T probe are available (Fig. 3).

***Fig.4.** Upwelling water at Werenskioldbreen, location W1, July 2007, radon concentrations 8 Bq/L. The continuous measurement device can be seen, before destruction by an outburst. In 2009 and 2010 the measuring setup was put directly into the outflow.*

Regular visits to the forefield showed that the outflows became active around July 15th 2007, witnessed by one of the authors as chaotic, having high outflow of sediments carrying ice and

sometimes stones (Fig. 4). In 2007, water sampled on July 18th and on July 23rd were 4.3 Bq/L and 8.3 Bq/L respectively.

Over the melting period, effective electrical conductivities (EC) were in the range 20 to 40 µS/cm. Measurements done on the outflow end of September 2006 and in April 2007-2010 show EC in the range of 220 µS/cm and radon concentrations of up to 33 Bq/L (April 2010 in K2). One could be tempted to apply a simple two-component conservative mixing model used in groundwater hydrology (Wadham; Brown, 2002; Kies 2005):

Total bulk discharge is usually separated into two hydrological components

$$Q_b = Q_c + Q_d ;$$

b for bulk-, c for quick-canalized-, d for delayed-flow.

In this model, the quick flow component is perceived to flow rapidly through the hydroglacial system, predominantly in ice-walled conduits at the glacier bed (canalized system) with short water–rock contact times and low water/rock ratios, limiting the potential for radon acquisition to rapid surface exchange reactions (Tranter et al., 1993). Conversely, the delayed flow component transports meltwater relatively slowly through the distributed hydrological system at the ice–bedrock interface, water/rock ratios are high and meltwaters intimately interacts with the products of subglacial physical abrasion and crushing, including finely comminuted glacial flour, debris-rich basal ice, and subglacial moraine (Brown 2002).

Assuming conservative mixing, continuity of mass requires that

$$C_bQ_b = C_cQ_c + C_dQ_d$$

where C_b and C_d are the radon concentrations of the outflow and from the water of the distributed system; C_c is the radon concentration from water of the canalized system, negligible in our model and will be put to zero.

Both equations allow deriving the magnitude of the canalized and the distributed system in terms of the global discharge:

$$Q_d = C_b/C_d * Q_b$$

$$Q_c = (C_d-C_b)/C_d * Q_b$$

$$Q_d/Q_c = C_b/(C_d-C_b)$$

Unfortunately for both outflows there are no measurements done on a particular outflow. Only the relative contributions can be predicted.

The subglacial hydrological interpretation based on this simple two-component mixing model is fraught with uncertainty, since the approach is limited by simplistic geochemical assumptions (Brown, 1990; Tranter 1991). For example, the model assumes the existence of only two hydrological components, which are characterized by a single, invariant value of radon concentration throughout the summer meltseason. Furthermore the radon concentration of the distributed system is guessed based on measurements of the end of the melt season and from end of winter in different outflows of the Werenskiold glacier. It is interesting that, in applying a similar model for conductivity, similar variation pattern come out. Radon concentrations vary between 4 and 8 Bq/L in the melting period can be compared to concentrations around 28 Bq/L end of winter , whereas conductivity around 35 µS/cm are to be compared to 220 µS/cm in winter outflows.

In 2009 a monitoring unit was installed at exactly the same outflow as in 2007. In 2009 the melting period started early. A visit to the forefield mid-July showed already the existence this important artesian outflow W1 out of dead ice situated some 150 m away from the receding glacier tongue. It was possible to install a specially adapted system in order to monitor directly in the outflow. Figure 5 gives an example of the continuous measurements.

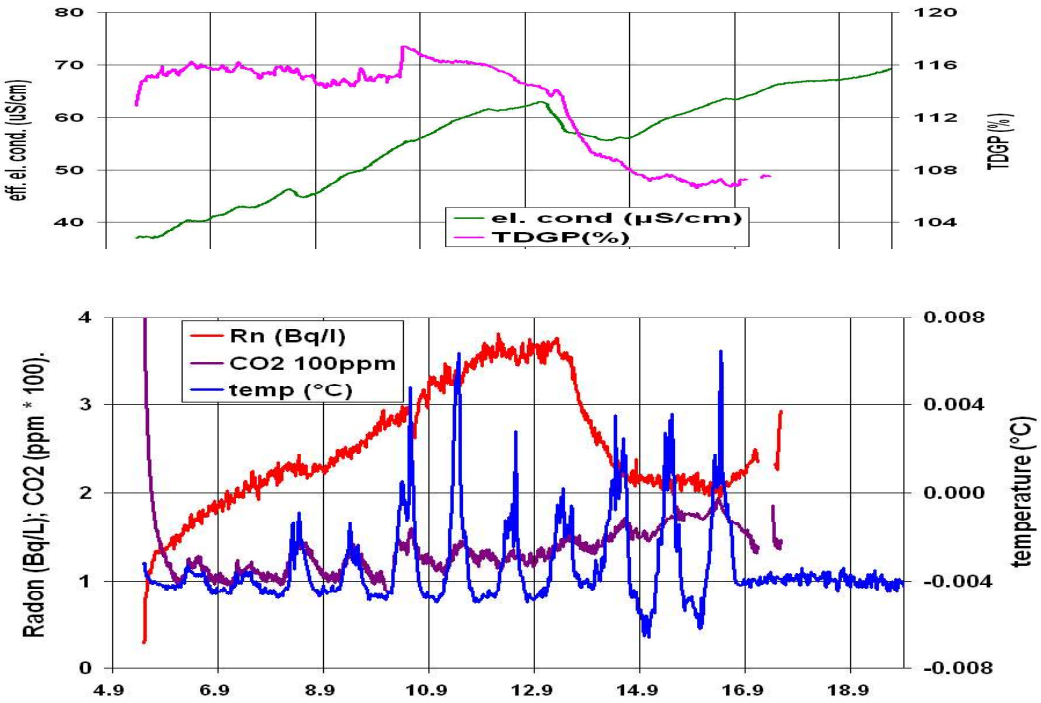


Fig. 5: *Werenskioldbreen W1, September 2009. Results from continuous measurements of radon, electrical conductivity, total dissolved gas pressure (TDGP), CO_2 and water temperature; note the water temperature slightly below 0 °C most of the time.*

The electrical conductivity is increasing as is expected at the end of the ablation period. For the documented period radon varies in a similar way, but over the whole period it is not always the case. Both EC and radon do not experience a daily pattern suggesting the suglacial origin of the meltwater. For the monitored period, radon concentrations vary between 1.5 and 4 Bq/L, much less that expected ≈ 20 Bq/L at the end of the ablation period.

End of accumulation period

Since 2007 each April we had the possibility to sample at Werenskiold glacier. Electrical conductivity and temperature were measured in situ by a RBE probe; radon by liquid scintillation at the Polish base together with pH; at the Luxembourg laboratory radionuclide's concentrations are measured, after radiochemical treatment, either by alpha spectroscopy or by liquid scintillation.

From 5th to 21st of April 2007, on six different days, 50 flowing water samples were collected. Over the 2.5 km glacier front 5 naled ice fields of varying area with ice domes, comprising radial fractures generated by pressure, could be observed, in three of them, K1, K2 and A-M, running water outflow close to the glacier could be accessed and sampled. It has often been asserted that the presence of

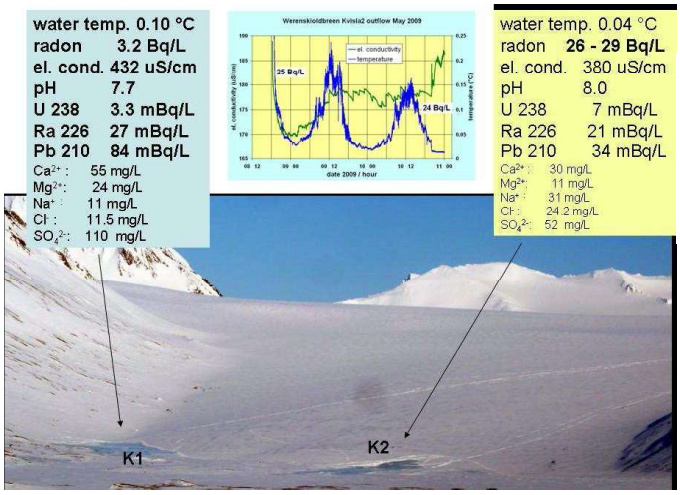
icing indicates that the bed of the associated glacier is at least partly at the pressure-melting temperature, and hence that icings are diagnostic of a polythermal or temperate glacier thermal regime (Hagen 1993).

Flowing water was normally on or close to ice domes, some of them 1.5 m high but generally there heights were below one meter. Sometimes an ice cover on the flanks of the domes or in their direct vicinity had to be broken to access running water, often under pressure at opening. A particular outflow never lasted more than 3 days before refreezing, leading to another output at some distance.

In April it was not possible to take samples at area W, the area sampled in September 2006 despite the presence of many frozen ice domes. In area K2 highest April radon (12-16 Bq/L) and conductivity values (specific el. conductivity 400-500 µS/cm) were measured. In K1, radon concentrations were lower (maximum 11 Bq/L) and very variable, sometimes down to 0.1 Bq/L, specific electrical conductivities varied around 400 µS/cm. In area S electrical conductivity was 2.5 times lower than in N-b, whereas with 12 Bq/L radon concentrations were high.

A general trend was that high radon concentrations were often linked to high electrical conductivity.

Each April there were observed many changes in the winter outflows, especially in K1 and K2 where most winter outflow was noticed and where always flowing water could be accessed, sometimes under pressure when ice cover was removed.



Loc	Rn	eff. el. cond.	uranium 238	radium 226	lead 210
K2	Bq/L	µS/cm	mBq/L	mBq/L	mBq/L
2007	12-16.2	235	4	6	18
2008	1	215	1	33.8	46
2009	24-29	238	7	21	100
2010	31-33	230			
2011	3.5	300			

Fig. 6 *gives an example of the different parameters (besides radon) measured in April-May 2009 in K1 and K2. The table gives an overview of measured parameters at K2.*

A continuous outflow in 2008 on top of a naled ice dome had very low and stable radon concentrations, around 1 Bq/L. As a prior degassing could hardly taken place, we can conclude that this outflow originated from a deep reservoir where most of radon decayed before the outflow. The electrical conductivity was similar as the other years.

In April 2009, at K2, radon concentrations were constant at an outflow over 3 weeks of survey; for some period continuous measurements by RBR probe was possible (Fig. 6). Radium concentrations at K2 are higher than Uranium, documenting reducing conditions at the uptake; we noticed high Lead210 concentrations (^{210}Pb, the long lived decay product of radon), what reflects that this water was charged with radon over a longer period.

April 2010 showed highest radon concentrations measured on an outflow at K2 that were sampled regularly over 2 weeks. Over this time period electrical conductivity and ionic concentration was constant, isotopic measurements gave -78 and -11.4 for δ^2H and $\delta^{18}O$ respectively.
The measuring campaign in 2011 allowed only few visits to the forefielsd of the glacier. No flowing water outflow could be located; there was presence of water aver large areas in the forefield, documenting a diffusive outflow. Electrical conductivity was always higher than measured the previous years. The reason is partially refreezing of the diffusive outflow water together with a depletion of ions in the frozen part and enrichment in the unfrozen part. As radon is not affected by this segregation, and assuming radon concentrations measured the years before, one can guess the age of this water and the amount of outflow.
Werenskioldbreen provides evidence for considerable basal routing of water. High radon concentrations and conductivity of the subglacial upwelling provides evidence of the passage of icemelt through a subglacial bedrock and basal moraine environment characterized by high rock-sediment to water contact ratios, prolonged residence times and restricted access to the atmosphere, preventing radon to degas. At higher discharges, basal bulk runoff becomes dominated by icemelt from the lower parts of the glacier that is conveyed through a subglacial environment, characterized by low rock: water ratios, short residence times and free contact with atmospheric gases, to the glacier margins. In Werenskioldbreen icemelt is routed via a hydrological system composed of englacial and supraglacial components to the glacier margins by the ice surface slope (Pälli, 2002).

In order to test radon in meltwater of other glaciers, outflows were sampled in April 2008, 2009 in the forefields of Nannbreen and Austre Torellbreen, two glaciers close to Werenskioldbreen. They showed radon concentrations between 5 and 12 Bq/L. A summer survey done by one of the authors in summer 2009 in artesian outflows of glaciers at Petunia Budka (Central Spitsbergen) showed very low radon concentrations, lower than 1 Bq/L.

Conclusions

At Werenskioldbreen high radon concentrations are measured in meltwater. Combined with traditional investigation tools, radon proves to be a valuable tracer for the study of artesian glacier meltwater.
The high radon concentrations document that meltwater has been recently, less than 15 days, in intensive interaction with basal sediment or rocks.
Highest radon concentrations were measured in September and April, in periods of no supraglacier melting, lowest in period of the beginning of thawing, intermediate concentrations in the periods of maximum thawing with high combined sub-, in- and supra- glacier circulation. The results support the hypothesis on year around activity of glacier drainage within polythermal glaciers with long lasting contact of waters with the bedrock. It seems to be much more effective during winter period when a tunnel drainage system is closed. Results are showing also that during winter season subglacial linked cavity systems are active and a channel system is organized during the melting season.
We report here of first investigations with radon as natural tracer in glaciology; it proves to be am important and innovative contribution to the study of arctic. Every knowledge on parameters describing glacier evolution is necessary as input on global climate models.

We have to learn more how to use and read the obtained radon information together with those obtained with other parameters.

Acknowledgements.- Thanks are due to the Polish Polar Station for hosting and logistic support; to friends and colleagues for assistance in the field research. The Polish authors like to acknowledge the support by the research grant No IPY269/2006 of the Ministry of Science and Higher Education, Republic of Poland.

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