Kriosfera Zemli, 2021, vol. XXV, No. 2, pp. 56–67

ABOUT THE INCORRECTNESS OF YU.K. VASIL'CHUK'S METHOD FOR THE RECONSTRUCTION OF PALEOTEMPERATURES USING ISOTOPE COMPOSITION OF WEDGE ICE

Review of the article by Yu.K. Vasil'chuk, A.C. Vasil'chuk "Air January paleotemperature reconstruction 48–15 calibrated ka BP using oxygen isotope ratios from Zelyony Mys Yedoma"

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It has been revealed that methodological techniques and formulas developed and widely used by Yu.K. Vasil'chuk for the reconstruction of average January air temperatures ($t_J = 1.5 \cdot \delta^{18}O$), the sum of winter negative air temperatures ($\Sigma t_w = 250 \cdot \delta^{18}O$), as well as average winter air temperatures ($t_w = \delta^{18}O$) based on the oxygen isotope composition of ice wedges are incorrect, and the paleoclimatic reconstructions obtained from these formulas are unreliable.

Key words: *stable isotopes* ^{18}O *and* D, *ice wedges, reconstruction of paleotemperatures, Pleistocene, Holocene, permafrost.*

INTRODUCTION

The first attempts to use water isotope composition of wedge ice for the assessment of paleotemperatures had been making since the 1970s. Initially, they generated a lot of interest and lively discussion. However, in 1980–1990 many researchers had come to the conclusion that the use of ice wedges as a source of paleotemperature information has many limitations [*Arkhangelov et al., 1987; Konyakhin, 1988; Vasil'chuk, 1990, 1991; Golubev et al., 2001*]. The formation of the isotope composition of wedge ice depends not only on climatic factors, but also on local growth conditions, which are currently not possible to take into account. Therefore, in most modern publications, the isotope composition of ice wedges is interpreted primarily on a qualitative rather than quantitative level [*Meyer et al., 2002, 2015; Schirrmeister et al., 2003; Derevyagin et al., 2010; Wetterich et al., 2011; Boereboom et al., 2013*].

Yu.K. Vasil'chuk is a renowned expert in the study of the isotope composition of various types of natural ice, and since the 1990s to the present, has published many works in that area. In the article reviewed here, the issues of using the oxygen isotope composition of ice wedges for quantitative paleoclimatic reconstructions of the second half of the Late Pleistocene in the lower Kolyma basin are considered. In it, the author uses several previously derived formulas [*Vasil'chuk, 1990, 1991; Vasil'chuk, Vasi'lchuk, 2017, 2018; and many others*], which, in his opinion, functionally relate the $\delta^{18}O$ values (‰) in ice wedges and air paleotemperature. For the mean January air temperatures that dependence has the form of

$$t_J = 1.5 \cdot \delta^{18}O, \quad (1)$$

for the sum of negative winter air temperatures it looks like

$$\Sigma t_w = 250 \cdot \delta^{18}O, \quad (2)$$

and for the mean winter air temperature it is

$$t_w = \delta^{18}O. \quad (3)$$

As follows from the formulas (1)–(3), the mean winter air temperature is numerically equal to $\delta^{18}O$ value, the January air temperature is one and a half times higher than $\delta^{18}O$ value, and the sum of winter negative air temperatures is 250 times higher than it. It is not only the simplicity of the dependences used by the author to describe a very complex multifactorial system for the formation of isotope compositions of ice wedges that raises doubts, but also the fact that all reconstructed temperatures are interconnected by simple linear equations and can be easily derived from each other. So, with a simple substitution of the formula (3) into the formula (1), it turns out that $t_J = 1.5 \cdot t_w$. According to the formulas of Yu.K. Vasil'chuk, the mean January air temperature is one and a half times lower than the mean winter air temperature. The same applies to the sum of negative winter air temperatures, which can be deduced from the mean winter air temperature or January air temperature. The reviewer believes that such consequences, which directly follow from formulas (1)–(3), completely contradict the results of current meteorological observations and the basic principles of climatology, they call into question the correctness of that method.

The aim of this article is to discuss the validity of of Yu.K. Vasil'chuk's methodology used in peer-reviewed articles and many other publications of the author [*Vasil'chuk, 1990, 1991; Vasil'chuk, Vasil'chuk, 2017; Vasil'chuk et al., 2019a,b*]. For this, initial data from methodological publications of Yu.K. Vasil'chuk, as well as key results of Russian and international research in that area, have been analyzed.

Some theoretical aspects of using ice wedge isotopic composition as paleoclimatic indicator

To assess the applicability of the methodology used by Yu.K. Vasil'chuk [*Vasil'chuk, 1990, 1991, 1992*], several basing theoretical assumptions of the use of ice wedges isotope composition as paleotemperature indicator should be highlighted. The first assumption is that the isotopic composition of ice wedges is formed out of the melted snow cover waters, which flow and refreeze in frost cracks. The second assumption is that the isotope composition of the snow cover is initially related to air temperature and reconstructed paleoclimatic characteristics; this relationship is reliably established for the study area. The third assumption is that the isotopic composition of atmospheric precipitation has not undergone significant fractionation (change) during the formation of the snow cover, its thawing and refreezing in frost cracks.

It is obvious that the correct use of wedge ice isotope compositions as paleoclimatic indicators provides for a continuous discussion of the results obtained within these assumptions when interpreting reconstructed paleotemperatures. Otherwise, the reliability of these results is highly questionable.

The first assumption concerns the hypothesis of the origin of syngenetic Late Pleistocene ice wedges widespread in the loess-ice (yedoma) sediments of the Arctic and Subarctic. According to this hypothesis, ice wedges grow due to systematic opening of the frost cracks in winter. During the warm period, melted snow water flows into vertical frost cracks and quickly refreezes there. That process is repeated from year to year and leads to an increase in ice wedges in width and height. The hypothesis is supported by most of modern researchers [*Meyer et al., 2002; Schirrmeister et al., 2003*], including Yu.K. Vasil'chuk [*1992*], and is not criticized here either. This formation mechanism is clearly confirmed by thin vertical banding and a very light isotopic composition. In general, it follows that ice wedges belong to the congelation type of ice formed by the freezing of snow meltwater. The elementary (annual) ice veins that make up ice wedges have different ages and different isotope compositions, which is associated with the short-period and long-period variations in the atmospheric air temperature during snowfall.

The vertical 'stratification' of ice wedges and the inability to predict where the next ice vein will form represent the most serious and almost unsolvable problems of using wedge ice for detailed paleoclimatic reconstructions [*Meyer et al., 2002*]. The available data on the absolute age of ice wedges and host sediments demonstrates that their formation took place over thousands and tens of thousands years under conditions of significant climatic fluctuations. In addition, in many cases, ice is significantly younger than the host sediments at the same elevation level, which is reflected in a wider variation in wedge ice isotopic composition in horizontal transects than in the vertical transects. At the same time, the age and isotopic composition of ice in the upper and lower parts of the wedge may turn out to be the same, which is why it is recommended to sample ice across the wedges.

All well-known specialists in this field point out to crucial importance of the sampling strategy in studying the isotope composition of ice wedges [*Meyer et al., 2002, 2015; Schirrmeister et al., 2003; Derevyagin et al., 2010; Wetterich et al., 2011; Boereboom et al., 2013*]. Thus, in the article by H. Meyer and colleagues [*Meyer et al., 2002*] devoted to the study of the isotope composition of ice wedges of the Bykovsky Peninsula, there is a special paragraph 'Sampling strategy', where the authors state: 'Stable isotopes of vertical transects of ice wedges show up to four times lower standard deviations than horizontal transects, because vertical sampling is carried out along the cracking direction (following one vein). Therefore, a randomly sampled vertical profile does not necessarily reflect climatic trends'. This article is cited in the peer-reviewed manuscript by Yu.K. Vasil'chuk, but the author does not comment on the conclusion of his colleagues on wedge ice sampling strategy.

Indeed, as further concludes H. Meyer and colleagues [*Meyer et al., 2002*], the variation in the isotopic composition of wedges in horizontal transect is much more significant (Fig. 1). The absence of a vertical plane of symmetry in the $\delta^{18}O$ variation graph (Fig. 1, *b*) indicates that ice wedge did not grow symmetrically, but by adding new ice veins, predominantly on the left side. As the wedge grew, the oxygen isotopic composition of ice changed almost one and a half times, from 32 to 24 ‰. That indicates significant changes in climatic conditions and the isotopic composition of the snow cover during the formation of ice wedges.

In the manuscript under review, Yu.K. Vasil'chuk, as in many of his publications, sampling has been performed along a vertical transect (see p. 49 of this issue, Fig. 5 of reviewed article). According to the concepts of wedge ice structure and formation mechanism considered above, these samples may represent some group of ice veins of a similar age. That assumption is fully confirmed by the absence of any regular changes in the oxygen isotopic composition in the vertical profile of the wedge. Single deviations are statistically insignificant and cannot be considered as

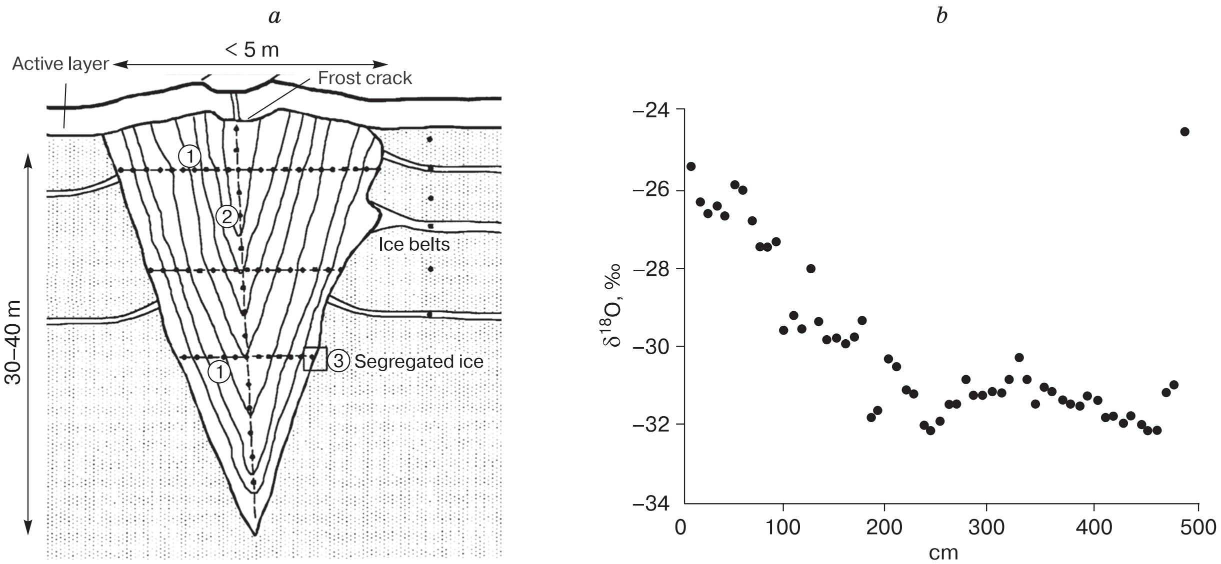

Fig. 1. Recommended sampling strategy for studying ice wedge isotope composition (*a*) and variation of δ^{18}O value across an ice wedge about 5 m wide along transect 1 (*b*), Bykovsky Peninsula, according to [*Meyer et al., 2002*].

a: black dots are sampling points; the numbers in circles: 1 – horizontal transect; 2 – vertical transect; 3 – exchange processes between ice wedge and segregated ice.

climatic events; moreover, they are very small and can be caused by changes in local conditions.

With this sampling method most of the samples fall into a narrow set of ice veins of a similar age, while the composition of the lateral and possibly more ancient parts of ice wedges remains unknown. Insignificant variation within the range of 30–32 ‰ and single deviations of the δ^{18}O values are rather random and cannot be considered as climatic events. In general, direct assessment of climate trends can't be made based on the vertical variation of the δ^{18}O values.

The second assumption, lying in the base of the use of ^{18}O and D as temperature indicators, is the fundamental dependence of the isotopic composition of atmospheric precipitation on its condensation temperature [*Craig, 1961; Dansgaard, 1964; Clark, Fritz, 1997*]. This dependence is substantiated by W. Dansgaard [*1964*] using a large amount of data. During condensation of atmospheric water vapor into ice (snow) in the temperature range of -30 °C $< t < 0$ °C, the isotopic composition of the condensate (ice, snow) is approximately described by the equations $\delta^{18}O = 0.68t - 13.6$ and $\delta D = 5.6t - 100$. The δ^{18}O and δD values are here expressed in permille (‰), and the temperature t is expressed in centigrade (°C). In very cold regions with low condensation temperatures of atmospheric vapor (–20 to –40 °C) the slopes of the equations for δ^{18}O and δD decrease to 0.58 and 4.5, respectively [*Dansgaard, 1964*].

Thus, the isotopic composition of the snow falling in winter depends on the air temperature at the time of its falling. The lower that temperature, the lighter the isotopic composition of the falling snow. Snow, snowpatches, glaciers and some other types of natural ice belong to the sedimentary-metamorphic type of natural ice. Their isotopic composition is directly related to the temperature conditions at the moment of condensation and can be used as a temperature indicator.

It is surprising that neither in the article reviewed here, nor in the methodological publications of Yu.K. Vasil'chuk [*Vasil'chuk, 1990, 1991; Vasil'chuk, Vasil'chuk, 2017; Vasil'chuk et al., 2019a,b*] the fundamental relationship established by W. Dansgaard [*1964*] and the formulas for the relationship between the δ^{18}O and D values of atmospheric precipitation and air temperature at the time of precipitation are not discussed in any way.

Since the air temperature changes significantly during winter, the isotopic composition of the falling snow changes along with it. For example, in Yakutsk, snow with the lightest isotopic composition usually falls during January, the coldest month of the year [*Kurita et al., 2005; Papina et al., 2017*]. During the observation period of 2013 to 2015, individual extremely low values of δ^{18}O and D (–45.0 and –350.1 ‰) have been observed in the January precipitation [*Papina et al., 2017*]. In general, the relationship between the isotopic composition of atmospheric precipitation in the cold period and the mean air temperature during it fallout is described by the equations

$$\delta^{18}O = 0.59t^\circ - 19.7\ (R^2 = 0.88),$$

$$\delta D = 4.16t^\circ - 149.38\ (R^2 = 0.89),$$

where t° – mean air temperature. The slopes of those equations (0.59 and 4.16) are close to the values of the coefficients (0.58 and 4.5) of Dansgaard's equations [*Dansgaard, 1964*] established for the conditions of condensation of the atmospheric water vapor into snow within the surface air temperatures range of –20 to –40 °C.

The above equations [*Papina et al., 2017*] have been obtained using data on snow precipitation isotopic composition and air temperature during precipitation. However, they in no way correlate with the equations of Yu.K. Vasil'chuk (for the mean January air temperature and for the mean air temperature of the cold period) [*Vasil'chuk, 1990, 1991; Vasil'chuk, Vasil'chuk, 2017*], which, for the convenience of comparison, can be written in the form of

$$\delta^{18}O = 0.67t_J,$$

$$\delta^{18}O = t_w.$$

It should be noted that the lowest temperatures during winter are associated with clear anticyclonic weather, in which there is practically no precipitation. Therefore, in the ultra-continental regions, the share of January snow in the total winter snow supply is small. At the same time, the maximum amount of snowfall is associated with the penetration of cyclones, strong thaws and higher condensation temperatures of the falling snow.

Meteorological data indicate that January is the coldest month of the year only in continental regions, while in maritime arctic climate the coldest month is February. Therefore, February (not January) snowfall will have the lightest isotopic composition. The areas of maritime Arctic climate, where the coldest month is February, include a significant part of the Chukotka Peninsula and some part of the Arctic coast of the northeastern Asia (see meteorological data of the Provideniya, Pevek, Bilibino, Mys Shmidta, Tiksi weather stations). So it is not clear what paleotemperatures Yu.K. Vasilchuk reconstructs using the formula (1) for those areas? Is that dependence also valid for the mean February air temperature? If so, in what cases?

In general, normalized values of the isotopic compositions of the snow cover demonstrate a strong relationship with the air temperature during its fallout. Therefore, they can be used to estimate the air temperature based on the formulas of W. Dansgaard [*1964*] after their calibration for specific climatic regions, as has been done in [*Papina et al., 2017*]. Those formulas can also be used to assess the temperature conditions of the formation of all sedimentary-metamorphic ice types since their isotopic composition is directly related to air temperature during condensation.

The third assumption of using the ice wedges as temperature indicators is that their composition is close to the initial snow cover and did not undergo significant fractionation at the stages of its thawing and refreezing in frost cracks. Fractionation of water isotope composition occurs continuously during its evaporation from the ocean, movement inland, and precipitation [*Craig, 1961; Dansgaard, 1964; Rozanski et al., 1993; Clark, Fritz, 1997; Kurita et al., 2005*]. The isotopic composition becomes much lighter away from the ocean.

It is known that the ratio between $\delta^{18}O$ and δD in atmospheric vapor near the dew point is very stable, it persists at different temperatures and is described by the equation $\delta D = 8 \cdot \delta^{18}O + 10$, called Global Meteoric Water Line (GMWL)', 'Craig's line', 'the equilibrium line of the isotopic composition' and others [*Rozanski et al., 1993; Clark, Fritz, 1997*]. As a result of complex fractionation processes during the water cycle, isotopic compositions can deviate above or below GMWL. The magnitude and nature of that deviation is usually measured in the form of deuterium excess (d_{exc}) calculated by the formula [*Dansgaard, 1964*]

$$d_{exc} = \delta D - 8 \cdot \delta^{18}O.$$

In arid regions partial evaporation occurs even at the stage of liquid atmospheric precipitation movement to the earth surface. In that case, lighter water (H_2O) returns to the vapor state, and heavy-water molecules ($H_2{}^{18}O$, $D_2{}^{16}O$) is accumulated in the liquid phase. However, the rate of evaporation of the $H_2{}^{18}O$ molecules is higher than that of the $D_2{}^{16}O$ molecules; therefore, the liquid phase is relatively depleted in heavy oxygen and enriched in deuterium. That process is called evaporative fractionation. In a graphical form, in $\delta^{18}O/\delta D$ coordinates, the isotopic compositions with pronounced evaporative fractionation lie significantly below the GMWL, and their deuterium excesses are often negative.

In winter, with the progressive cooling of air masses, the amount of water vapor is significantly reduced and its isotopic composition becomes increasingly lighter. That is due to the depletion of water vapor with heavy water molecules, which condense first. Under such conditions, isotopic equilibrium $\delta D = 8 \cdot \delta^{18}O + 10$ is not maintained due to the difficulty of isotopic exchange in the ice – vapor system [*Dansgaard, 1964*]. Therefore, the isotopic composition of the atmospheric vapor shifts above GMWL, and the deuterium excess acquires high positive values (>10).

In winter snow cover isotopic composition also does not remain constant even before the beginning of snow melting. This is associated with intense snow sublimation (bypassing the liquid phase). It has been instrumentally established that in Central Yakutia in winter up to 30 % of the snowfall and more evaporate [*Are, 1972; Golubev et al., 2001*]. During sublimation, mainly the light water molecules evaporate, and the snow residue is enriched in heavy isotopes. An increase in the concentration of ^{18}O and D (1.5–3 times) in the snow cover as a result of its sublimation is evidenced by the research results of V.N. Golubev with colleagues [*2001*].

In the Central Yakutia 10 generalized snow cover samples (for its entire thickness) were taken during one winter period. The $\delta^{18}O$ and δD variations reached about 10 and 75 ‰, respectively, and the average values were $\delta^{18}O = -32.0 \pm 5.1$ ‰ and $\delta D = -248.4 \pm 35.4$ ‰, $d_{exc} = 7.5 \pm 6.5$ ‰ [*Galanin et al., 2019*]. The studied composition is described by the equation $\delta D = 6.8 \cdot \delta^{18}O - 31.9$ [*Galanin et al., 2019*] and poled apart from the composition of winter snowfall described by the equation $\delta D = 8.2 \cdot \delta^{18}O + 21.9$ [*Papina et al., 2017*]. A significant decrease in deuterium excess and slope in the snow cover indicates a powerful evaporative fractionation both before the beginning of the spring snowmelt and throughout it. The heaviest isotopic compositions ($\delta^{18}O = -19.3$ ‰, $\delta D = -160.9$ ‰, $d_{exc} = -6.7$ ‰) differ by almost 2 times and are typical for the samples taken from the last snowpatches in June [*Galanin et al., 2019*].

It follows from the above that when calculating paleotemperatures based in isotope composition of wedge or other ice types, first of all it is necessary to assess fractionation degree, deuterium excess, and to compare values relative to the GMWL. Otherwise, it is impossible to establish the real genesis of the studied water or ice, as well as reconstruct temperature conditions of their formation.

For example, during the coldest and dry winters the role of sublimation of the snow cover inevitably increases, which will be reflected in a significant increase in the isotopic composition of the snow cover and ice wedges. While at methodology of Yu.K. Vasil'chuk heavier isotopic composition of ice wedges is always compared with climate warming.

Unfortunately, the issues of snow cover isotope composition formation and fractionation mechanisms at the stage of transformation into ice wedges are not considered at all in the reviewed article by Yu.K. Vasil'chuk. Many important and well-known works in that area [*Golubev et al., 2001; and many others*] are not cited or commented by the author. In most of his studies Yu.K. Vasil'chuk operates only oxygen isotope composition and does not take into account deuterium in any way. The reviewer believes that using only the $\delta^{18}O$ values it is impossible to assess the fractionation degree of the studied water and ice, as well as to establish the real origin of their isotopic composition.

Analysis of methodology of Yu.K. Vasil'chuk for the reconstruction of paleotemperatures based on isotope composition of ice wedges

A critical aspect of the reviewed article by Yu.K. Vasil'chuk, A.C. Vasil'chuk is not only the incorrect sampling strategy and the lack of data on the isotopic fractionation of ice wedges studied by the authors. The lack of explanations in methodological publications of the author [*Vasil'chuk, 1990, 1991, 1992; Vasil'chuk, Vasil'chuk, 2017, 2020; Vasil'chuk et al., 2019a,b; and many others*] of how the author's formulas (1)–(3), see Introduction, were mathematically derived and on what data they are based, causes skepticism. While studying the works of Yu.K. Vasil'chuk, the reviewer was surprised to find that those formulas were first used by the author in 1990 [*Vasil'chuk, 1990*], but initial data lying in their base had been published only in 1992 [*Vasil'chuk, 1992*].

It is paradoxical that none of the author's work over the past 30 years, where these formulas were used, considered the primary data and the method of their approximation, did not indicate the accuracy, reliability and reproducibility of the obtained results. The author only reports that according to the formula (1) ($t_J = 1.5 \cdot \delta^{18}O$), the mean January air temperatures are reconstructed with an accuracy of ±3 °C [*Vasil'chuk, 1990, 1991, 1992; Vasil'chuk, Vasil'chuk, 2017*].

In the peer-reviewed article and in his other publications the author reports that the method for obtaining this formula was first elaborated by him and published in the English version of the Russian journal *Water Resources* [*Vasil'chuk, 1991*]. If that formula is so important for paleoclimatic reconstructions, then why, for almost 30 years after its publication, the author did not carry out additional methodological studies on its refinement, calibration, verification on a more representative sample of primary data? It is strange that the author has no later publications on the development and the improvement of methods for the reconstructing paleotemperatures based on wedge ice isotope composition.

The publication of Yu.K. Vasil'chuk's methodology [*Vasil'chuk, 1991*] in the English version of the journal had been remaining inaccessible to most researchers for a long time. More than 15 years ago, the reviewer tried to find that publication and analyze the methodology used by the author. However, attempts to get acquainted with that most self-cited work of the author [*Vasil'chuk, 1991*] was unsuccessful at that time due to remoteness from large libraries, as well as poor development of domestic and international scientific electronic resources, lack of access to international citation databases. The reviewer assumes that for most other researchers access to the primary data of the Yu.K. Vasil'chuk's methodology was limited and practically impossible for a long time.

While reviewing the article, the reviewer has found that both Russian [*Vasil'chuk, 1990*] and English [*Vasil'chuk, 1991*] versions of that article have become available on the scientific electronic library eLibrary.Ru. The comparison of both versions has revealed that they are completely identical. The reviewer is quite surprised that the author never refers to the Russian-language version [*Vasil'chuk, 1990*] of his methodological publication, which would undoubtedly be more accessible to a wide range of readers.

To his next surprise, examining the main most self-cited methodological publications of Yu.K. Vasil'chuk [*Vasil'chuk, 1990, 1991*], the reviewer has not found the formula (1) ($t_J = 1.5 \cdot \delta^{18}O$) for the mean January air temperature as well as the method of its elaboration in their text. After careful study of this publication, the formula has nevertheless been found in the title of one of the column headings of the table, along with the mean January air temperatures reconstructed on its basis. But any indications about the initial data and the method of obtaining the formulas (1)–(3) in publications [*Vasil'chuk, 1990, 1991*] has not been found by the reviewer.

In the same publication, the reviewer has found the formula (2) ($\Sigma t_w = 250 \cdot \delta^{18}O$), elaborated by Yu.K. Vasil'chuk for the reconstruction of the sum of negative winter air temperatures. But there are no algorithms or methodological techniques for elaborating the formula (2) in the publications of Yu.K. Vasil'chuk [*Vasil'chuk, 1990, 1991*]. However, it is in those publications that all the formulas appear for the first time without any references to the previous methodological works. That is also confirmed by earlier publications, in which the author has not yet applied any formulas for reconstructing paleotemperatures.

In Annotation of articles [*Vasil'chuk, 1990, 1991*], Yu.K. Vasil'chuk also does not report anything about the formulas he has elaborated, but declare that he has compared the maps of the $\delta^{18}O$ value distribution in recent ice veins (ice veinlets) and the maps of isotherms of the sums of negative winter air temperatures within the USSR regions with low-temperature permafrost. Indeed, those publications contain the highly generalized small-scale climatic maps from the USSR climate handbook [*USSR climate..., 1966a,b, 1967*], which demonstrate the mean January air and mean winter air temperatures of the northeast Asia in the form of isotherms. On the same maps, the author has placed the locations and oxygen isotopic compositions of the ice wedges tested by him. Moreover, the latter are located mostly hundreds of km away from the nearest weather station. Nothing is said about how exactly functional dependencies (1) and (2) were obtained based on the analysis of the map data. It is also misleading that in all his subsequent publications the author points out that the formulas (1)–(3) have been obtained using precisely the data from

Table 1. **The $\delta^{18}O$ values in modern ice veins of syngenetic ice wedges on Ayon Island, in the north of Chukotka and the nearby islands of the Eastern Russian Arctic, after [*Vasil'chuk, 1992*] with additions after [*Vasil'chuk Yu.K., Vasil'chuk A.C., 2017*]**

Location of recent wedges	Coordinates	$\delta^{18}O_{IW}$, ‰ in recent ice wedges	Climatic data from weather stations			
			Σt_w	t_w	t_J	t_s
Ayon Island	69°47′ N, 168°39′ E	−20.0	−5047	−20	−29	−12
Mouth of the Rauchua River	69°30′ N, 166°43′ E	−22.0	−5436	−21	−32	−13
Kuvet River	69°16′ N, 175°02′ E	−21.0	−4700	−18	−27	−11
Wrangel Island	71°14′ N, 179°24′ W	−20.0	−4272	−17	−25	−11
Amguema River	67°03′ N, 178°53′ W	−19.0	−4992	−19	−29	−11
Lake Koolen	65°59′ N, 170°58′ W	−16.0	−3400	−14	−22	−7
Lake Elgygytgyn	67°30′ N, 172°00′ E	−20.4	−4598	−18	−27	−10
Henrietta Island	77°06′ N, 156°30′ E	−15.3	−5330	−17	−27	−12
Zhokhov Island	76°09′ N, 152°43′ E	−20.0	−5363	−18	−29	−13
Kotelny Island	75°27′ N, 140°50′ E	−18.1	−5408	−19	−29	−14
Bunge Land Island	75°24′ N, 141°16′ E	−17.6	−5989	−21	−28	−14
Maly Lyakhovsky Island	74°07′ N, 140°40′ E	−18.0	−5408	−20	−31	−14
Bolshoy Lyakhovsky Island, south	74°07′ N, 140°40′ E	−20.4	−5400	−20	−31	−14
New Siberia Island	75°03′ N, 148°28′ E	−18.0	−5500	−20	−30	−14
Chetyrekhstolbovy Island	70°47′ N, 161°36′ E	−20.0	−5143	−19	−30	−13
Plakhinskii Yar	70°47′ N, 161°36′ E	−25.0	−5733	−23	−35	−13

Note: $\delta^{18}O_{IW}$ is the $\delta^{18}O$ values in ice wedges, ‰ vs. SMOW; Σt_w is the sum of winter air temperatures, degree-days; t_w is the mean winter air temperature, °C; t_J is the mean January air temperature, °C; t_s is mean annual ground temperature (°C) without snow and vegetation. (The title of the table and notes are preserved in the author's version [*Vasil'chuk, Vasil'chuk, 2017*].)

weather stations, and not the generalized small-scale maps compiled on their basis!

At the same time, as one gets acquainted with other publications of Yu.K. Vasil'chuk, it becomes obvious that these maps [*Vasil'chuk, 1990, 1991*] were used for deriving formulas (1)–(3). It is obvious that the climatic characteristics for all sampling points of the recent ice wedges (ice veinlets) have been established by Yu.K. Vasil'chuk by extrapolating the isotherms of small-scale climatic maps out of the handbook [*USSR climate..., 1966a,b, 1967*] into a table, probably obtained by the author after the derivation of the formulas, since it is absent in his most cited methodological works [*Vasil'chuk, 1990, 1991*], and appears 2 years later in another inaccessible publication [*Vasil'chuk, 1992*]. Finally, in 2017, original table and the formulas based on it were published in a widely available publication [*Vasil'chuk, Vasil'chuk, 2017*] and are now available for analysis. For convenience of consideration, the table with initial data for the formulas (1)–(3) is given below (Table 1).

Analysis of the correctness and reliability of the initial data for formulas (1)–(3)

Initial data (the $\delta^{18}O_{IW}$ value, Table 1) of the oxygen isotopic composition of the recent ice veins (ice veinlets) of different regions of the permafrost zone of the northern Eurasia, used by the author to elaborate formulas (1)–(3) [*Vasil'chuk, 1990, 1991, 1992; Vasil'chuk, Vasil'chuk, 2017*] arises many questions. What does the author mean by *the recent age* and how has it been established?

According to the statement of the author, one standard 10 × 10 cm wedge ice sample includes many ice veins and covers the interval of 100 to 300 years [*Vasil'chuk, 1990, 1991*]. In that case, the 'recent' ice veins10–20 cm thick studied by the author could have been forming starting from the Little Ice Age up to the present time. During that time, both the global and regional climates have undergone significant changes, as evidenced by the data of meteorological observations. The mean winter and mean annual air temperatures during this period have increased by several degrees. This warming has been reflected in a significant retreat of glaciers. Since older veins preserved in permafrost for several thousand years could also have been included in the author's initial sample, the reviewer believes that their oxygen isotope composition can characterize not current climatic conditions, but averaged ones over the entire Late Holocene, since no absolute dating of these veins is available.

Variations in the oxygen isotope composition of recent ice veins reach significant values even in one region. Thus, in the area of Oyogoss Yar (Dmitry Laptev Strait), in 38 samples of recent ice veins, the $\delta^{18}O_{IW}$ value varies from –18.24 to –25.27 ‰ [*Opel et al., 2011*], and on the Bykovsky Peninsula (22 samples) it does the same from –22.38 to –29.02 ‰ [*Meyer, 2001*] and others. When trying to determine the modern mean January air temperature (t_J) for those areas according to the formula (1) of Yu.K. Vasil'chuk ($t_J = 1.5 \cdot \delta^{18}O$) by substituting the $\delta^{18}O_{IW}$ values, it turns out that in the Oyogoss Yar it varies from –27 to –38 °C, and on the Bykovsky Peninsula it fluctuates from –34 to –44 °C, respectively. However, when using the formula (1) to interpret the isotopic compositions of ancient ice wedges, much smaller deviations of the $\delta^{18}O$ value of 2–5 ‰, obtained from 1–2 samples, are interpreted by Yu.K. Vasil'chuk as changes in the mean January air temperature by 5–7 °C or more. That approach seems to be absolutely unacceptable and contradicting the real data.

Another controversial aspect of using the composition of Holocene ice wedges to reconstruct the temperatures during formation of the Late Pleistocene ice wedges is the possibility of a fundamental difference in their genesis and formation conditions. The Late Pleistocene ice wedges in loess-ice (yedoma) deposits were formed syngenetically. Many researchers believe that loess-ice sediments, together with syngenetic ice wedges, are Pleistocene relics. During the Holocene and at present they practically did not form, but only degraded, forming vast thermokarst alas plains [*Katasonov, 1979; Ershov, 1989*]. The landscape and climatic conditions of their formation are classified as 'extinct' [*Katasonov, 1979; Tomirdiaro, Chernenky, 1987*].

On the contrary, the Holocene ice veins investigated by Yu.K. Vasilchuk can be epigenetic ice wedges formed during freezing of the recent and Holocene floodplains. Relic ice wedges of the Late Pleistocene age can also undergo secondary (epigenetic) freezing and frost cracking. However, the ice that composes recent ice wedges may turn out to be an isotopic derivative of not only melted snow water, but also the supra-permafrost and flood river waters flowing into frost cracks.

Thus, the analysis of 22 isotopic determinations for icings congelation ice in the Central Yakutia [*Galanin et al., 2019*] reveals that their averaged composition ($\delta^{18}O = -21.1 \pm 1.2$ ‰, $\delta D = -172.2 \pm 9.5$ ‰, $d_{exc} = -2.5 \pm 2.5$ ‰) is even lighter than the averaged composition ($\delta^{18}O = -19.4 \pm 2.3$ ‰) of recent Arctic ice wedges from the publications of Yu.K. Vasil'chuk [*1990, 1991*].

However, the icings are of hydrogenic origin and are formed by freezing of the river water. The isotopic composition of river water is always much heavier than of melt snow water, as for snow cover is formed of the atmospheric precipitation in the cold season.

The fundamental difference in the genesis of relict syngenetic ice wedges from the recent epigenetic veins is indicated by the cardinal difference in their deuterium excess. That should be known to Yu.K. Vasil'chuk by the publication [*Budantseva, Vasil'chuk, 2019*], in which he is a co-author.

It is possible to distinguish between different genetic types of ices of close oxygen isotope composition by the value of d_{exc}. Sedimentary-metamorphic ice (snow cover, glaciers) and their close derivatives have $d_{exc} > 5$ ‰, which indicates their close relationship with atmospheric precipitation.

That relationship is usually observed in the isotopic composition of the Late Pleistocene ice wedges (5 ‰ < d_{exc} < 10 ‰) [*Galanin et al., 2019*]. Lower deuterium excess in ice wedges and heavier values of isotope composition are characteristic of the coldest and driest intervals, in particular, the last cold stage of MIS 2. A low deuterium excess $d_{exc} < 5$ ‰ may indicate a significant fractionation and a very indirect relationship between the isotope composition of ice wedges and the composition of the initial snow cover and air temperatures at the time of its formation.

As it follows out of Table 1 [*Vasil'chuk, Vasil'chuk, 2017*], as well as from other data [*Meyer, 2001; Opel et al., 2011*], the oxygen isotope composition of recent ice wedges in the northern Eurasia is completely different from the isotopic composition of the modern snow cover that falls in those areas at temperatures below −20...−40 °C [*Kurita et al., 2005; Papina et al., 2017; Galanin et al., 2019*]. Unfortunately, the author does not provide any convincing descriptions of the structure of the studied ice veins, the isotopic composition of which he used to elaborate the formulas (1)–(3). The lack of information on the δD value makes it impossible to estimate the value of d_{exc} and draw the conclusions about the nature of fractionation and the ice origin. All that leads to a decrease in the reliability of methodological constructions, the formulas (1)–(3) based on this data, as well as the author's paleotemperature reconstructions made on their basis.

Weather stations records used by Yu.K. Vasil'chuk [*Vasil'chuk, Vasil'chuk, 2017*] for the elaboration of formulas and (given in Table 1) causes most serious skepticism. It is not clear what weather station the author has in mind and for what observation period. Most readers obviously do not dwell on that question. At the same time, in all publications of the author there are no references to the source of these data.

Most of the locations of recent ice wedges investigated by Yu.K. Vasil'chuk are extremely remote from any weather stations, however, the author also provides detailed climatic characteristics for them (Table 1). The author confidently manipulates the climatic data of long-term observations of such distant objects as the Henrietta Island, Kotelny, Zhokhova, Maly Lyakhovsky, Bunge Land islands, citing not only the mean winter and mean January air temperatures, but also the mean annual air temperatures of the earth surface. That issue can only be dealt with by analyzing the first publications [*Vasil'chuk, 1990, 1991*], in which the formulas (1)–(3) appear.

However, even in those publications there are no any initial tables with a list of weather stations and data on meteorological observations, but small-scale climatic maps from the USSR climate handbook for 1966–1967 are given [*USSR climate..., 1966a,b, 1967*]. The author does not explain exactly how those small-scale maps have been transformed into the quantitative temperature characteristics and converted from the graphical form to the digital format. However, the author reports that he used data from 250 weather stations for his analysis! The reviewer considers that information to be speculative and unreliable.

In the context of those publications and the illustrations presented in them, it is easy to understand that all meteorological data have been taken by the author by graphical extrapolation of isotherms. Such method of obtaining the initial climatic characteristics for approximating the isotope compositions of recent ice wedges and deriving the formulas (1)–(3), according to the reviewer, is categorically unacceptable. That is due to both a very sparse network of weather stations in the region and the significant distortions associated with the generalization of meteorological data when plotting isotherms. The maps also do not take into account changes in climatic parameters due to altitudinal zonality and local climatic features.

It causes great skepticism that up to the present time the author continues to use the formulas built on the basis of climatic data derived more than half a century ago, without thinking about the need to recheck and adjust them in accordance with ongoing climatic changes, with an increase in the duration of time series of observations at weather stations, etc.

Analysis of the mathematical reliability of formulas (1)–(3) and the connection with the initial data

The list of critical uncertainties and the possible sources of errors identified above is so large and extremely critical that further proof of the ineligibility of Yu.K. Vasilchuk's methodology [*Vasil'chuk, 1990, 1991*], it would seem, is no longer required. At the same time, since the author is silent about the algorithms and methods on the basis of which his formulas have been derived, the reviewer tried to do it on his own.

For that, an analysis of the statistical relationship (correlation) between the $\delta^{18}O_{IW}$ values and the instrumental data (Σt_w, t_w, t_J) taken from the publication [*Vasil'chuk, Vasil'chuk, 2017*] has been carried out (Table 1, Fig. 2). To assess the nature and magnitude of the correlation of those parameters and to construct graphs, standard Microsoft Excel tools have been used.

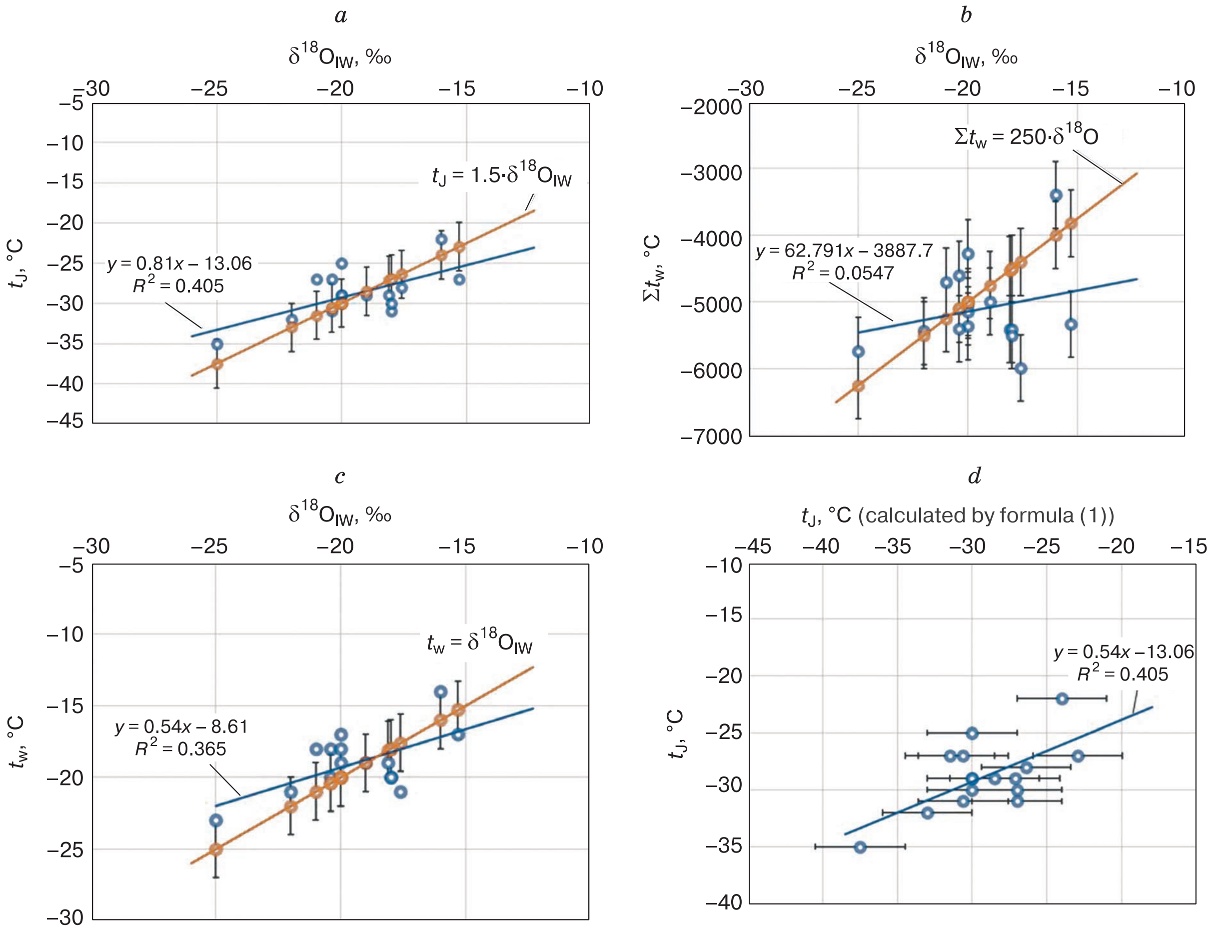

Fig. 2. Linear regressions (blue dots and lines) between climatic parameters and the $\delta^{18}O_{IW}$ values in recent ice veins (ice veinlets) in different regions of the northern Eurasia and their approximation by Yu.K. Vasil'-chuk's formulas (orange dots and lines).

a – linear regression between $\delta^{18}O_{IW}$ and the mean January air temperature and approximation by the formula $t_J = 1.5{\cdot}\delta^{18}O$; *b* – linear regression between the $\delta^{18}O_{IW}$ values and the sum of winter negative air temperatures and approximation by the formula $\Sigma t_w = 250{\cdot}\delta^{18}O$; *c* – linear regression between the $\delta^{18}O_{IW}$ values and mean winter air temperature and approximation by the formula $t_w = \delta^{18}O$; *d* – linear regression between the mean January air temperatures according to weather stations data and the same temperatures calculated by the formula $t_J = 1.5{\cdot}\delta^{18}O$ based on the oxygen isotope composition of recent ice veins . The initial data and error values are taken from the publication [*Vasil'chuk, Vasil'chuk, 2017*] and are shown in Table 1.

Analysis of Fig. 2 indicates the nature of the statistical relationship between the content of the ^{18}O isotope in the recent ice wedges from different regions and the climatic characteristics for those regions, extrapolated to sampling points by overlay. It is fair to assume that the lines and regression equations demonstrated in Fig. 2 reflect the correlation not with the data of instrumental observations at weather stations, but with the contours of the isotherms of those parameters on the climatic maps of 1965–1966 [*USSR climate..., 1966a,b, 1967*]. For comparison, the graphs reflect both real correlations (blue dots and lines) obtained by the reviewer and the results of approximating those parameters (orange dots and lines) by Yu.K. Vasil'chuk [*Vasil'chuk, 1990, 1991*]. The reviewer has suggested that if the equations (1)–(3) have been derived by the author precisely on the basis of the data in the table and according to the formulas (1)–(3) they have a linear form, then the linear regression equations derived by the reviewer will have the same form. To his surprise, the reviewer has found (Fig. 2) that the obtained regression lines and the equations approximating them are fundamentally different from the equations (1)–(3) of Yu.K. Vasil'chuk. So, the relationship between the $\delta^{18}O$ value and the mean January air temperature according to the data in Table 1 is approximated by the equation $t_J = 0.81{\cdot}\delta^{18}O - 13.06$ with large deviations ($R^2 = 0.405$), while on the basis of the same data Yu.K. Vasil'chuk has deduced the dependence $t_J = 1.5{\cdot}\delta^{18}O$.

There is no relationship (R^2 = 0.055) between the $\delta^{18}O$ value and the sum of negative winter air temperatures (Σt_w) and it is described by random regression with the equation $\Sigma t_w = 62.79 \cdot \delta^{18}O - 3887.7$, while Yu.K. Vasil'chuk has derived the dependence $\Sigma t_w = 250 \cdot \delta^{18}O$ from the same data. The same applies to the relationship between the $\delta^{18}O$ value and the mean winter air temperature (t_w), which is statistically insignificant (R^2 = 0.365) and is described by the regression equation $t_w = 0.54 \cdot \delta^{18}O$, while Yu.K. Vasil'chuk has derived the formula $t_w = \delta^{18}O$.

The result of the analysis of the formulas (1)–(3) is the graph in Fig. 2, *d*, which demonstrates the regression equation ($y = 0.54x - 13.06$) between the observed mean January air temperatures at weather stations and the same temperatures reconstructed based on the $\delta^{18}O$ values according to the formula (1) of Yu.K. Vasil'chuk. Note that it is one and the same climatic characteristic, therefore, it should be approximated with high significance ($R^2 > 0.9$) by an equation in the form of $y = x$ and pass through the point (0; 0). But there is no correlation between the measured and calculated values (R^2 = 0.405). The magnitude of the systematic discrepancy between the measured and calculated values can be easily estimated by substituting the zero value for x or y. As a result, we obtain the value of the systematic discrepancy between the calculated and observed mean January air temperature equal to 13.06 °C.

Thus, based on the reviewer's analysis of the formulas (1)–(3) of Yu.K. Vasil'chuk, originally published by him in [*Vasil'chuk, 1990, 1991, 1992*] and repeatedly used in all subsequent publications, it has been found that those formulas are not substantiated by facts and do not follow from the primary data on the isotope composition of recent ice veins and meteorological data given in [*Vasil'chuk, 1992; Vasil'chuk, Vasil'chuk, 2017*]. Data given by Yu.K. Vasil'chuk is approximated by completely different dependencies (Fig. 2). The real primary data lying in the base of the formulas (1)–(3), as well as the way they have been derived, remain unknown.

At the end of the review of the article by Yu.K. Vasil'chuk and his method for reconstructing paleotemperatures based on the oxygen isotope composition of ice wedges, it is necessary to state the following. Many present-day researchers studying the isotopic composition of ice wedges [*Meyer et al., 2002*] restrict themselves to very modest qualitative conclusions about the paleotemperatures of their formation. Interpreting the vertical and horizontal variations in the isotope composition of ice wedges, those authors indicate that winter air temperatures were colder or warmer at one time or another, but they do not translate them into specific absolute values, as Yu.K. Vasil'chuk does in most of his reconstructions and in the article reviewed here. Despite the incorrectness of the methodology of Yu.K. Vasil'chuk and the unreliability of the paleoclimatic reconstructions obtained on its basis, the author continues to use the formulas derived in 1990 [*Vasil'chuk, 1990*] and actively publish his results in many journals.

The recent statement of Yu.K. Vasil'chuk that his formulas were officially criticized back in 1991 by Professor J. Ross McKay and Professor A. Washbourne in the responses sent to the abstract of his doctoral dissertation [*Budantseva, Vasil'chuk, 2019*] – is extremely perplexing. They tested Yu.K. Vasil'chuk's formulas on the isotopic compositions of ice wedges in North America and have come to the conclusion that they are completely inapplicable. However, Yu.K. Vasil'chuk writes that for a long time after the elaboration of formulas, he was engaged in their examination and verification, and now has come to the conclusion that they are good for the entire northern Eurasia [*Budantseva, Vasil'chuk, 2019*]. All that reminds of a pun, since neither the formulas, their coefficients, nor errors have been changed in any way since the time of their publication [*Vasil'chuk, 1990*], and the methods of their development remain unknown until now.

CONCLUSIONS

Yu.K. Vasil'chuk is a well-known specialist in the study of the isotopic composition of fossil ice, the reviewer is familiar with many of his works, including some generalizations. Over the past 25–30 years, Yu.K. Vasil'chuk has published a lot of factual data, including borrowed ones, characterizing the isotopic compositions of underground and surface ice from different regions of Russia. The works of Yu.K. Vasil'chuk is often cited, and the actual data is used for comparative analysis.

At the same time, the method for reconstructing of the air January paleotemperatures, mean winter air temperatures, and the sum of negative winter air temperatures, proposed by the author in 1990, causes great skepticism from foreign and Russian researchers. Sampling method along vertical transect predominantly used by Yu.K. Vasil'chuk, is incorrect, contradicts the general regularities of the structure and origin of ice wedges and does not allow to estimate reliably the real variation of their isotope composition. That method contradicts the sampling strategy recommended by the leading present-day experts in the field of ice wedge research.

The formulas for recalculating the oxygen isotopic composition into air paleotemperatures, elaborated by Yu.K. Vasil'chuk, have no physical justification, they have been derived in an incorrect way, contradict the data of meteorological observations, including those cited by the author himself in his publications, as well as those obtained by other authors. The reconstructions of air paleotemperatures in the Pleistocene and Holocene, obtained on the basis of these formulas, are unreliable.

In their paleotemperature reconstructions, Yu.K. Vasil'chuk and his co-authors do not use the concentration of deuterium and the value of deuterium excess at all, do not pay attention to the analysis of the fractionation degree of the studied ice wedges, their genetic relationship with the Global Meteoric Water Line [*Craig, 1961*] and atmospheric precipitation. Most of the publications do not take into account the key foreign works [*Dansgaard, 1964*] in the field of studying the relationship between the isotope composition of natural water and ice and the temperature conditions of their formation.

After these critical remarks all other shortcomings of the reviewed article do not deserve special comments. In general, the reviewer believes that the further continuation of the publication of the results of applying the methodology of Yu.K. Vasil'chuk in scientific publications will negatively affect not only the image of the author himself. To a greater extent, this will discredit the journals themselves, causing great skepticism on the part of foreign and Russian researchers not only in the field of geochemistry of stable isotopes, but also in geocryology, paleogeography and paleoclimatology.

High scientific status of Yu.K. Vasil'chuk demands from his publications the highest possible level of elaboration, adherence to the principles of statistics, scientific ethics and common sense, since those publications will be considered by some researchers, especially the young ones, as methods for further research. The continued use of the Yu.K. Vasil'chuk's methodology by his students and followers will lead to an exacerbation of the theoretical crisis in the study of the isotope compositions of ice wedges and geocryology in general.

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Received December 7, 2020
Revised version received December 20, 2020
Accepted December 24, 2020