

RUSSIAN GEOGRAPHICAL SOCIETY

FACULTY OF GEOGRAPHY,
LOMONOSOV MOSCOW STATE UNIVERSITY

INSTITUTE OF GEOGRAPHY,
RUSSIAN ACADEMY OF SCIENCES

No. 03 (v. 09)
2016

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DOI: 10.15356/2071-9388_03v09_2016_01

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STABLE ISOTOPE GEOCHEMISTRY OF MASSIVE ICE

ABSTRACT. The paper summarises stable-isotope research on massive ice in the Russian and North American Arctic, and includes the latest understanding of massive-ice formation. A new classification of massive-ice complexes is proposed, encompassing the range and variability of massive ice. It distinguishes two new categories of massive-ice complexes: homogeneous massive-ice complexes have a similar structure, properties and genesis throughout, whereas heterogeneous massive-ice complexes vary spatially (in their structure and properties) and genetically within a locality and consist of two or more homogeneous massive-ice bodies. Analysis of pollen and spores in massive ice from Subarctic regions and from ice and snow cover of Arctic ice caps assists with interpretation of the origin of massive ice. Radiocarbon ages of massive ice and host sediments are considered together with isotope values of heavy oxygen and deuterium from massive ice plotted at a uniform scale in order to assist interpretation and correlation of the ice.

KEY WORDS: massive ice, stable isotopes, radiocarbon dating, homogeneous and heterogeneous

INTRODUCTION

The research on massive ice began for one of the authors in July 1977 during the boating expedition of the Geological Faculty of Moscow State University in the Yuribey River valley (68°26'N, 72°08'E) on central Yamal Peninsula, west Siberia. Here, the senior author encountered a complex exposure of massive-ice bodies that probably represent an assemblage of buried river ice and injection (intrusive) ice. This exposure has contributed significantly to the development of a new massive-ice classification by Y.K. Vasil'chuk, the basic principles of which are set out in Fig. 1. A new classification of massive ice, as well as most of the currently available data on the stable isotope geochemistry of massive ice are summarized in the two-volume monograph Yu.K. Vasilchuk [2012, 2014], a critical analysis which is mainly devoted to this paper.

STUDY AREA

The paper is based primarily on the senior author's experience, involvement and field studies over more than 35 years (from 1977 to 2014) in numerous expeditions concerning massive ice in Russian permafrost. It also summarizes the experience of many international researchers, and describes exposures with large bodies of massive ice in west and east Siberia, Chukotka, Alaska and Yukon, the Tuktoyaktuk Coastlands, the Canadian Arctic Archipelago and Russian Arctic islands, China and the Antarctic.

MASSIVE-ICE CLASSIFICATION

Yu. Vasil'chuk [2012] presents a new classification of massive-ice bodies and includes two new categories: homogeneous and heterogeneous (Fig. 1). Homogeneous

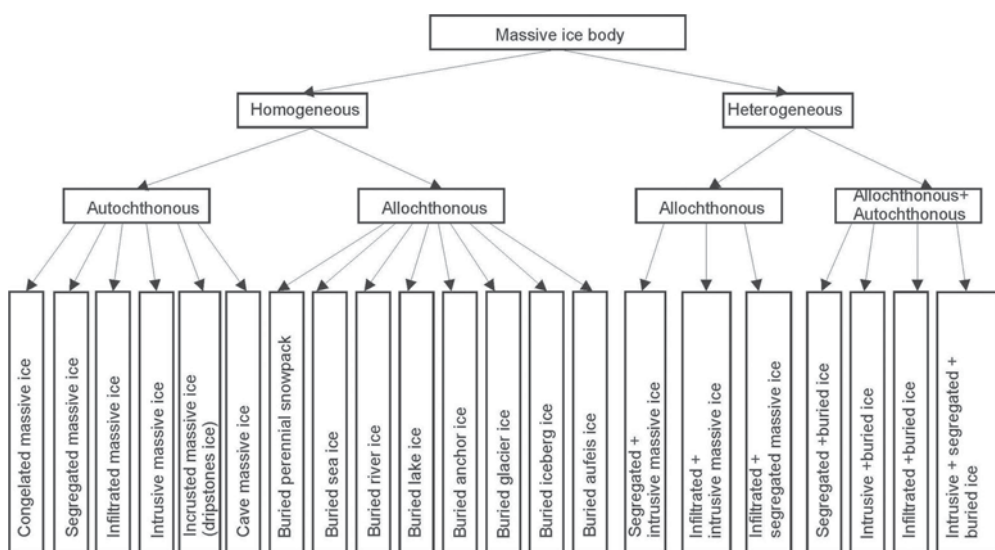


Fig. 1. The classification of massive-ice bodies, involving a three-tier system: (tier 1) homogeneous and heterogeneous categories, (tier 2) autochthonous and allochthonous categories, and (tier 3) specific ice types.

massive-ice bodies have a similar genesis, composition and properties in all parts of a massive-ice complex, whereas heterogeneous massive-ice bodies have a variable genesis, composition and properties across a massive-ice complex, and consist of two or more homogeneous ice bodies. The distinction between homogeneous and heterogeneous massive-ice bodies elucidates the wider complex structure of massive-ice bodies and encourages the search for different mechanisms of ice formation.

Homogeneous massive-ice complexes

Homogeneous massive-ice complexes are usually no more than a few meters high, ≤ 20 –30 m wide and occur as single layers of ice or, less commonly, as multiple layers of the same genesis. Typical examples of segregated (or infiltrated and segregated) ice were studied by Y.K. Vasilchuk [1992] in the first terrace of the Gyda River estuary (70°53'N, 78°30'E). Four similar lens-shaped bodies of massive ice (up to 0.3–0.4 m thick and 6–8 m wide) were composed of clear ice and, as a rule, associated with peat. The structure of the ice bodies and their bedding parallel to the

sedimentary stratification suggest that they formed synchronously with the accumulation and freezing of the ground mass, consistent with the occurrence of a 4.5 m high syngenetic ice wedge in the sedimentary sequence. The ice is interpreted as infiltrated or segregated in origin. The wide range of $\delta^{18}\text{O}$ values (–33.8 to –16.2‰) in these ice bodies indicates closed-system freezing with a small inflow of water from outside the system. Such a wide range of the heavy oxygen values indicates significant cryogenic fractionation during freezing of waters whose initial average composition was close to –20‰. This could occur only under conditions of closed-system freezing, when isotopically heavier ice was the first to form ($\delta^{18}\text{O}$ values of about –16 and –18‰), while the $\delta^{18}\text{O}$ values of the remaining water were about –22‰. The partial freezing of the water led to the formation of ice with $\delta^{18}\text{O}$ values of about –20‰, while the rest of the water had $\delta^{18}\text{O}$ values of about –24 to –25‰. Repeated freezing of this water provided extremely low $\delta^{18}\text{O}$ values (about –34‰) in the last portions of the water to freeze. The low average $\delta^{18}\text{O}$ values in this massive ice (about –20‰) indicate that the ice formed under conditions more severe than

those at present. In view of the radiocarbon age of the ground mass (more than 15 ^{14}C ages from 10,260 to 15,890 BP obtained on allochthonous peat), the accumulation of the ground mass and the formation of massive ice and the syngenetic ice wedge occurred no earlier than 14,000–11,000 years ago [Y.K. Vasilchuk, 1992].

Heterogeneous massive-ice complexes

Heterogeneous massive-ice complexes comprise two or more ice layers (tiers) of different genesis. The layers may be in contact or adjacent to each other, influencing the shape of the ice complex and the conditions of its occurrence. Examples include massive

ice of the Yuribey River valley (Fig. 2a), massive ice in the Erkutayaha River valley [Y.K. Vasil'chuk et al., 2012] in the south of Yamal Peninsula (Fig. 2b, 3), and in many places in the Bovanenkovo gas condensate field [Y.K. Vasil'chuk et al., 2009, 2014; Kritsuk, 2012].

The second division of the classification distinguishes between autochthonous (i.e., intrasedimental in terms of Mackay and Dallimore [1992]) and allochthonous (i.e. buried) ice (see Fig. 1). Heterogeneous massive-ice complexes can include a combination of autochthonous and allochthonous deposits. The third division classifies the massive ice according to its specific genetic process (e.g., injection,

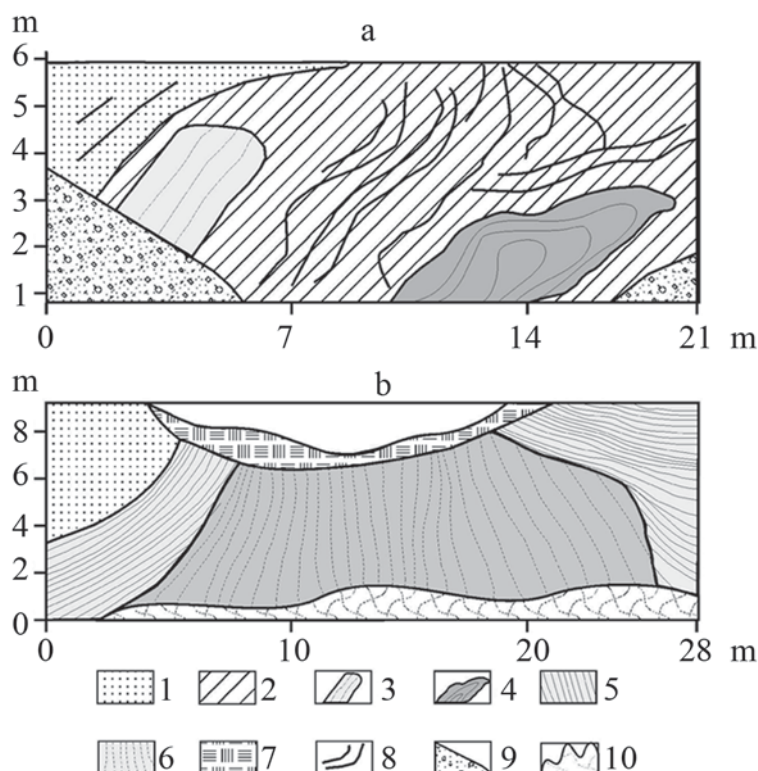


Fig. 2. Vertical stratigraphic sections through heterogeneous massive-ice bodies in west Siberia: assemblage of buried and intrusive ice in the upper Yuribey River valley, central Yamal Peninsula (a) and assemblages of segregation and intrusive ice, Erkutayaha River valley, southern Yamal Peninsula (b).

1 – sand; 2 – loam; 3 – layered pure ice; 4 – deformed intrusive ice rich in mineral inclusions; 5 – segregated layered massive ice; 6 – intrusive vertically layered massive ice; 7 – Holocene lacustrine-marsh loam and sandy loam and peat; 8 – laminated sediment; 9 – scree; 10 – slumped material (i.e. debris covering the section)



Fig. 3. Assemblages of segregation and intrusive ice, Erkutayaha River valley, southern Yamal Peninsula. Photograph by Yu.Vasil'chuk.

segregation, infiltration, burial) and shows the wide diversity of genetic ice types.

The proposed classification is illustrated through examples in Yu.Vasil'chuk's monograph [2012], which critically examines the main hypotheses of massive-ice formation.

MODERN AND HOLOCENE ANALOGUES OF PLEISTOCENE MASSIVE ICE, AND THE MAIN HYPOTHESES OF MASSIVE-ICE FORMATION

Vasil'chuk [2012] discusses modern and Holocene analogues of Pleistocene massive ice, beginning with massive ice in marine sediments. One of the most convincing analogues of Pleistocene massive ice is Holocene massive segregated ice 8–9 m thick on the Fosheim Peninsula, Ellesmere Island, in the Canadian Arctic (79°59'N, 85°56'W; Pollard and Bell, 1998). The $\delta^{18}\text{O}$ values of the ice range between –28.9 and –34.8‰ for reticulate ice, –33.1 and –36.8‰ for massive ice, and –36.1‰ for an ice vein in adjacent Tertiary sandstone. The massive ice is interpreted as intrasedimental ice because: a) it is conformably overlain by marine sediments and contains internal structures parallel the upper ice contact; the ice lacks evidence for primary thaw or erosional contacts, which would indicate buried ice; and b) sediment within inclusions in the massive ice is similar to the overlying marine sediments, indicating that the overlying sediment was deposited

before the ice formed. Radiocarbon ages of shells from raised marine deposits in the Slidre River valley suggest that the Holocene marine limit was likely established by 10.6 ka BP, with sea level remaining high (within 10 m of marine limit) until 8.7 ka BP or later. The massive-ice deposits formed time transgressively as permafrost aggraded into marine sediments during the Holocene [Pollard and Bell, 1998]. Ice segregation occurred as permafrost aggraded downward through a fine-grained layer of silt that overlay saturated sands with an ample water source. The injection of water under high pressure into the overlying frozen bedrock at Eureka Sound formed intrusive massive ice [Robinson and Pollard, 1998]. As a result, a heterogeneous massive-ice complex (according to Y.K. Vasil'chuk's classification) developed.

Massive-ice bodies are extraordinarily widespread in Holocene sediments of the first lagoon-marine terrace and the modern lagoon-marine floodplain of the Ob Bay, at the mouth of the Sabettayaha River, in west Siberia (71°15'N, 72°06'E). More than 1000 boreholes through Holocene marine lagoon and floodplain deposits have been analyzed [Y.K. Vasilchuk et al., 2016b] and show massive-ice bodies up to 5.7 m thick in the upper 5–10 m of Holocene silty sand. Their δD values vary from –107 to –199.7‰, and their $\delta^{18}\text{O}$ values vary from –15.7 to –26.5‰. The massive ice is mostly autochthonous and of segregated origin [Y.K. Vasil'chuk et al., 2016b]. It formed

syngenetically during freezing of water-saturated soils under intensive cryogenic fractionation in the late Holocene. Thick massive-ice bodies also occur in saline sediments, for example a 14 m thick massive ice layer in beach sediments near the mouth of the Khatanga River [Ponomarev, 1960], fresh (salinity is 620 mg/l) massive ice at a depth of 19–29 m beneath the sea bottom [Melnikov and Spesivtsev, 2000], and a 1.5 m thick layer of salty ice at the depth about 10 m in sediments beneath the shallow waters of the Mechigmen Gulf (Chukotka). Y.K. Vasil'chuk proposed the original mechanism of the formation of icy bodies in saline lake (meromictic lakes) sediments.

Other possible modern and Holocene analogues of Pleistocene massive ice are freshwater ice deposits in shallow, saline (up to 103 g/l) lakes at 4117–4730 m above sea level (asl) in Bolivia. The ice deposits (consisting of several ice lenses, each up to 1 m thick) are up to several hundred meters wide and elevated up to 7 m above the lake or playa surface. They are located near the lake or salar (salt-crust desert) margins; some are completely surrounded by water, others by playa deposits or salt crusts [Hurlbert and Chang, 1984]. The $\delta^{18}\text{O}$ values for the ice lenses (–10.6 to –11.5‰) are much lower than those of lakewater (+ 13.5‰) but similar to those of precipitation ($\delta^{18}\text{O}$ value in fresh snow –13.2‰).

Ice in the cores of modern pingos provides another analogue of Pleistocene massive-ice deposits. The distribution of stable isotopes in pingo ice cores indicates that the ice formed under conditions of open and closed systems. Ice in the core of the Holocene pingo in the Pestsovoe gas field area (66°10' N 76°30'E) formed in closed-system conditions; its δD values vary from –93.2 to –123‰, and $\delta^{18}\text{O}$ values vary from –11.6 to –15.8‰ [Y.K. Vasil'chuk et al., 2016a].

The main hypotheses of massive-ice formation identify the ice as segregated, intrusive, repeated intrusive and buried

glacier ice [Vtyurin, 1975; Mackay, 1973; Rampton, 1988; Zhestkova and Shur, 1978; Y.K. Vasil'chuk, 1992, 2012, 2014; Dubikov, 2002; Murton, 2005, 2009; French, 2007; Solomatin, 2013; Streletskaya et al., 2013; Belova, 2014]. Holmsen [1914] proposed the infiltrated and segregated hypothesis of massive-ice genesis. He hypothesized that the formation of thick (up to 15 m) massive ground-ice deposits is linked to the infiltration of surface water through seasonally thawed ground and the freezing of this water on the top [see also Zhestkova and Shur, 1978]. Vtyurin [1975] favoured ice segregation, with the most favorable conditions for the formation of massive segregated ice being near the contact between clayey sediments and water-bearing coarse-grained sediments. Gasanov [1969] hypothesized that the main factor of ice formation is water intrusion, and distinguished different types of intrusive ice: seasonal intrusive ice, multi-seasonal intrusive ice (short-term permafrost), intrusive ice, repeated intrusive ice and hydrolaccoliths. Mackay [1971, 1973] proposed that the mechanism of water injection and segregation in closed-system conditions that is widely applied to explain pingo growth can also apply to the mechanism of massive-ice formation.

COMPARISON OF POLLEN SPECTRA OF MASSIVE ICE AND GLACIERS FOR CRYOGENIC INDICATION

Palynological analysis of deposit-forming ground ice has identified several distinctive characteristics of the pollen spectra. First, pollen and spores are present in almost all types of deposit-forming ground ice, at concentrations from 50 to 1500 units per 1 kg ice or 1 litre of ice meltwater. Second, pollen spectra with characteristics similar to those of subfossil tundra, including the predominance of dwarf birch and ericaceous pollen and green moss spores, occur in most massive-ice deposits. Third, the massive-ice deposits frequently contain redeposited pre-Quaternary palynomorphs of Cenozoic, Mesozoic and Palaeozoic age. Fourth, pollen of

hydrophilous plants (e.g., pondweed, bur reed and reed mace), as well as horsetail spores, limnetic diatoms and green algae remains also occur in most of the studied massive-ice deposits, indicating a non-glacial genesis of the ice. Pollen spectra that are typical of non-glacial deposit-forming ice show: 1) a lack of exotic thermophilic species such as *Acer*, *Fraxinus*, *Quercus*, *Ulmus*, *Populus*, *Tilia* and *Abies* in the initial occurrence; 2) the presence of cloudberry, aquiherbosa species, as well as green moss and horsetail; and 3) the presence of redeposited pollen and spores. This palynological approach indicates that the massive ice on the Yamal Peninsula of west Siberia is mainly non-glacial in origin [A.C. Vasil'chuk and Y.K. Vasul'chuk, 2010, 2012].

ISOTOPIC COMPOSITION OF MASSIVE ICE IN RUSSIAN PERMAFROST

The senior author considers his own isotopic studies of massive ice in Siberia and interprets the isotope records obtained by others [Vasil'chuk, 2012]. He considers the vertical variations in more than 35 isotope plots published in the last 30 years [Vaikmäe and Karpov, 1986; Y.K. Vasil'chuk and Trofimov, 1988; Vaikmäe and Y.K. Vasil'chuk, 1991; Korolyov, 1993; Kotov, 1998; Dubikov, 2002; Leibman et al., 2003; Ingólfsson and Lokrantz, 2003; Y.K. Vasil'chuk et al., 2009, 2011, 2012, 2014; Kritsuk, 2010; Slagoda et al., 2012; Ivanova, 2012; Belova, 2014].

The isotope curves are plotted at a single vertical and horizontal scale to facilitate their comparison.

The isotope composition of the massive-ice deposits in northern European Russia is considered for a number of localities, including the More-Yu River valley, Cape Shpindler, and the Oyuyakha River valley (68°51'N, 66°44'E). For the massive-ice body at Cape Shpindler in the Yugorski Peninsula (69°43'N; 62°48'E), Ingólfsson and Lokrantz [2003] concluded that it is buried glacier ice and suggested that it is older than 190–200 kyr, whereas Leibman et al. [2003],

who also examined the internal structures, stratigraphy and isotopic composition of the massive ice, attributed it to syngenetic or epigenetic freezing after marine regression. The senior author assumes that this massive ice is intrasedimental, heterogeneous and autochthonous because the $\delta^{18}\text{O}$ values in different types of massive ice at Cape Spindler vary from –13.1 to –25.6‰. Such variability may be explained by fractionation during ice segregation in a closed system.

The isotope composition of massive-ice deposits is also considered for northwest Siberia. Localities there include: 1) the Erkutayaha River valley (68°11'N, 68°51'E), 2) the Bovanenkovo gas field area (70°21'N, 68°26'E), 3) the Morddyakha River valley (69°33'N, 68°59'E), 4) the Kharasavey settlement (71°10'N, 66°51'E), 5) near Marre-Sale meteorostation (69°45'N; 66°50'E), 6) at Tyurinto Lake (70°44'N, 67°57'E), 7) at Voivareto Lake (68°43'N; 72°25'E), 8) near Gyda settlement (70°53'N, 78°30'E), 9) the Yuribey River valley (68°26'N, 72°08'E), 10) near Tab-Salya settlement (71°45'N; 82°45'E), 11) near Dorofeevskaya settlement (71°23'N; 82°58'E), 12) at the Sopochnaya Karga Cape (71°50'N, 82°40'E) and 13) Ledyanaya Gora in the Yenisey River valley (66°35'N, 86°34'E).

On the southernmost Yamal Peninsula heterogeneous autochthonous massive ice is located on the left bank of the Erkutayaha River (68°11'N, 68°51'E). A massive-ice body approximately 100 m long is embedded predominantly in stratified sand. The ice layers sharply drop on both sides of the central part, and just 15 m from the centre the cover of the massive ice appears at a depth of 8 m. The central part of the massive-ice body takes a form similar to a stock (a type of igneous intrusion), with vertical and subvertical ice layers, whereas the peripheral parts comprise horizontally layered ice. The range of $\delta^{18}\text{O}$ (~4‰) and δD (~20‰) values indicates comparatively small fluctuations of the isotopic composition for ice with different characteristics: pure white ice has $\delta^{18}\text{O}$ values from –19.6 to –20.5‰, and δD varies from

–152.4 to –156.9‰; clear transparent ice has $\delta^{18}\text{O}$ values from –19.2 to –20.3‰, and δD varies from –149.6 to –160.7‰; transparent gray ice with a steely shimmer has $\delta^{18}\text{O}$ values from –19.4 to –21.3‰, and δD varies from –150.3 to –163.8‰; and gray ice and in the dirty gray ice has $\delta^{18}\text{O}$ values from –22.1 to –23.4‰, and δD varies from –165.5 to –172.7‰. Hence, the difference between the isotope signal of the initial water and ice is comparatively small. The isotopic differences almost did not exceed the usual isotopic difference that results from fractionation when free water freezes. Significantly, the pollen spectra in the vertically layered ice from the central stock (most likely of injection genesis) lack reworked pollen and spores, whereas those from the horizontally layered peripheral ice (most likely of segregation or infiltration-segregation genesis) contain a high concentration of reworked pollen and spores (35 %).

On the central part of the Yamal Peninsula (69°33'N, 68°59'E) beside the upper Mordyyakha River is a heterogeneous autochthonous massive-ice body at 66–70 m a.s.l. The ice body is more than 4 m thick and has horizontal bedding that passes laterally into vertical bedding and is crossed by syngenetic ice wedges 4–5 m in high. The isotopic composition of ice from obliquely oriented ice lenses (lenticular-layered cryostructure) in the north part of the outcrop shows insignificant isotopic variations (from –22.4 to –23.3‰ $\delta^{18}\text{O}$) and thus suggests that ice segregation occurred under open-system conditions. The pollen spectra are characterized by high contents of pollen and spores of hygrophilous plants, with sedge pollen and horsetail spores dominant. Such specific features were noted for sediments of small floodplain lakes. It can be assumed that the ice deposits formed during freezing of a talik after a former lake drained.

In the Bovanenkovo gas field area (70°21'N, 68°26'E) heterogeneous autochthonous and allochthonous massive-ice bodies occur as layers, laccoliths, rods and lenses.

The maximum thickness of the tabular ice is 28.5 m, and the mean thickness is about 8 m. $\delta^{18}\text{O}$ values of massive ice range from –12.4 to –22.9‰ [Michel, 1998; Y.K. Vasil'chuk et al., 2009], and deuterium (δD) values vary from –91.7 to –177.1‰. The contrasting distribution (like vertical bilateral rake with very long teeth of different lengths) $\delta^{18}\text{O}$ and (δD) vs. depth in massive ice bodies suggests a segregated and/or infiltrated-segregated origin of the ice. Pollen, spores and algal spectra from the massive ice are similar to pollen characteristics of modern lacustrine and coastal floodplain sediments in the area. The senior author inferred that the ingress of cold seawaters on a coastal flood plain caused freezing and ice segregation, with the formation of extensive ice layers under the large but shallow lakes.

The material presented shows that the methodological use of isotopic data from massive ice is still far from ideal. Even within the same article, the authors have expressed different hypotheses about the origin of massive ice in Ledyanaya Gora (Ice Mountain) on the Yenisei River valley (66°35'N, 86°34'E) because intrasedimental ice may be difficult to distinguish from basal glacier ice, as both ice types can form by the same freezing processes [Vtyurin and Glazovskiy, 1986]. Stratigraphic and isotopic study of this massive ice and its host sediments led Vaikmäe and Karpov [1986] and Astakhov and Isayeva [1988] to interpret the ice as relict glacier ice, probably emplaced during the Early Weichselian. However, interpretation of the Ledyanaya Gora massive ice is problematic. Most of the $\delta^{18}\text{O}$ values from the ice range from –20 to –21.5‰ [Vaikmäe and Y.K. Vasil'chuk, 1990; Vaikmäe et al., 1993], pointing to uniformity of the oxygen isotope profile. The isotopic composition of the massive ice is similar to that of vertical ice schlieren in the overlying diamicton ($\delta^{18}\text{O} = -20.7$ ‰). This similarity, coupled with a significant change from a salinity of 10–80 mg/l in the upper part of the massive ice to one of 200–340 mg/l in the middle and lower parts of it, according Y.K. Vasil'chuk, indicates an intrasedimental

origin. In conclusion, the massive ice at Ledyanaya Gora can be regarded as heterogeneous autochthonous massive ice.

Isotope data summarized from Chukotka include homogeneous autochthonous massive ice at the Koolen'Lake, near the town of Anadyr' and at Onemen Bay [Vasil'chuk, 1992], Tanyurer River valley [Kotov, 1998], and heterogeneous allochthonous and autochthonous massive ice in the Amguema River valley [Korolyov, 1993].

Finally, heterogeneous allochthonous and autochthonous massive-ice bodies are found on Novaya Siberia Island (75°05'N, 148°27'E). Ivanova [2012] showed that $\delta^{18}\text{O}$ values of massive ice there vary from -8.9 to -29‰ , and δD values vary from -66.8 to -228.4‰ . The $\delta^{18}\text{O}$ and δD values in the upper and lower horizons of massive ice are very different. These data can be interpreted to indicate an injected origin for the lower horizon of massive ice, and a segregation origin for the upper horizon [Ivanova, 2012].

ISOTOPIC COMPOSITION OF MASSIVE ICE IN PERMAFROST OF THE CANADIAN ARCTIC

Vasil'chuk [2014] examines the vertical variations in more than 30 isotope plots of massive ice from the Canadian Arctic [Mackay, 1983; Fujino et al., 1983; Lorrain and Demeur, 1985; Michel, 1983, 2011; Dallimore and Wolfe, 1988; French and Harry, 1990; Mackay and Dallimore, 1992; Moorman et al., 1996, 1998; Robinson and Pollard, 1998; Pollard and Bell, 1998; Hyatt, 1998; Murton et al., 2004, 2005; Lacelle et al., 2004, 2007, 2009, 2011; Murton, 2005, 2009; Cardyn et al., 2007; French, 2007; Lacelle, 2011; Fritz et al., 2011]. Here we consider a few of them.

Massive ice adjacent to Tuktoyaktuk (69°27'N, 133°02'W), near the mouth of the Mackenzie River, has been isotopically studied by Mackay [1983], Fujino et al. [1983, 1988], Mackay and Dallimore [1992] and others. Fujino et al. [1983] concluded that most of the massive-

ice body at Peninsula Point originated from superimposed ice formed by congelation of water in which it was submerged. Mackay and Dallimore [1992], however, rejected this interpretation. They reported that the geochemical and stable isotope values of the massive ice were similar to those of ice dikes that extended from the ice into the overlying diamicton, which indicates a common water source and suggests that the massive ice is intrasedimental in origin. Y.K. Vasil'chuk concluded that massive ice at this site is heterogeneous: autochthonous and allochthonous.

A massive-ice complex is often well exposed by coastal erosion at North Head, on Richards Island (69°20'N, 134°30'W), in the Tuktoyaktuk Coastlands. According to Murton [2005], some of the massive ice is buried and some is intrasedimental. Y.K. Vasil'chuk agreed and identified the ice as heterogeneous: autochthonous and allochthonous.

Massive ground-ice bodies in the Sandhills Moraine of southern Banks Island, and the southern Eskimo Lakes region of the Tuktoyaktuk Coastlands, according to French and Harry [1990], are interpreted as basal glacier ice. Other massive ground-ice bodies in the Western Canadian Arctic, however, are explained better in terms of segregation-injection [French and Harry, 1990]. Assessing the isotopic variations in ice around the Eskimo Lakes, Y.K. Vasil'chuk noted that the bottom of the massive ice described by French and Harry [1990] is characterized by a relatively stable distribution and a small range (about 1.5 ‰) of $\delta^{18}\text{O}$ values (from -33.5 to -35‰) and by abrupt changes in the upper 2 m of ice: upward, the value increases to -31‰ , and then sharply decreases to -36‰ . Y.K. Vasil'chuk suggested that the isotopic changes in the upper 2 m of ice are consistent with ice segregation commencing in a semi-closed or open system, and ending in a closed system, leading to an appreciable isotope differentiation in the top of the ice deposits.

Massive ice also occurs within glacially deformed permafrost in the coastal lowlands near Tuktoyaktuk (e.g. at Liverpool Bay – 70°N, 129°W, southwest of Nicholson Island; and on northern ‘Crane Island’, in the central Eskimo Lakes; Murton et al., 2004]. The massive ice is at least 2.5–8 m thick, and either white and bubble-rich, or grey, debris-rich and banded. Two types of ground ice are identified in the deformed permafrost: (1) massive ice and ice clasts, both of which have been glacially deformed, eroded or moved; and (2) segregated ice and ice-wedge ice that have not been glacially disturbed because their postdate deformation. Y.K. Vasilchuk agreed with these interpretations and determined the massive ice as heterogeneous: autochthonous and allochthonous.

Within the limits of the Willow River drainage basin, on the Aklavik Plateau (69°N, 124°W), Lacelle et al. [2004] examined four exposures of debris-rich massive ice. The $\delta^{18}\text{O}$ values of the ice change abruptly from an average of about -30‰ (for Late Pleistocene ice) to -22.6‰ (for Holocene ice). Physical and isotopic properties of the former suggest that it is segregated-intrusive ice, because the CO_2 content and $\delta^{13}\text{C}$ value in the debris-rich ice was acquired during movement of CO_2 through the sediments, giving CO_2 concentrations that are 3–9 times higher than those for air trapped in glacier ice and $\delta^{13}\text{C}$ values in the range of CO_2 produced by the decay of C_3 plant material [Lacelle et al., 2004]. Y.K. Vasilchuk agreed with these interpretations and determined the massive ice as heterogeneous: autochthonous and allochthonous.

Massive ice within but close to the glacial limit of the Laurentide Ice Sheet, on Herschel Island (69°N, 139°W), in the southern Beaufort Sea, is highly depleted in heavy isotopes (mean $\delta^{18}\text{O}$ value: -33‰ ; δD : -258‰ ; [Fritz et al., 2011, 2012]). These authors noted that such stable isotope signatures indicate a full-glacial water source for the massive ice on Herschel Island. However, an

origin as glacially deformed segregated or segregated-intrusive ice cannot be excluded. Pollard [1990] concluded that segregated ice is the most common massive-ice type in this area and in places constitutes up to 70 % of the upper 10–15 m of permafrost. Y.K. Vasilchuk suggested that the origin of massive ice on Herschel Island varies, and the ice includes both heterogeneous and homogeneous types.

DATING OF MASSIVE ICE OF RUSSIA AND NORTH AMERICA, AND CORRELATION OF STABLE ISOTOPE CURVES

Radiocarbon dating of organic material in the sediments that surround massive ice in Russia and Canada, and direct accelerator mass spectrometry (AMS) radiocarbon dating of organic microinclusions and trapped gases within massive ice in Canada are analyzed by Vasilchuk [2014]. The radiocarbon ages suggest that most of the massive ice accumulated between the Holocene and 20–40 ka BP (Fig. 4).

Comparison of isotopic plots of massive ice in Russia and Canada (Fig. 5–7) shows that they have more similarities than differences in the regional isotopic record of ice formation. An initial isotopic signature indicates the nature of the water and the conditions of ice formation. Ice segregation in a closed system leads to a contrasting distribution of $\delta^{18}\text{O}$ and δD values, both vertically and laterally (Fig. 5). The shape of isotopic plots of massive ice relates to the type of ice formation. Homogeneous, undifferentiated isotope plots with a narrow range of isotopic changes ($\delta^{18}\text{O}$ range $< 4\text{‰}$, $\Delta\delta\text{D}$ range $< 32\text{‰}$) characterize massive ice formed in an open system, with freezing of inflowing water under homogeneous conditions. By contrast, isotope plots with a wide range of isotopic changes ($\Delta\delta^{18}\text{O}$ range $> 8\text{‰}$, $\Delta\delta\text{D}$ range $> 64\text{‰}$) characterize massive ice formed in a closed system, where there is no inflowing water. Closed-system freezing is typical of segregation ice formation, or rarely for the final phase of injection ice formation when there is no inflow of water (Fig. 6 and 7).

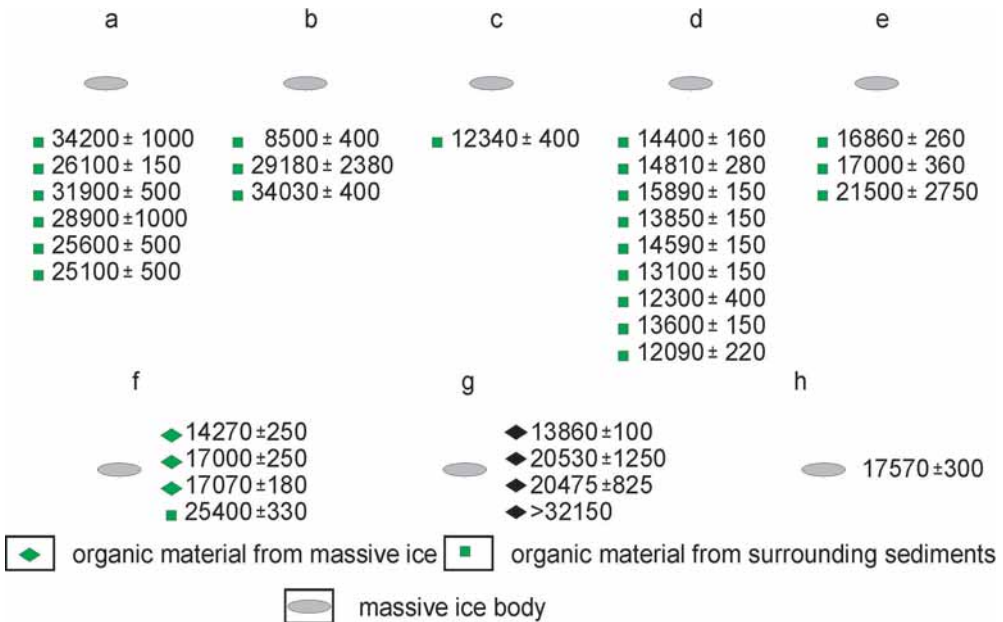


Fig. 4. Comparison of the radiocarbon ages (years BP) of massive ice: a–e obtained by ^{14}C dating of organic material from host sediments surrounding massive ice in Russian permafrost, f–h obtained by direct AMS ^{14}C dating of organic material from ice in Canadian permafrost. Sites:

a – Bovanenkovo [Y.K. Vasil'chuk, 2012], b – Tyurinto Lake, c – Tab-Salya town, d – Gyda town [Y.K. Vasil'chuk, 1992], e – Tanyurer River valley [Kotov, 1998], f – Peninsula Point (4.5 km southwest of Tuktoyaktuk) [Kato et al., 1988], g – Peninsula Point [Moorman et al., 1998]; h – Herschel Island [Moorman et al., 1996].

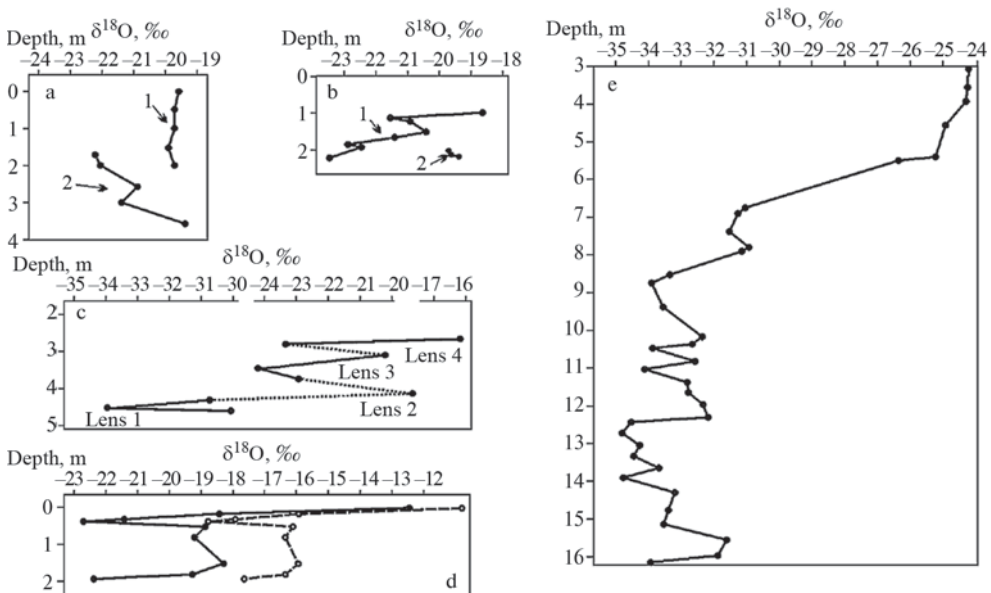


Fig. 5. The comparison of oxygen isotope plots of massive ice of Russian (a–d) and Canadian (e) permafrost, formed under closed-system freezing.

a–d Yamal Peninsula: a – Erkutayakha [Y.K. Vasil'chuk, 2012]; b – Kharasavey [Belova, 2012]; c – Gyda [Y.K. Vasil'chuk, 1992]; d – Bovanenkovo [Y.K. Vasil'chuk, 2012]; e – borehole 96BGS-06, Contwoyto Lake [Wolfe, 1998].

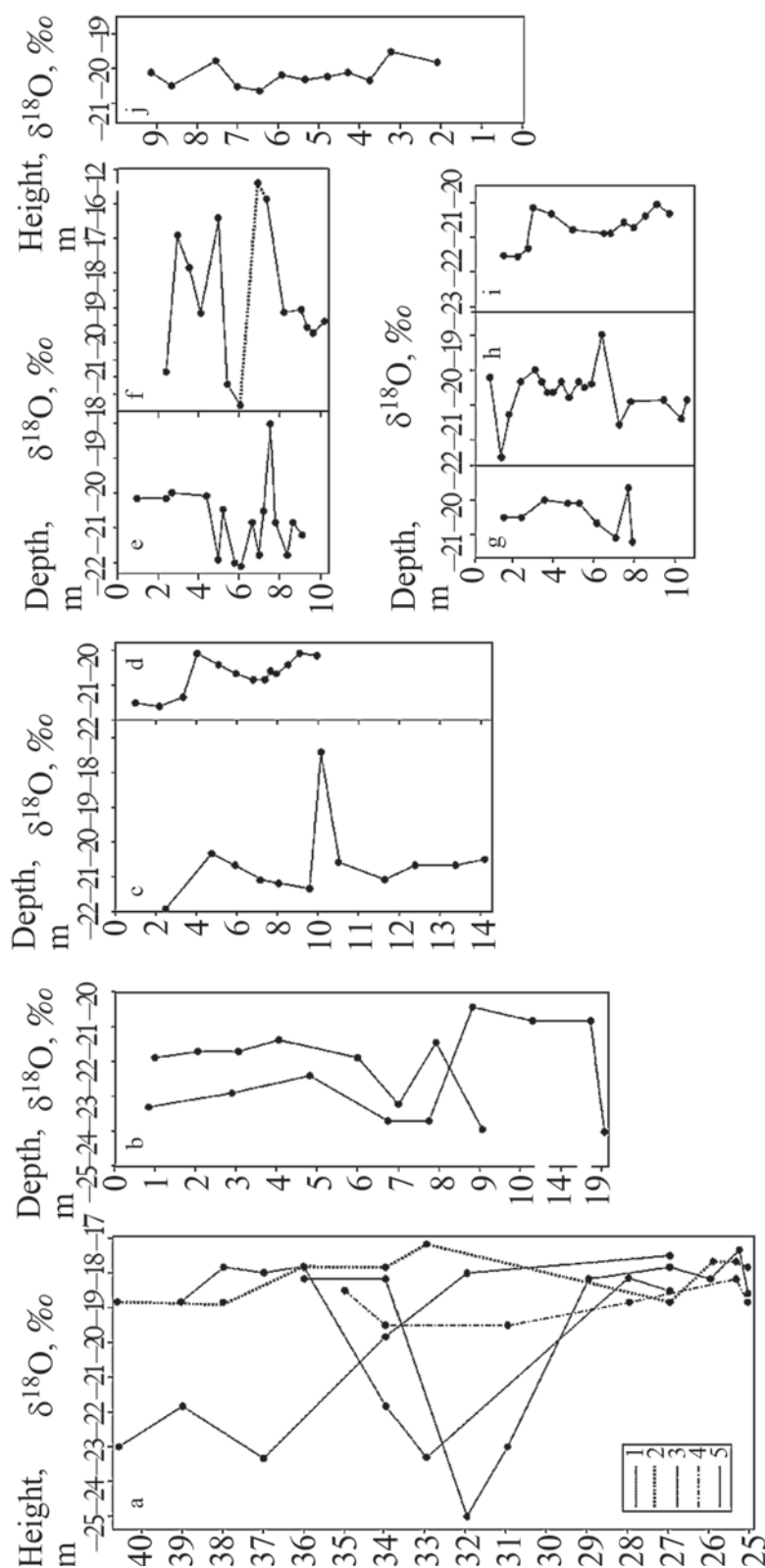


Fig. 6. The comparison of oxygen isotope plots of massive ice from Russian permafrost, formed under open- and closed-system freezing.

a – Cape Shpindler on Yugorski Peninsula: 1–5 – different parts of exposure [Ingolfsson and Lokrantz, 2003]; b – Yuribey, Gydan Peninsula [Kritsuk, 2010]; c – i – different parts of the Ledyanaya Gora (or Ice Mountain) exposure, on the right bank of the Yenisey River near the Arctic Circle [Vaikmäe and Karpov, 1986; Vaikmäe and Y.K. Vasil'chuk, 1991]; j – Onemen Bay, Chukotka [Kotov, 2001].

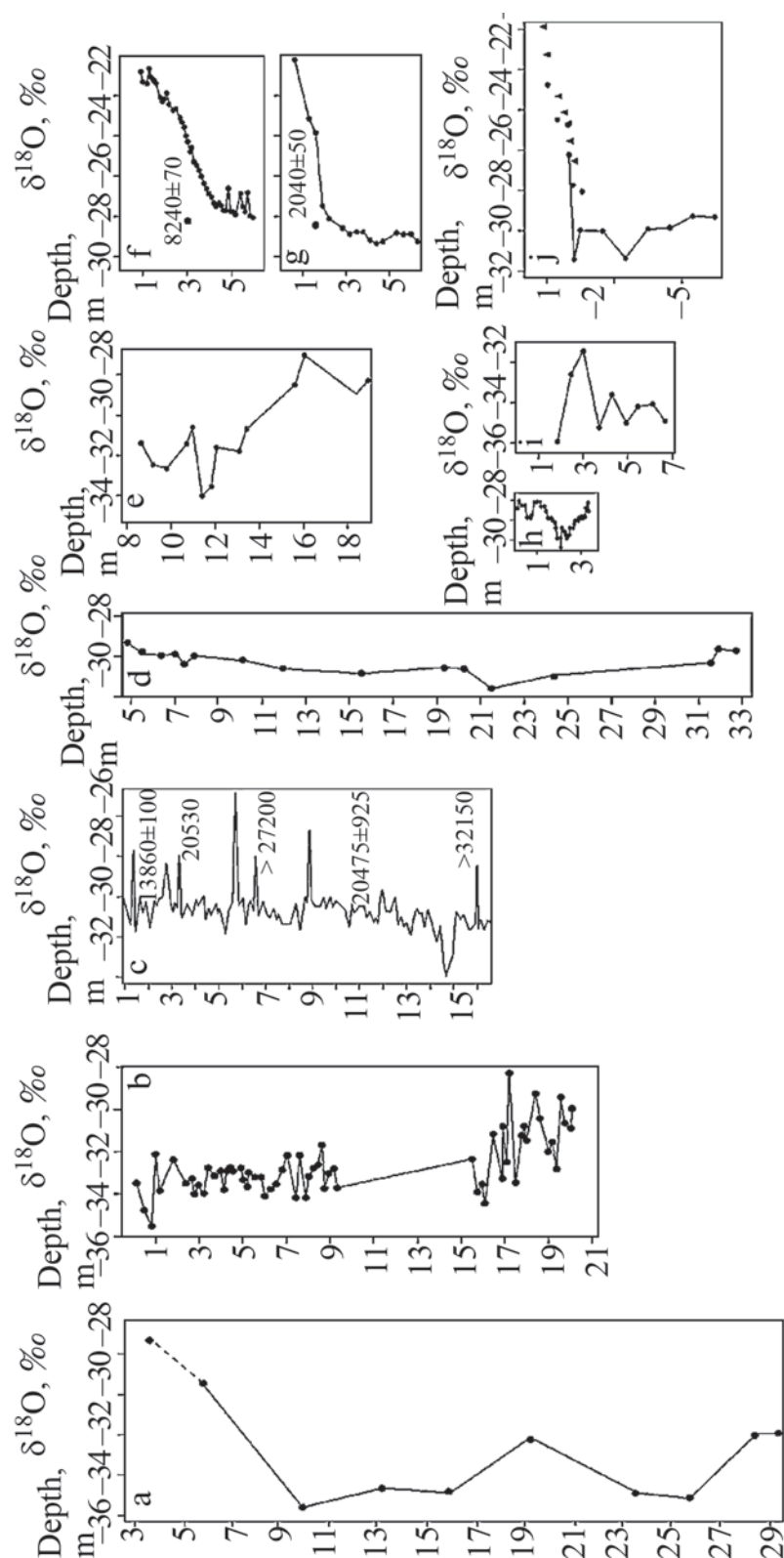


Fig. 7. The comparison of oxygen isotope plots of massive ice of Canadian permafrost, formed under open- and closed-system freezing:

a – Involut Hill site, to the northeast of Tuktoyaktuk [Mackay, 1983]; b – Peninsula Point (4.5 km southwest of Tuktoyaktuk) [Fujino et al., 1988]; c – Peninsula Point [Moorman et al., 1998]; d – 7 km to the east of Ya Ya Lake, on southern Richard Island [Dallimore and Wolfe, 1988]; e – Lousy Point, near Ya Ya Lake, on southern Richard Island [Dallimore and Wolfe, 1988]; f – g Willow River region, Aklavik Plateau, Richardson Mountains; f – profile of site WR-00-5, g – profile of site WR-00-3 [Lacelle et al., 2004]; h – 5 km southwest of Tuktoyaktuk [Kato and Fujino, 1981]; i – southern Eskimo Lakes region, Tuktoyaktuk Coastlands [French and Harry, 1990], j – Crumbling Point, Summer Island, Tuktoyaktuk Coastlands [Murton et al., 2005].

CONCLUSIONS

- The study considers practically all the selected ages and mechanisms of massive-ice formation. The senior author proposed the original mechanism of the formation of massive ice in saline lake sediments. New mechanisms will undoubtedly be proposed in the future.
- A new genetic classification of massive-ice deposits introduces two new categories at its highest level: homogeneous and heterogeneous massive-ice deposits.
- Assemblages of different massive-ice types are common in permafrost exposures in the Yamal Peninsula of west Siberia and

the Tuktoyaktuk Coastlands and Yukon of northwest Canada.

- Plotting of isotopic data from massive ice on graphs with a single vertical and horizontal size facilitates objective assessment of the isotopic characteristics of massive ice.

ACKNOWLEDGMENTS

Research by Yu.Vasil'chuk is financially supported by the Russian Scientific Foundation (grant RSF No. 14-27-00083, generalisation of stable isotope data) and by a grant from the Russian Foundation for Basic Research (grant RFBR No. 14-05-00795, stable isotope analyses). ■

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Received 24.04.2016**Accepted 29.08.2016**



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