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Dating of syngenetic ice wedges in permafrost with ^{36}Cl

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Abstract

A new method of permafrost dating with the cosmogenic radionuclide ^{36}Cl is presented. In the first application, syngenetic ice wedges are dated using the ratio of ^{36}Cl and Cl concentrations in ice as the signal. ^{36}Cl is produced in the atmosphere by nuclear reactions of cosmic rays on argon. Stable chlorine enters the atmosphere from the oceans. Their ratio does not depend on chloride concentration in precipitations and on sublimation of snow. *In situ* production of ^{36}Cl in permafrost ice via cosmic ray-induced reactions and neutron capture are calculated and the dating age limit is estimated as 3 million years. $^{36}Cl/Cl$ ratios in permafrost samples from cape Svyatoy Nos (Laptev Sea coast), North-Eastern Siberia, are measured by accelerator mass spectrometry. Analysis of the first results and the calculated dates support the feasibility of the ^{36}Cl permafrost dating method

1. Introduction

Two types of permafrost could be separated concerning the relation between sedimentation and freezing. Therefore, in a general cross-section, the cryolithosphere can be divided into two sections, and namely epigenetic and syngenetic permafrost. The main (lower) part represents epigenetically frozen layers, where freezing occurred downward from the top after pre-Pliocene sedimentation in accordance with Global Cooling in the northern hemisphere at the end of the Neogene. In this case the age of epigenetic permafrost is younger than those of the sediments and according to the effects of thermal inertia on the temperature wave propagation the deeper these deposits lay, the more recently they were frozen. Consequently, the age of this kind of permafrost is assumed to be younger. The late Cenozoic (upper) part of the section represents syngenetically frozen layers formed under harsh climatic Arctic conditions within the last few million years. This sedimentation occurred synchronously with the freezing from below, and in general, the age of the permafrost here is taken to be similar to the age of the freshly accumulated sediments (Basis of Geocryology, 1959; Washburn, 1980).

But even in the latter case, permafrost as a part of the uppermost lithosphere was very sensitive to climate changes and reacted to these oscillations by aggradations in cold periods (cryochrones), and by thawing in warm periods (thermochrones). The cryochrones following the thermochrones resulted in refreezing of thawed parts and thus, the whole section represents now one monolithic frozen sequence containing refrozen (epigenetic) and never-thawed (syngenetic) parts. This scheme shows that the duration of permafrost does not coincide with the age of sediments. Therefore, the cross-section of the

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cryolithosphere represents a sequence of sediments of known as well as unknown permafrost ages that could differ from the age of the sediments. For this reason the reconstruction of the Quaternary history and the interpretation of Pleistocene climatic signals and geological events archived within permafrost have very few relative temporal proofs, i.e. they are not well grounded. From this point of view the direct dating of the frozen, most dynamic part of the Earth crust, is a key aim of geocryology in order to estimate the permafrost age. Until now a lot of palaeo-environmental studies in permafrost had used different geochronological methods (e.g. Mackay et al., 1972; Moorman et al., 1996; Sulerzhitsky and Romanenko, 1997; Murton et al., 1997; Péwé et al., 1997, etc.). All these methods reveal the age of sediment accumulation or of organic remains within permafrost but never the age of permafrost formation. This problem has not been solved yet, especially for early Pleistocene to late Pleistocene deposits, which are older than the methodological range of radiocarbon dating. Direct records of permafrost do not extend beyond ~40,000 years, and we know only one publication with the data for mid Pleistocene permafrost (Froese et al., 2004).

Permafrost represents a unique natural archive containing numerous palaeoecological records, which needs clear age determination. Therefore, geochronology by long-lived cosmogenic radionuclides will extend the dating range and certainly would find a wide application in Quaternary palaeo-environmental and palaeo-ecological reconstructions, e.g. to estimate the long-term preservation of fossils, greenhouse (methane and carbon dioxide) gases and the inclusions of life (viable micro-organisms, which are adapted to permanently frozen environment) (Gilichinsky, 2002).

In the north-eastern Arctic the first traces of cryogenesis are related to the late-Pliocene deposits. According to palaeontological interpretations (Sher, 1974, 1997) the most ancient permafrost dates back to 3 million years as a result of persisting extremely cold climatic conditions. Today, permafrost underlies most of the Arctic area and whether the permafrost has existed permanently during the last few million years is still under discussion. Its age determination is an important objective of geocryological and paleo-climatological studies as a way to outline the cryostratigraphy and Quaternary history of the permafrost area and to detect the temporal dynamics of the permafrost table in the vertical cross-section.

Here we propose a dating method based on ^{36}Cl measurements quiet similar to dating of ground water, for which the ratio $N(^{36}Cl)/N(Cl)$ and the ^{36}Cl concentration $N(^{36}Cl)$ are used. The cosmogenic radionuclide ^{36}Cl is produced in the atmosphere and falls out on the ground with wet precipitation or as a dry fall-out. Stable chlorine in precipitations mainly originates from a sea spray. A more detailed description can be found e.g. in (Bentley et al., 1986; Philips et al., 1986; Nolte et al., 1991; Fröhlich et al., 1991). The cosmogenic radionuclide ^{10}Be also originates from the atmosphere and follows the similar transport patterns to the earth's surface. The measured $^{36}Cl/^{10}Be$ ratio in the permafrost sample could provide an additional determination of its age. This dating is limited by the experimental accuracy, by differences in the nuclides' geochemical properties and by the *in situ* production of ^{36}Cl and ^{10}Be (Heisinger et al., 2002a, b).

The present paper is organized in the following way. In paragraph 2, the dating methods with the ratios of $^{36}Cl/Cl$ and $^{36}Cl/^{10}Be$ are developed, and *in situ* production of both radionuclides limiting the dating is described. First measurements of $N(^{36}Cl)/N(Cl)$ ratios in ice wedges by accelerator mass spectrometry (AMS) are presented in paragraph 3. The corresponding to the first measurements permafrost date is compared with the sediment ages deduces by various methods. The conformity of the data is discussed in paragraph 4.

2. Dating of permafrost with the cosmogenic radionuclide ^{36}Cl

The occurrence of ice wedges is a good evidence for prevailing stable permafrost conditions. The process of refreezing of snowmelt water, which penetrates into frost cracks during spring, leads to ice wedge formation. Due to the repetition of this process huge ice wedges have been formed within thousands of years. Ice wedges are composed of winter precipitation and can be used for the reconstruction of winter temperatures by means of stable oxygen and hydrogen isotopes (Vaikmäe, 1989; Meyer et al., 2002a, b). Therefore, exact dating of ice wedges is also important to estimate the variability of winter temperatures during the Quaternary. Generally, the permafrost deposits and ice wedges are very useful archives for reconstructing Arctic palaeo-environments. The system is frozen and water is less mobile than in e.g. any ground water system. Consequently, the conditions of a closed system are met, though even at low permafrost temperatures free water exists. During frost cracking and ice wedge growth, the upper soil layer above the ice wedge, the so-called active layer remains frozen. Thus, the mass exchange with the soil is negligible. A limited exchange of ions and isotopes takes place only in the contact zone between ice wedge and adjacent sediment. The most suitable for dating samples should be taken far away from the ice wedge rim.

2.1. Formation of ice wedges

Ice wedges are mainly composed of winter precipitation and can be used for the reconstruction of winter temperatures by means of stable oxygen and hydrogen isotopes. If surface water precipitation and the formation of permafrost can be considered as simultaneous (syngenetic permafrost) the age of ice wedges should be approximately equal to the water age. In this case, atmospherically produced cosmogenic radionuclides such as e.g. ^{36}Cl and ^{10}Be can be used for dating of permafrost. In spring, the snow that has been accumulated in polygonal

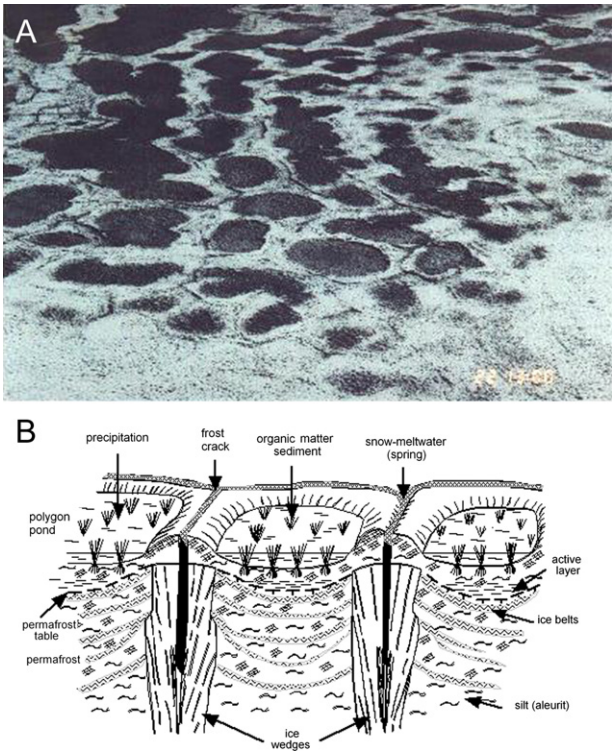

Fig. 1. (A) Polygons on the tundra surface with snow accumulated in cracks; (B) scheme of ice wedge formation (in Meyer, 2003, according to Romanovskii, 1977).

cracks (Fig. 1a) during about 8 winter months, melts. The melting water enters ice wedges along frost cracks, which were formed typically in its central part (Fig. 1b). The age difference within an ice wedge is small compared to the half-lives of ^{36}Cl (301,000 years) and ^{10}Be (1,500,000 years). The fresh snow has a typical mass thickness (the product of the linear thickness and density) of about $20\,kg\,m^{-2}$ corresponding to 0.2 m of water equivalent.

The atmospheric water vapour forming the snow is considered to originate from relatively warm oceans. According to the main moisture fluxes in northern Europe and Siberia (Kuznetsova, 1998), for western longitudes $<140^{\circ}$E, the main source of humidity is the North Atlantic Ocean. For more eastern longitudes it is mainly the Pacific Ocean. During the wintertime the Arctic Ocean is dominantly covered by ice and thus, is considered not to contribute much to winter precipitation in Siberia. Even though the persistence and dominance of the moisture source regions during interglacial and glacial periods is not exactly known, for our calculations we consider the initial ^{36}Cl/Cl ratio at the moment of the ice wedge formation as a time-independent constant. This strong assumption has to be verified in future studies.

2.2. Dating with ^{36}Cl

^{36}Cl is produced in the stratosphere and the troposphere by cosmic ray-induced nuclear reactions on the atmospheric argon (Lal and Peters, 1967; Huggle et al., 1996; Masarik and Beer, 1999). The stratospherically produced ^{36}Cl enters the troposphere following the seasonal mass exchange through the tropopause essentially at mid latitudes (Scheffel et al., 1999). In the troposphere ^{36}Cl is deposited to the surface of the Earth by precipitation and by dry fall-out. Due to the transport through the tropopause the ^{36}Cl deposition flux $\Phi_{36}(\lambda)$ is latitude dependent (Blinov et al., 2000). The global mean production rate of ^{36}Cl is approximately equal to $P_{36} = 20\,atoms\,m^{-2}\,s^{-1}$ (Huggle et al., 1996; Masarik and Beer, 1999).

Most of the stable chlorine enters the troposphere by sea spray (Blanchard, 1985). It is deposited to the earth with precipitation and by dry fall-out. The deposition flux to the earth depends on the distance to the oceans and on wind directions and speed. The directions of moisture fluxes from west to east in northern Europe and Asia (Kuznetsova, 1998) indicate that presently for Siberian regions with longitudes lower than 140°E, the main humidity originates from the relatively warm northern Atlantic Ocean. Humidity transport from the cold Arctic Ocean to Siberia is considered to be negligible. Therefore, the change in distance of north Siberian regions to the Arctic Ocean is not expected to influence the deposition flux of stable chlorine. A contribution of the gaseous fraction of HCl to the fixed in the ice wedge dissolved chlorine seems to be not important in contrast with the Antarctic surface firn snow layers (Delmas et al., 2004).

The precipitation fallen in winter enters the ice wedges by melt water in spring and freeze. One of our basic assumptions is that the ratio of concentrations of cosmogenic ^{36}Cl to stable chlorine at this time $N_{36}(\lambda,0)/N(Cl)$ corresponds to the mean atmospheric value which remains constant and does not critically depend on the climatic conditions. The ratio seems not to be disturbed by the effects of gas diffusion conjectured for the old ice (Rempel et al., 2001).

The lifetime of ^{36}Cl is $\tau_{36} = T_{1/2}/\ln 2 = 434{,}000$. ^{36}Cl concentration and its ratio to stable chlorine decrease with time t since formation of the ice wedge according to the exponential law of decay $N_{36}(\lambda,t)/N(Cl) = N_{36}(\lambda,0)/N(Cl)e^{-(t/\tau_{36})}$. Thus, the absolute age of the permafrost can be found as $t = \tau_{36}\,\ln((N_{36}(\lambda,0)/N(Cl))/(N_{36}(\lambda,t)/N(Cl)))$, where $N_{36}(\lambda,t)/N(Cl)$ is the ratio of ^{36}Cl to stable chlorine measured in the permafrost sample at present and $N_{36}(\lambda,0)/N(Cl)$ is the estimated initial ratio.

Ground-water ages established on the base of ^{36}Cl concentration measurements in the range of up to million years have been reported (Bentley et al., 1986; Philips et al., 1986; Nolte et al., 1991; Fröhlich et al., 1991). With a similar procedure, it is expected that syngenetic permafrost ice samples with ages up to millions of years can be dated.

2.3. Dating support with the ratio of ^{36}Cl/^{10}Be

^{10}Be is another long-lived radionuclide produced in the atmosphere by cosmic rays in the nuclear reactions with atmospheric nitrogen and oxygen. The mean production

rate of ^{10}Be is $P_{10} = 184\,\text{atoms}\,\text{m}^{-2}\,\text{s}^{-1}$ (Masarik and Beer, 1999). Atmospheric transport and deposition pattern of ^{10}Be are similar to those of ^{36}Cl. ^{10}Be enters the ice wedges with the winter snow melting in spring. The active layer, the soil cover above the ice wedge, is still frozen when frost cracking takes place thus, no filtering of ^{10}Be by the soil or its absorption on the particulate is expected during transport from the surface to the rupture in the ice wedge. It could be wrong for the dusty ice where the influence of the colloid processes on the ^{10}Be initial concentration in water should be additionally studied (Baumgartner et al., 1997). The ^{10}Be concentration in precipitation can be estimated in the following way. At $\lambda = 70^\circ$ latitude the ^{10}Be deposition flux is approximately $\Phi_{10}(70^\circ\text{N}) = 210\,\text{atoms}\,\text{m}^{-2}\,\text{s}^{-1}$. After 8 months of winter snow formation the accumulated flux is $\Phi_{10}(70^\circ\text{N}) = 4.4 \times 10^9\,\text{atoms}\,\text{m}^{-2}\,\text{winter}^{-1}$. With a mean winter snow cover of $d = 20\,\text{kg}\,\text{m}^{-2}\,\text{winter}^{-1}$ the ^{10}Be initial concentration in the melted water and in the ice wedge is $c_{10} = \Phi_{10}(70^\circ\text{N})/d \approx 0.2 \times 10^6\,\text{atoms}\,\text{g}^{-1}$. This estimate can be compared with ^{10}Be measurements in late Pleistocene and Holocene ice wedges of Bykovsky Peninsula, 71.40°N, 129.25°E. At this location, ^{10}Be concentrations between $c_{10} \approx 1 \times 10^6$ atoms g^{-1} and $c_{10} \approx 0.1 \times 10^6$ atoms g^{-1} were measured (Meyer, unpublished data). These concentrations agree within a factor of 2–5 with the estimation showing a rather strong variability and the possible dependence on local and global climatic conditions.

The ratio of ^{36}Cl/^{10}Be fixed in ice at the time of the ice wedge formation decreases then with time t as

$$\frac{\text{N}(^{36}\text{Cl}, t)}{\text{N}(^{10}\text{Be}, t)} = \frac{\text{N}(^{36}\text{Cl}, 0)}{\text{N}(^{10}\text{Be}, 0)} \text{e}^{-(t/\tau_{\text{eff}})}$$

with the effective lifetime given by

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{36}} - \frac{1}{\tau_{10}} = \frac{1}{541,000a}$$

2.4. Initial values

The initial values, i.e. the start values, of $\text{N}_{36}(\lambda,0)/\text{N(Cl)}$ and $\text{N}(^{36}\text{Cl},0)/\text{N}(^{10}\text{Be},0)$ for the region can be determined by direct measurements in the accumulated winter snow in spring just before melting. However, the corresponding ratios in the young ice from the last glacial stage could be more suitable as the reference points for the dating exponent. The second ratio can be also taken from the calculations, e.g.

$$\frac{\text{N}(^{36}\text{Cl}, 0)}{\text{N}(^{10}\text{Be}, 0)} = \text{P}_{36}/\text{P}_{10} = 0.1$$

(Masarik and Beer, 1999). There is a certain danger of natural contaminating of the elder ice by excessive ^{36}Cl concentration produced in the atmosphere by the bomb tests in early 1960s of the last century. This possibility should be checked at least once by measuring samples from the ice wedges corresponding to the last millennia.

2.5. In situ production of ^{36}Cl and ^{10}Be

In situ, that means at the place of fixation in the permafrost, ^{36}Cl is mainly produced by the neutron activation of stable ^{35}Cl contained in the permafrost ice. The neutrons originate from the cosmic rays and from decay of natural uranium and thorium. According to Heisinger et al. (2002a, b), the production rate of ^{36}Cl at a depth H includes production by secondary neutron component of the cosmic rays, by stopped negative muons, by fast muons and by decay of thorium and uranium and can be calculated as a function of depth:

$$P_{36}(h) = \begin{pmatrix} \frac{2525}{ga}\text{e}^{-(h/\Lambda_h)} + \sum_Z f_{\text{C}}(Z) f_{\text{D}}(Z) f_n(Z) R_{\mu^-}(h) \\ +4.8 \times 10^{-6}\,\text{cm}^2\,\text{g}^{-1} \times \beta(h) \times \Phi(h) \times \overline{E_9(h)}^{0.75} + P_{\text{Th,U}} \end{pmatrix} f(^{36}\text{Cl}). \quad (1)$$

Here, h is expressed in the mass thickness units: $h = \int_0^H \rho(l)\text{d}l\,\text{g}\,\text{cm}^{-2}$, where H is the linear depth below the surface in *cm* and ρ the density of the overlying deposits in g cm^{-3}; $\Lambda_h = 150\,\text{g}\,\text{cm}^{-2}$ is the mean path of neutrons, $f_{\text{C}}(Z) = a(Z)P(Z)/\sum_{Z'} a(Z')P(Z')$ is the chemical compound factor with the atomic capture probability $P(Z)$ relative to oxygen (Egidy and Hartmann, 1982) and the atomic abundance $a(Z)$ of the element Z, $f_{\text{D}}(Z)$ is the probability that the negative muon does not decay in the atomic shells (Suzuki et al., 1987), $f_n(Z)$ is the number of emitted neutrons from the element Z (Singer, 1974), $R_{\mu-}(h)$ is the rate of stopped negative muons (Heisinger et al., 2002b) and the function $\beta(h)\Phi(h)\overline{E_9(h)}^{0.75}$ describes the depth dependence of the production rate by fast muons (Heisinger et al., 2002a) $E_9(h)$ is the muon energy in GeV. $P_{\text{Th,U}}$ is the production rate of neutrons originating from decays of thorium and uranium (Feige et al., 1968). The term

$$f(^{36}\text{Cl}) = \frac{a(^{35}\text{Cl})o(^{35}\text{Cl})}{\sum_Z a(Z)\sigma(Z)}$$

describes the fraction of thermal neutrons which produce ^{36}Cl (Heisinger et al., 2002b) and $\sigma(Z)$ is the thermal neutron cross section. For ice wedges the neutron diffusion length can be supposed to be larger than the dimensions of the ice wedge. Therefore, in Eq. (1) the chemical composition of the ice wedge can be used.

Similarly to ^{36}Cl, ^{10}Be is produced *in situ* mainly by reactions of the neutrons, of stopped negative muons and of fast muon induced showers of cosmic rays (Heisinger et al., 2002b). Main targets for the reactions are the oxygen atoms in ice. With the above notations the depth-dependant production rate is given by

$$P_{10}(h) = \frac{8.86}{ga}\text{e}^{-(h/\Lambda_h)} + 7.9 \times 10^{-4} R_{\mu^-}(h) + 6.1 \times 10^{-8}\,(\text{cm}^2\,\text{g}^{-1})\beta(h)\Phi(h)\overline{E(h)}^{0.75}.$$

If we consider that the mass of the material deposited at the place of interest above the ice wedge has been increasing with the mean accumulation rate ε, the *in situ* produced ^{36}Cl concentration in the permafrost is given by

$$c_{36}^{\mathrm{is}}(h) = \int_0^{h/\varepsilon} P_{36}(h-\varepsilon t)\mathrm{e}^{-(t/\tau_{36})}\,\mathrm{d}t. \quad (2)$$

The expression (2) shows that the built-up *in situ* concentration does not depend directly on the actual depth of the ice wedge, but on the mass of the material shielding it from above. The calculated *in situ* concentration of ^{36}Cl is shown in Fig. 2 as a solid line, together with the concentration of atmospherically produced ^{36}Cl (dotted line). The latter was estimated as $c_{36}^{\mathrm{atm}}(h) = c_{36}^{\mathrm{atm}}(0)\mathrm{e}^{-(h/\varepsilon\tau_{36})}$, where the ^{36}Cl concentration at the upper layers of the permafrost was taken as $c_{36}^{\mathrm{atm}}(0) = 1.2\times10^5\,\mathrm{atoms\,g^{-1}}$ and the mean accumulation rate for the soil was arbitrary taken as $\varepsilon = 10^{-2}\,\mathrm{g\,cm^{-2}\,a^{-1}}$.

The concentration of *in situ* produced ^{10}Be is in the same way given by

$$c_{10}^{\mathrm{is}}(h) = \int_0^{h/\varepsilon} P_{10}(h-\varepsilon t)\mathrm{e}^{-(t/\tau_{10})}\,\mathrm{d}t.$$

It is shown in Fig. 3 as a function of depth together with the atmospherically produced ^{10}Be for the same accumulation rate $\varepsilon = 10^{-2}\,\mathrm{g\,cm^{-2}\,a^{-1}}$. The concentration of atmospheric ^{10}Be was calculated from $c_{10}^{\mathrm{atm}}(h) = c_{10}^{\mathrm{atm}}(0)\mathrm{e}^{-(h/\varepsilon\tau_{10})}$ with $c_{10}^{\mathrm{atm}}(0) = 3.6\times10^5\,\mathrm{atoms\,g^{-1}}$.

2.6. Dating limit

In a given sample the measured concentrations of ^{36}Cl and ^{10}Be are composed of the atmospherically produced and partially decayed radionuclides and the *in situ* produced ones. The exponential decay law is valid only for the atmospheric contribution. This means that the contribution of *in situ* production has to be subtracted from the experimental values:

$$c_{36}^{\mathrm{exp}} - c_{36}^{\mathrm{is}} = c_{36}^{\mathrm{atm}}(0)\mathrm{e}^{-(t/\tau_{36})} \quad \text{and} \quad c_{10}^{\mathrm{exp}} - c_{10}^{\mathrm{is}} = c_{10}^{\mathrm{atm}}(0)\mathrm{e}^{-(t/\tau_{10})}.$$

Taking into account uncertainties of the *in situ* contribution, the dating limit is reached when the atmospheric concentrations of the radionuclides in ice have decayed to the level of the *in situ* production, i.e. when $c_{36}^{\mathrm{atm}} \approx c_{36}^{\mathrm{is}}$ and $c_{10}^{\mathrm{atm}} \approx c_{10}^{\mathrm{is}}$. According to Fig. 2, for ^{36}Cl this condition is reached for the mass thickness of the covering material of $h \approx 3\times10^4\,\mathrm{g\,cm^{-2}}$ corresponding to an age limit of $t = h/\varepsilon \approx 3\,\mathrm{Ma}$ (3 million years). The detection limit for ^{10}Be (Fig. 3) is not approached for all the Cenozoic formations.

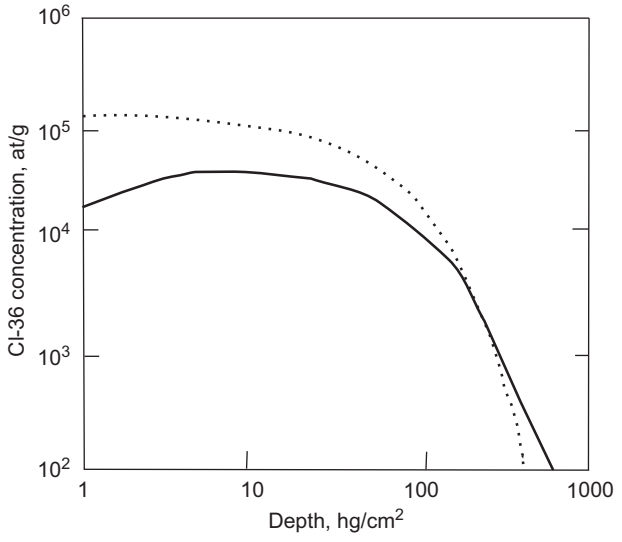

Fig. 2. The calculated concentration of ^{36}Cl in the permafrost in dependence of the depth under the surface: solid line—*in situ* produced ^{36}Cl; dotted line—atmospherically produced ^{36}Cl.

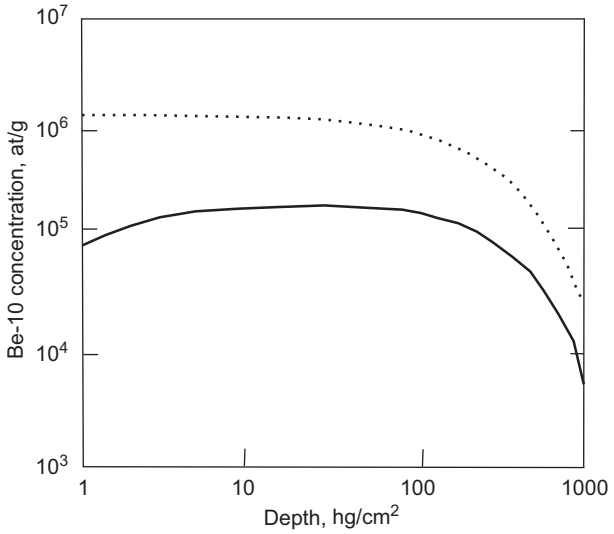

Fig. 3. The calculated concentration of ^{10}Be in the permafrost in dependence of the depth under the surface: solid line—*in situ* produced ^{10}Be; dotted line—atmospherically produced ^{10}Be.

3. First ^{36}Cl measurements in permafrost samples

Similar geological series of Quaternary syngenetic permafrost deposits with two levels of large ice wedges exist in the western part of East Siberian Sea along the Dimitrii Laptev Strait on both main land coasts of Cape Svyatoy Nos and Oyogossky Yar and on the southern coast of Bol'shoy Lyakhovsky Island (Fig. 4). In the coastal exposures the cross-section of Quaternary deposits were disclosed with several stratigraphic units and ice wedges on certain levels. These sections have been already the objects of extensive stratigraphic, cryolithologiclal and palaeoenvironmental studies during the last century (Ermolaev, 1932; Romanovskii, 1958a, b, c; Pirumova, 1968; Ivanov, 1972; Konischev and Kolesnikov, 1981; Ukraintseva et al., 1989; Nagaoka, 1994; Nagaoka et al., 1995; Arkhangelov et al., 1996; Kunitsky, 1996,

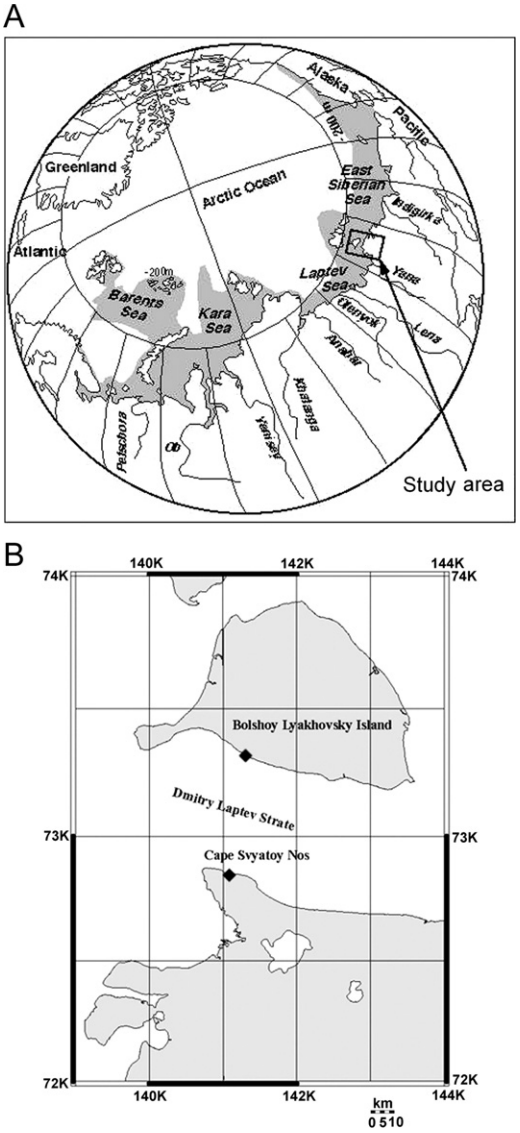

Fig. 4. Map of study area (A) and coordinates of Bol'shoy Lyakhovsky Island and Cape Svyatoy Nos (B).

1998; Nikolskiy et al., 1999; Nikolskiy and Basilyan, 2004; Schirrmeister et al., 2002; Meyer et al., 2002a, Andreev et al., 2004; Romanovskii et al., 2004; Sher et al., 2005).

The permafrost samples for dating were taken from the cross section of Cape Svyatoy Nos (72.84 °N, 140.85 °E). This section includes several units with two systems of ground ice wedges, which were clearly formed during different periods. The basal layer of the section (Fig. 5) is represented by sandy gravel and pebbles. Overlain is a buried Icy Complex composed of syncryogenic sediments and ice wedges, called the Jukagir Suite. The age of Jukagir Suite is estimated on the base of the evolution stage of collared lemmings within the geological interval 220–390 ka (Nikolskiy and Basilyan, 2004). The thickness of Jukagir Suite is not quite constant, because of its partial thawing during the following warming period. The average width of the ice wedges grown in light-brownish-grey silty sand with some unrounded pebbles and gravels is 2 m, the distance between wedges is in the range of 10–15 m. Cryolithological characteristics of Jukagir Suite (textural composition, volumetric moisture, ice wedges presence) are similar to the Edoma Suite characteristics (see below). The difference is only in the presence of a significant part of a sandy fraction and inclusions of poorly rounded pebbles. Na and Cl ions with the pH–8 dominate in the ultra fresh pore solution. The visible thickness of this Icy Complex averages to 3 m. In general both, Jukagir and Edoma, suites are considered as deposits accumulated on flat slope areas.

The sediments of Jukagir Suite are covered by sandy-loam and silt loam with numerous plant roots and thin epigenetic ice wedges, described in details as Kuchugui Suite (Ivanov, 1972) and, probably, represented by alluvial deposits. The thickness of Kuchugui Suite varies from 7–15 m. The rare epigenetic ice wedges, about 30 cm width, cross the suite and root in the underlying horizon. The suite is characterized by the absence of sandy fraction, the massive cryogenic structure (pore ice only) and moisture 20–30 vol%. Pore water is also ultrafresh with dominate

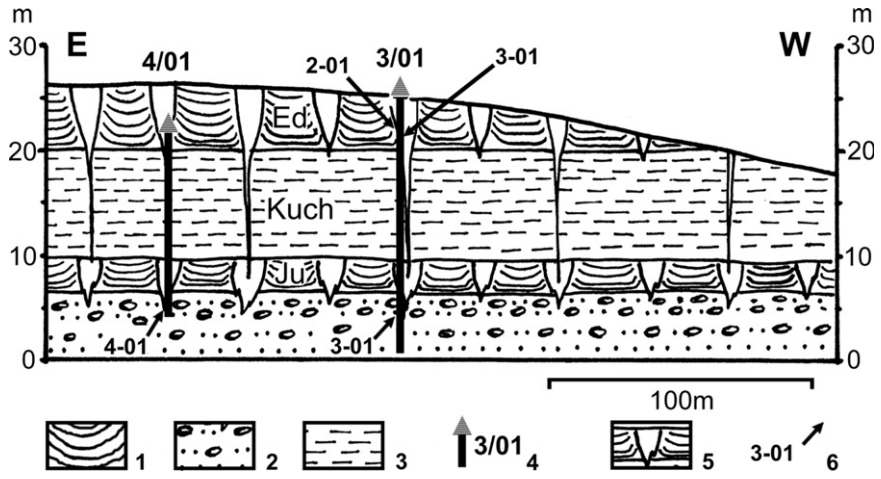

Fig. 5. Scheme of the studied permafrost sequence and sampling sites at Cape Svyatoy Nos. Ju—Jukagir Suite (mid Pleistocene Ice Complex), Kuch—Kuchchugui Suite; Ed—Edoma Suite (late Pleistocene Ice Complex). 1—silty loam; 2—sand with pebble; 3—sandy loam; 4—boreholes; 5—ice wedges; 6—sample locations and numbers.

iones: Na, Ca, Cl and SO_4, pH–8.5. On the base of the evolution stage of collared lemmings, the age of Kuchugui Suite falls in the same range as Jukagir Suite: 220–390 ka.

The top of cross section is represented by dun loams with thick ice wedges. This upper level of ice wedges confines with late Pleistocene Icy Complex (the so-called Edoma Suite), which is widely spread on the coastal lowlands of eastern Arctic. On Svyatoy Nos its thickness is about 10 m. The width of ice wedges is 2–3 m, the distance between wedges 10–12 m. The ice content in Icy Complex is similar to the Jukagir Suite and avarages to 70–75 vol%. The segregative ice is represented by cellular and stratiform cryogenic structures. On the base of pore water mineralization (<0.05%) the sediments are ultrafresh with dominate ions: Na, Ca, Cl and HCO_3^2 and pH varying from 7.2 to 7.7. The age of Edoma Suite, according to numerous radiocarbon data, is 50–17 ka (Nikolskiy and Basilyan, 2004).

Based on the above-mentioned data, the maximal temporal interval between the bottom of Jukagir Suite and the top of Edoma Suite is about 370 ka.

The section on Bol'shoy Lyakhovsky Island has a similar stratigraphic sequence and, therefore, the material from Bols'hoy Lyakhovsky Island can be used for comparison. Whereas the upper level with large ice wedges is 50–30 ka old according to radiocarbon dating (Nagaoka et al., 1995; Kunitsky, 1998; Meyer et al., 2002a) the lower level with large ice wedges for a long time has been considered of the early Pleistocene age (Arkhangelov et al., 1996; Tumskoy et al., 2000). New studies of the thick peat layer, embedded between Jukagir and Kuchugui Suites, using U/Th- and optical-stimulated luminescence dating methods showed that these deposits were formed during the Saalian Glacial about 130–200 ka BP (Schirrmeister et al., 2002; Andreev et al., 2004). Thus, the lower Icy Complex of Bol'shoy Lyakhovsky Island was formed earlier then 200 ka, as well as the minimal difference between lower and upper Icy Complexes is not less than 150 ka.

Summarizing the data from Bol'shoy Lyakhovsky Island and Cape Svyatoy Nos we can conclude that the age difference between samples from the upper and buried Icy Complexes is between 150 and 370 ka.

Four samples from 3 different ice wedges at depths between 3 and 21 m were taken from this section. The upper two samples of late Pleistocene Icy complex (Edoma Suite) were collected from the same ice wedge. The lower two samples of mid Pleistocene Icy complex (Jukagir Suite) were taken from two different ice wedges that belong to the same horizon and consequently to the same time of formation.

Aliquots of the samples were used to determine the stable chloride concentration. The rest of each sample was filtered first through a paper filter to remove sand and then through 0.45 μm Nuclepore® filter. The volume of the solution was reduced by rotation evaporation. $AgNO_3$ was added in order to obtain an AgCl deposition. The deposits were rinsed once with a weak solution of HNO_3 and twice times with distilled water. Before and after each cleaning cycle the suspended particles were separated from the liquid by centrifuging. The produced AgCl was dried in vacuum at 60 °C and pressed into a high-purity copper holder. Ratios of $N(^{36}Cl)/N(Cl)$ were measured with AMS at the Munich accelerator laboratory following the standard procedure (Nolte et al., 1979, 1982; Kubik et al., 1984).

In Table 1 the depth range of the samples, the measured chloride concentration, the measured ratio $N(^{36}Cl)/N(Cl)$, and the deduced ^{36}Cl concentration are given. The ratios $N(^{36}Cl)/N(Cl)$ were measured in the range from 0.9×10^{-13} to 3.7×10^{-13}.

4. Discussion

The values of the samples 2/01 and 3/01a, which belong to the same ice wedge, coincide within one standard deviation and with the correction on the relative mass of each sample lead to the mean value $\left[N(^{36}Cl)/N(Cl)\right]_{2,3} = (2.9 \pm 0.5) \times 10^{-13}$. The samples 3/01b and 4/01 show even closer values with the mass corrected mean equal to $[N(^{36}Cl)/N(Cl)]_{4,4} = (1.0 \pm 0.14) \times 10^{-13}$. These two mean values were used to determine the time difference Δt between the formation of the ice wedge of the upper horizon and the ice wedges of the lower horizon. From the expression $[N(^{36}Cl)/N(Cl)]_{4,4} = [N(^{36}Cl)/N(Cl)]_{2,3} e^{-(\Delta t/\tau_{36})}$, the result is calculated as

$$\Delta t = -\tau_{36} \ln\left\{ \left[\frac{N(^{36}Cl)}{N(Cl)}\right]_{4,4} \Big/ \left[\frac{N(^{36}Cl)}{N(Cl)}\right]_{2,3} \right\} = (460 \pm 140)\,\text{ka} \quad (3)$$

and presented in Table 2. A correction for *in situ* production was estimated unimportant for the relatively

Table 1
Depth range, chlorine and ^{36}Cl concentrations and their ratio in the permafrost samples

Sample	Depth range, m	Mass of the sample, g	Concentration		$Na(^{36}Cl)/N(Cl)$, 10^{-13} atom/atom
			$N(Cl^-)$, ppm	$N(^{36}Cl)$, 10^4 at g^{-1}	
2/01	3.35–4.35	1926	7.2±0.2	3.1±0.8	2.5±0.6
3/01a	4.35–5.10	986	6.2±0.2	3.9±0.8	3.7±0.8
4/01	7.85–8.40	1432	50.8±0.3	9,7±2.1	1.1±0.2
3/01b	20.5–20.7	1455	27.1±0.9	4.0±0.8	0.9±0.2

Table 2
Determination of the absolute time interval for the permafrost samples

Sample	Mean Na(^{36}Cl)/N(Cl), 10^{-13} atom/atom	Time interval, 10^3 years
2/01, 3/01a	2.9±0.5	460±140
4/01, 3/01b	1.0±0.14	

Fig. 6. Kuchugui Suite underline by mid Pleistocene buried Ice Complex (Jukagir Suite) with a 2 m broad ice wedge.

young samples and was not performed for this dating. The calculated time difference of the two ice wedge formations can be compared to the previously estimated time difference of $\Delta t_{est} = 400$ ka (Nikolskiy and Basilyan, 2004) based on microfossil analyzes and to the time difference of the upper two horizons of Bol'shoy Lyakhovsky Island, $\Delta t = (80-170)$ ka (Nagaoka et al., 1995; Arkhangelov et al., 1996; Kunitsky, 1998; Tumskoy et al., 2000; Meyer et al., 2002a) based on radiocarbon and luminescence datings. Because these are the first tests of the proposed absolute dating method we think that the general stratigraphic consequences of the age results would be premature. Our main conclusion, which is supported by some independent age determinations of the sediment sequences, is that the proposed dating method has shown practical feasibility and the presented results fit quite well to the general stratigraphic picture.

5. Conclusion

It has been pointed out that the cosmogenic radionuclide ^{36}Cl can be used for dating of permafrost samples. The method with the ratio of ^{36}Cl/Cl is similar to the dating of old ground waters in aquifers. Here, the ^{36}Cl/Cl method was used for the first time for a relative quantitative dating of permafrost (ice wedge) samples. Measurement of the ^{36}Cl/^{10}Be ratio in the same sample looks potentially useful as an independent check of the age, though it still waits for an experimental proof. First AMS measurements of N(^{36}Cl)/N(Cl) ratios provide ages, which agree well with the expected ones. These results encourage us in the further development of the method and the substantiation of its wide application to permafrost dating (Fig. 6).

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