Palaeohydrogeological reconstruction of groundwater recharge during Late Weichselian in the Baltic Basin

Robert Mokrik,
Jonas Mažeika

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Several hypotheses were framed to explain the low $\delta^{18}O$ values of groundwater in Estonian Homocline. Traces of depleted groundwater were found also in other parts of Baltic Basin near the shoreline. According to collected data and relevant publications, the $\delta^{18}O$ values of groundwater in most aquifers range from –7.7 to –13.9‰. However, the groundwater in Estonia in the Cambrian-Vendian aquifer system has a significantly lower $\delta^{18}O$ values, which vary mainly from –18 to –22.5‰. The overlying Ordovician-Cambrian aquifer is also depleted by ^{18}O, but, as a rule, the degree of depletion is several per-mil less than in the Cambrian-Vendian aquifer. The thickness of the depleted water in Estonia reaches 450 m. In Gotland Island (Sweden Homocline) at the same depths groundwater has significantly higher $\delta^{18}O$ values (from –5.7 to –6.1‰). To explain the isotope data on groundwater, we analysed a model of pre-Late Glacial permafrost environments, where the groundwater in the cryolite zone is hydraulically communicating with the lake and river systems through taliks. According to the model, penetration through valleys of isotopically depleted surface water related to a cold climatic cycle reached up to 500 m. The mixing processes provided a possibility of subglacial penetration of meltwaters and mixing them with the old Huneborg-Denekamp time groundwater through permafrost-free talik zones. Traces of this penetration were discovered only near the shoreline, where $\delta^{18}O$ values vary from –12 to –13.9‰ and ^{14}C is below 4%. On the territory of Estonian Homocline a hydraulically close connection via the Cambrian-Vendian aquifer between talik systems of the Gulf of Riga and the Gulf of Finland existed through the permafrost before Late Glacial, also through the subglacial recharge during the recessional Pandivere (12 ka BP) and Palivere (11.2 ka BP) phases, thus influencing groundwater recharge by isotopically depleted water.

Keywords: oxygen isotope, meltwater, permafrost, groundwater recharge, modelling

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Robert Mokrik, Vilnius University, M. K. Čiurlionio 21/27, LT-2009 Vilnius, Lithuania
Jonas Mažeika, Institute of Geology and Geography, T. Ševčenkos 13, LT-2600 Vilnius, Lithuania

INTRODUCTION

Isotopic investigations of underground water from the Cambrian-Vendian rocks started in the middle of the 1970s. Works on determination of underground water age by the radiocarbon method started in connection with a regional evaluation of exploiting resources of underground water, which was carried out jointly by the Lithuanian Institute of Geology and the Estonian Hydrogeologic Department. A little later, radiocarbon dating was carried out by the Laboratory of Isotopic Investigations of VSEGINGEO (Moscow Institute of Hydrogeology an Engineering Geology). In the end of the 1970 and beginning of 1980 in St. Petersburg, in addition to the radiocarbon investigations, the content of stable isotopes of oxygen-18 and deuterium was studied. On the grounds of these studies in the environments of St. Petersburg, a supposition was that in the past, during the existence of the aquaglacial basin of the Baltic Ice Lake (BIL), the substitution of recharge zone of the Cambrian-Vendian aquiferous system for its discharge zone took place (Bondarenko et al., 1981).

The isotopic investigations on a larger scale were continued in the Estonian Homocline on the initiative of the Estonian Hydrogeologic Department in cooperation with the Laboratory of Isotopic Investigations of VSEGINGEO, the Lithuanian Institute of Geology and the Geologic Institute of the Academy of Sciences of Estonia. The radioisotopes of ^{14}C and tritium, stable isotopes of oxygen-18, deuterium, a little later also ^{13}C, radium, and the ratio of 234U/238U were studied by specialists of VSEGINGEO. At the Lithuanian Institute of Geology the concentrations of tritium and at the Geological Institute of the Estonian Academy of Sciences the stable isotope of oxygen-18 were determined.

The Quaternary glacial history of the formation of groundwater recharge of the Baltic Basin is still uncertain. Several hypotheses were built up because very low δ^{18}O values of groundwater have been found in Estonian Homocline. The first of them was related with the aquaglacial recharge from Baltic Ice Lake (BIL) (Yezhova et al., 1996) and the second with cryogenic metamorphization in the presence of permafrost during the Pleistocene (Mokrik, 1997). In the first case the problem of the mechanism of the penetration of glacial meltwater of BIL into the Cambrian-Vendian aquifer remained unclear. It was supposed that it became possible owing to the existence of lowered pressures in the aquifer during the glacial period, what further caused the instant penetration of surface water from BIL through the aquitard clays of the Lontova Regional Stage (Yezhova et al., 1996). However, taking into consideration the quite good screening properties of clays of the Lontova Regional Stage (k_0/m_0 ranges within the interval from 10^{-7} to 5.10^{-6} d^{-1}), the more intensive areal penetration of the BIL water from above is hardly real. Besides, in the opposite case, it is difficult to imagine on a large scale the mechanism of full exclusion of "older" groundwater from the Cambrian-Vendian aquifer. The low ^{14}C concentrations (below 3–4 pmC) could suggest that the age of the groundwater was about 26–34 ka BP, which indicated that the recharge in cold climate conditions took place much earlier, at the time when the Estonian territory was not covered by the Late Glacial ice sheet. The model of paleo-recharge of the Cambrian-Vendian groundwater formed during the epoch of Denekamp Interstadial in the western part of the Estonian Homocline, where aquitard clays of the Lontova Regional Stage are replaced in facies by the terrigenous complex of the Voosi Formation deposits, was proposed by R. Mokrik (Mokrik, 1997). It follows from the aforesaid that the model of groundwater formation in the Cambrian-Vendian aquifer is complicated and requires further elaboration. This work considers a more extended model of the possibilities of a subpermafrost communication of the aquifers with isotopically depleted surface waters through talik zones before the Last Glacial period, taking into account also later effects as subglacial recharge after glacier degradation, BIL influence, modern water intrusion from the Baltic Sea, modern recharge in the terrestrial part of the Baltic Artesian Basin. This model firstly was analyzed in (Mokrik et al., 2000; Mokrik, 2000).

The Quaternary period in the Baltic region is characterized by a number of repeated glaciations related with isostatic movements of the Earth's crust, caused by the load of glaciers. In the epochs before the Menapian, Elsterian, Saalian and Late Weichselian Glacial, there formed the permafrost zones the depth of which could reach 450 m in the Estonian Homocline. The surface permafrost before Late Weichselian Glacier froze the discharge areas of the Ordovician-Cambrian and Silurian-Ordovician shallow aquifers. This freezing increased the hydrostatic pressure of shallow groundwater and caused a squeezing depleted by the isotopic composition of groundwater via taliks downwards to the Cambrian-Vendian aquifer. The best conditions for groundwater to penetrate into the Cambrian-Vendian aquifer existed only on the territory of the West Estonian Homocline and on the present Gulf of Finland domain. During the Huneborg Stadial time (34–35 ka BP) the Cambrian-Vendian aquifer could be recharged by arctic meteoric water. The Denekamp subsequent permafrost (26 ka BP) initiated percolation into the Cambrian-Vendian aquifer above the layered subsurface groundwater and the deeper underground freezing. A manifestation of such a process is observed at present in the West Siberian Platform (Kononova, 1973): between underground ice and freezing water the redistribution of salts occurred simultaneously with the formation of underground ice, calcium carbonates and calcium sulphates, which have reached the limit of saturation and at low temperatures come out from the solutions. Calcium and bicarbonate contents in the Cambrian-Vendian groundwater are decreased very much in comparison with groundwater from the overlying zone of active water exchange. The mean content of bicarbonates varies in the interval of 380–500 mg/l in the zone of distribution of fresh groundwater of the Baltic basin, whereas in the Estonian Homocline it reaches 165–220 mg/l only. The calcium content also decreases by 5–10 times in the Cambrian-Vendian aquifer as compared to non-cryogenic conditions. Calculation of the solubility indices by thermodynamic reaction constants shows that calcite is undersaturated and could be precipitated during the Pleistocene. A sharp increase of calcium content in groundwater is observed under conditions of shallow occurrence of aquifers near buried paleovalleys, where during the Holocene due to atmospheric influence water was enriched with calcium, as well as during the mixing with the basement calcium chlorides under conditions of intensive development, a cone of depression arose as a result of operation of coastal water intakes. Besides, the calcium content is increased at a depth of about 500 m in the mixing zone with saline water advancing from the south.

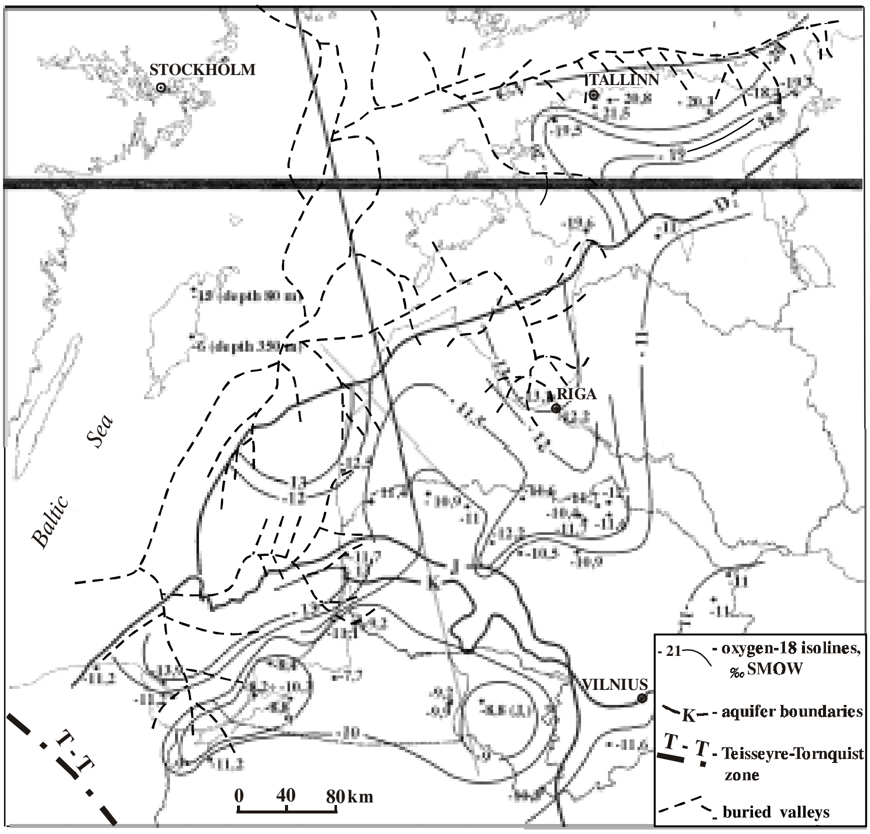

Fig. 1. Oxygen-18 distribution (‰ SMOW) in fresh groundwater of the Baltic Basin
1 pav. Gėlo požeminio vandens deguonies-18 izotopo (‰ SMOW) pasiskirstymas Baltijos baseine

ISOTOPE EVIDENCE IN THE BALTIC BASIN

The process of data collection on isotopes in the groundwater of Baltic Basin was not very purposeful, however, many researchers worked here during two decades. On the basis of the results obtained by them and considering new data it is possible to characterize the isotope significance for the study of groundwater origin and formation in the Baltic Basin. In the period 1972–1997, in vareous territories of the Baltic Basin (in Estonia, Latvia, Lithuania, Russia, Poland) groundwater by different isotope methods was studied by R. Mokrik (Mokrik, 1997); M. Yezhova, V. Polyakov (Yezhova et al., 1996); G. Bondarenko (Bondarenko et al., 1981); J. Banys, V. Juodkazis, J. Mazeika, R. Petrosius (Juodkazis et al., 1995); and others (Rozanski, Zuber, 2000; Vaikmäe et al., 1999).

Based on the available data and relevant publications, changes on δ^{18} O in the Baltic Basin groundwater for the main aquifers of active water exchange zone (up to 450 m deep) are presented in Fig. 1.

The δ^{18}O values of groundwater in most aquifers in North Poland (Rozanski, Zuber, 2000), Kaliningrad District of Russian Federation, Lithuania and Latvia range from –7.7 to –13.9‰. However, groundwater in Estonia in the Cambrian-Vendian aquifer system has a significantly lower δ^{18}O values which vary mainly from –18 to –22.5‰. The overlying Ordovician-Cambrian aquifer is also depleted by ^{18}O, but the degree of depletion is several per-mil less than in the Cambrian-Vendian aquifer. The thickness of the depleted water in Estonia reaches 450 m, while in Gotland Island (Sweden Homocline) at the same depths groundwater has significant-

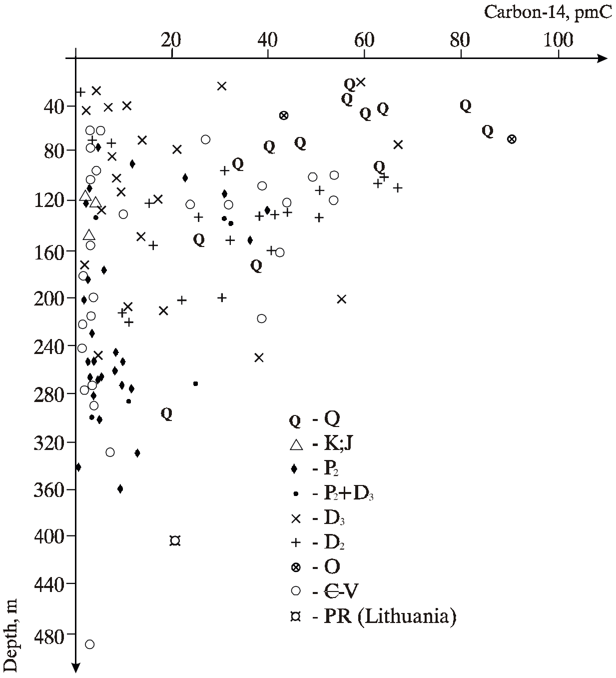

Fig. 2. Radiocarbon content (pmC) *versus* sampling depth of fresh groundwater of the Baltic Basin
2 pav. Radioaktyvios anglies koncentracijos (pmC) priklausomybė nuo gėlo požeminio vandens slūgsojimo gylio Baltijos baseine

ly higher $\delta^{18}O$ values (from –5.7 to –6.1‰) (Mokrik, 1997).

Thus, in the Baltic Basin according to $\delta^{18}O$ distribution in groundwater three main zones can be distinguished. These are: zones with $\delta^{18}O$ values from –10.9 to –11.6‰ (close to meteoric water), which are related to modern watersheds and highlands (eastern part of the Baltic Basin); zones with $\delta^{18}O$ values from –8.2 to –10.5‰ (more positive values than meteoric water), located in the southwestern part of the Baltic region; zones with $\delta^{18}O$ values from –11.7 to –22.5‰ (more negative values than of meteoric water), located in Estonian Homocline (extremely depleted water) and in other lowlands close to the shoreline with occurrence of buried palaeovalleys. The presented differences in $\delta^{18}O$ of groundwater reflect changes of paleoclimatic conditions and their impact on groundwater formation during the Pleistocene and Holocene.

The conventional radiocarbon dating of groundwater within the Baltic Basin is quite controversial due to a complicated evolution of the DIC (Dissolved Inorganic Carbon) system and mixing of groundwater originated from different sources in regional flow systems during palaeoclimatic changes that took place in the Pleistocene and Holocene. Radiocarbon content in groundwater of the active exchange zone varies in a wide range (from almost 0 to 80–90 pmC). Radiocarbon content data plotted depending on sampling depth show a complicated and irregular view (Fig. 2.).

If to plot the corrected (according to statistical and carbonate dilution approaches) radiocarbon age of groundwater depending on a reduced altitude (from 300 m above sea level), two types of isotopically different groundwater could be distinguished (Fig. 3.). These are: groundwater with quite normal $\delta^{18}O$ values and with the radiocarbon age changing from modern to 18 (ka BP) depending on a reduced altitude according to a linear relationship characterising the regional flow system, and groundwater with $\delta^{18}O$ values ranging from –12.5 to –22.5‰ and with radiocarbon age 20–35 ka BP.

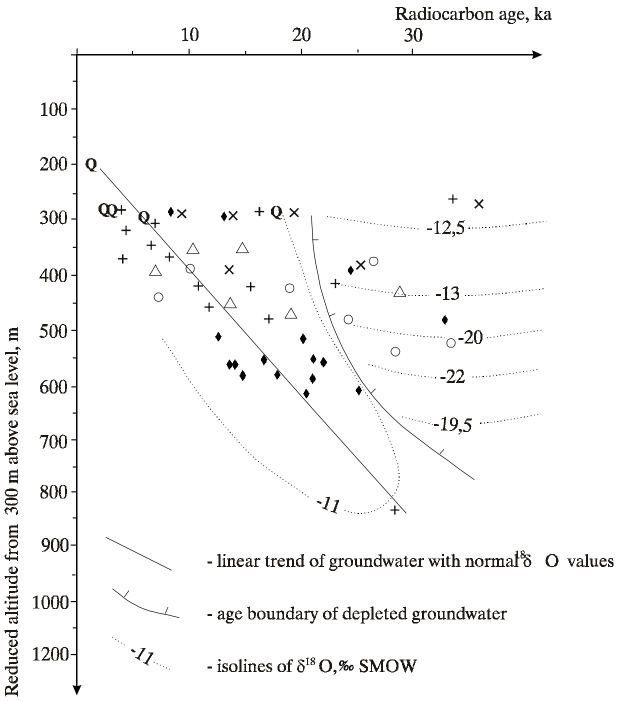

Fig. 3. Radiocarbon age (ka BP) *versus* reduced altitude in fresh groundwater of the Baltic Basin

3 pav. Požeminio vandens absoliutaus amžiaus (tūkst. m.) priklausomybė nuo palyginamosios altitudės Baltijos baseine

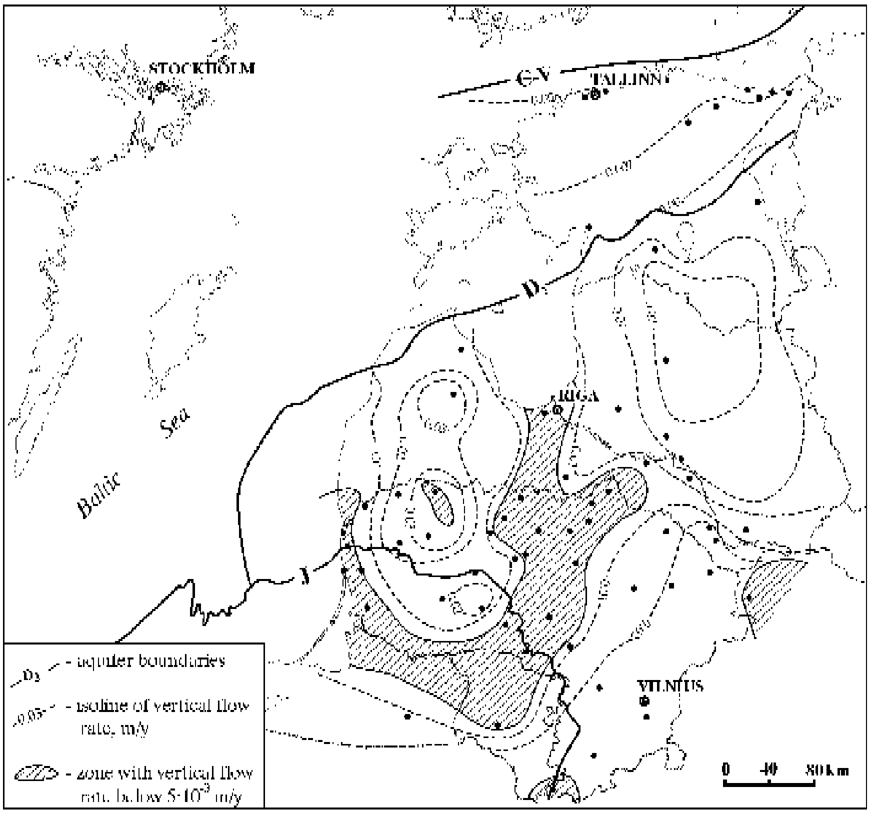

Fig. 4. Distribution of apparent vertical flow rate (m y^{-1}) calculated according to ^{14}C for fresh groundwater of the Baltic Basin

4 pav. Baltijos baseino gėlo požeminio vandens menamas vertikalus filtracijos greitis (m/metai), apskaičiuotas pagal ^{14}C duomenis

Using the distribution of ^{14}C content in groundwater in the regional flow system, an apparent vertical flow rate (sampling depth difference/radiocarbon age difference) was calculated (Fig. 4).

The highest vertical flow rate values are peculiar to modern watersheds. The lowest flow rate values were observed in lowlands, where traces of depleted by ^{18}O water were fixed many times.

MODEL OF GROUNDWATER ALTERATIONS IN QUATERNARY PERIOD

Differences in isotope and chemical composition and radiocarbon age of groundwater cannot be explained only basing on the subglacial recharge model. To explain the formation of zones with the mentioned $\delta^{18}O$ and ^{14}C values, the mixing of water originated from several sources in different palaeoclimatic conditions (Denekamp–Huneborg palaeorecharge in permafrost conditions from depleted surface water through talik zones approximately 34–26 ka BP; subglacial areal recharge by meltwater during Late Weichselian Ice retreating and from Baltic Ice Lake approximately 10–12 ka BP; the modern Holocene recharge by meteoric water and from the Baltic Sea) was adopted (Fig. 5).

On the highlands with a higher water exchange rate there prevails groundwater recharged in the Holocene by meteoric water with $\delta^{18}O$ values close to those of modern precipitation. Glacial meltwater was drained from this zone by hydrographic systems during the Holocene (see Fig. 1).

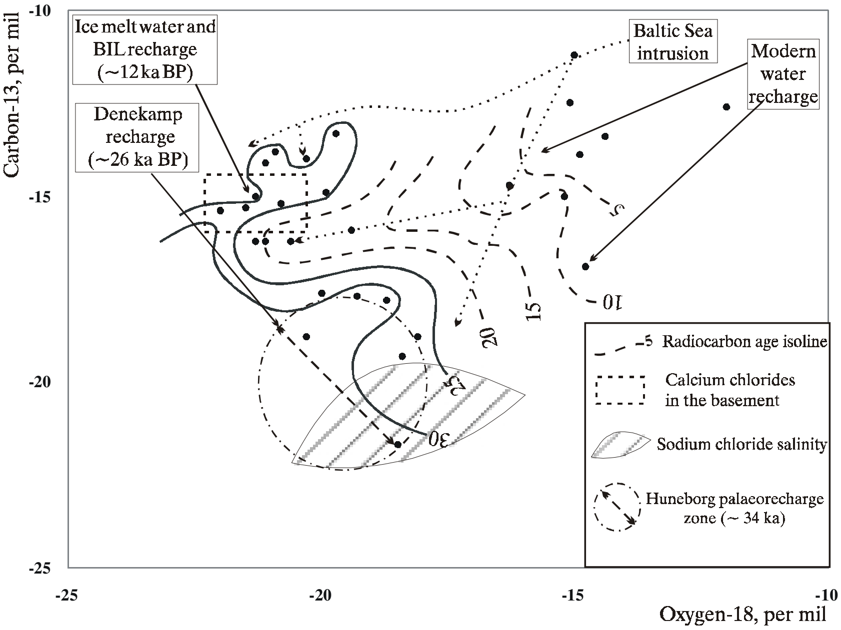

Fig. 5. Different mixed sources of the Cambrian-Vendian groundwater projected onto $\delta^{18}O$–$\delta^{13}C$ plot in the Baltic Basin
5 pav. Baltijos baseino kambro–vendo komplekso požeminio vandens maišymosi diagrama $\delta^{18}O$–$\delta^{13}C$ duomenimis

On the lowlands with a relatively slow water exchange in the lower part of section (especially in Southern Baltic) prevails groundwater excluded from the northern area southwards by the penetrating subglacial meltwater according to the plug-flow mechanism during recessional Middle-North Lithuanian phases (13–14 ka BP). This water originated from the lower part of the section and has more positive $\delta^{18}O$ values.

On the talik zone with negative $\delta^{18}O$ values of groundwater, in the mouths of the Nemunas and the Visla river basins close to the shoreline, also the Nevėžis–Lielupė river system due to mixing of Holocene water with one or another type of palaeorecharged water depleted isotope composition ($\delta^{18}O$ values range from –12 to –13.9‰) of groundwater has remained.

Most significant traces of mixed different recharge portions (Denekamp-Huneborg palaeorecharge; subglacial recharge; palaeorecharge from Baltic Ice Lake close to the northern shoreline of Estonia; Holocene modern recharge, regional lateral flow of groundwater with sodium chloride salinity from the south) have remained in Estonian Homocline (Fig. 6).

It is assumed that during Denekamp-Huneborg time in pre-Late Glacial permafrost environments (26–34 ka BP) groundwater in cryolite zone aquifers could be hydraulically communicating with the lake and river systems through taliks and could be recharged by surface water depleted by ^{18}O and ^{13}C. The $\delta^{18}O$ values could vary from –18.5 to –22.2‰ and the $\delta^{13}C$ values from –18.8 to –21.7‰. The Denekamp subsequent permafrost (~ 26 ka BP) initiated percolation into the Cambrian-Vendian aquifer above the layered subsurface groundwater and the underground freezing. Between underground ice and freezing water the redistribution of salts occurred simultaneously with the formation of underground ice, calcium carbonates and calcium sulphates, which have reached the limit of saturation at low temperatures and came out from the solutions. The calcareosity of the Cambrian-Vendian groundwater is decreased very much in comparison with the groundwater from the above zone of active water exchange.

Analysis of the Cambrian-Vendian aquifer system groundwater bicarbonate composition equilibrium with carbonates shows that a permafrosted groundwater plot took place (Fig. 7).

The Cambrian-Vendian aquifer could be also palaeorecharged in several different palaeoenvironments later on: by subglacial meltwater with the age also close to ~26 ka BP, or from Baltic Ice Lake (~10 ka BP). Depleted $\delta^{13}C$ values of old groundwater (–19 to –21‰) in Eastern Estonia most likely depend on methanogenesis in pre-Huneborg time. However, the $\delta^{13}C$ stable isotope depletion was probably caused by groundwater freezing during the permafrost, when the weaker $\delta^{12}C$ and oxygen bonds are broken, producing a $\delta^{13}C$ depleted carbon dioxide product and enriched calcite. Aquifer palaeorecharge from Baltic Ice Lake became evident only locally near buried valleys on the coastal area of the Gulf of Finland, while ice meltwater $\delta^{18}O$ values extended up to –25 or –35‰ and $\delta^{13}C$ values were about –7‰. Most likely on the territory of Estonian Homocline there existed a hydraulically close connection via the Cambrian-Vendian aquifer between talik systems of the Gulf of Riga and the Gulf of Finland, what had an influence on groundwater recharge by isotopically depleted water. This northward flow direction could be favourable, because the surface falls towards the ice sheet in the Bothnian area.

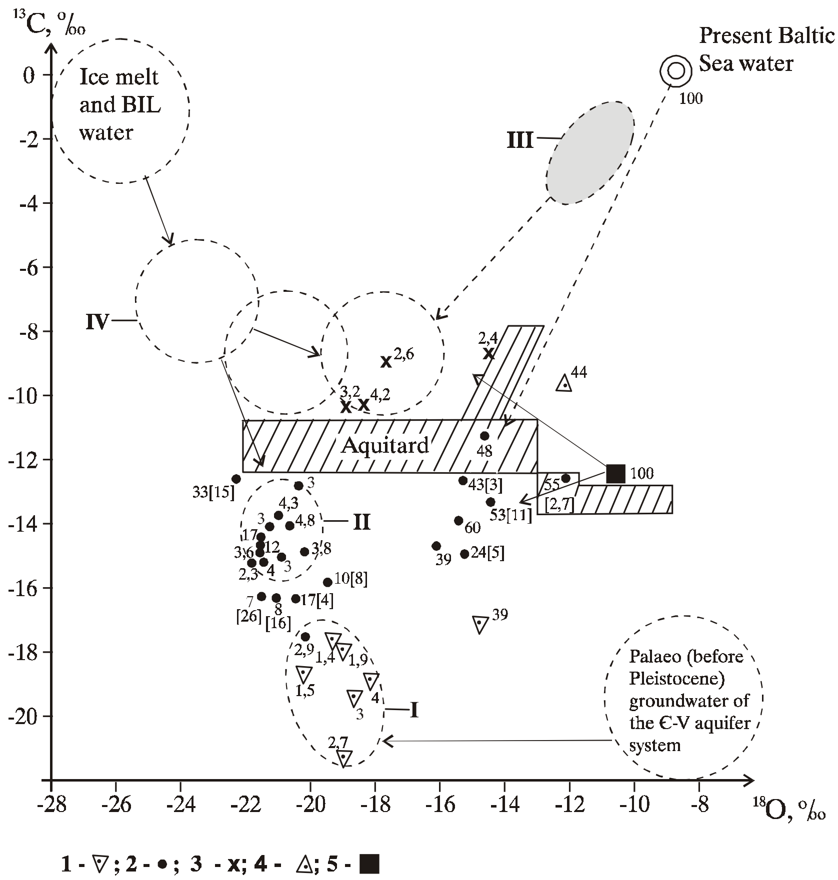

Fig. 6. Oxygen-18 and Carbon-13 diagram of Estonian groundwater. Samples of: *1* – Gdov aquifer; *2* – Cambrian-Vendian aquifer system; *3* – Ordovician-Cambrian aquifer system; *4* – Ordovician aquifer; *5* – shallow modern groundwater. Numbers by samples – Carbon-14 content, %; in brackets – Uranium-234 and Uranium-238 ratio. Plot numbers: I – Cambrian-Vendian palaeogroundwaters recharged during Huneborg-Denekamp and later mixed with the Late Weichselian ice meltwater; II – Cambrian-Vendian groundwaters mixed with the BIL lacustrine water through buried valleys; III – water of palaeo Baltic Sea stages during Holocene; IV – Ordovician-Cambrian groundwater recharged during Huneborg-Denekamp and later mixed with Late Weichselian ice melted waters, also meteoric

6 pav. Požeminio vandens deguonies-18 ir anglies-13 izotopų pasiskirstymo diagrama Estijoje. Mėginiai paimti iš: *1* – Gdovo vandeningo horizonto; *2* – kambro–vendo vandeningo komplekso; *3* – ordoviko–kambro vandeningo komplekso; *4* – ordoviko vandeningo horizonto; *5* – gruntinio vandeningo horizonto. Skaičiai prie mėginių – anglies-14 koncentracija %; laužtiniuose skliaustuose – urano-234 ir urano-238 santykis. Išskirtų plotų numeriai: I – kambro–vendo komplekso požeminis vanduo, susiformavęs Huneborgo–Denekampo laikotarpiu ir vėliau susimaišęs su Vėlyvojo Nemuno stadijos ledo tirpsmo vandeniu; II – kambro–vendo komplekso požeminis vanduo, susiformavęs per paleoslėnius maišantis su Baltijos ledyninio ežero vandeniu; III – Baltijos jūros holoceno vanduo; IV – ordoviko–kambro komplekso požeminis vanduo, susiformavęs Huneborgo–Denekampo laikotarpiu ir vėliau susimaišęs su vėlyvojo Nemuno stadijos ledo tirpsmo bei meteogeniniu vandeniu

The degradation of permafrost zones, which began since the retreating of the Late Weichselian Ice sheet in the Baltic region, led to a further mixing of different recharge portions and to a discharge of aquifers with isotopically traced groundwater. During the Pandivere recessional phase, a highly pressed meltwater flow beneath the ice determined the maximum subglacial recharge to the aquifer (Fig. 8). Preliminary simulations using the MODFLOW and MT3D codes confirm this glacial forcing. Computation was employed to solve the finite difference approximations of the unsteady flow equations for 11 aquifers and aquitards. The cell raster dimension was 25 km to 25 km. At the aquifer boundaries on the northern part of the model, the potentiometric surface was modelled by presuming that the head valu-

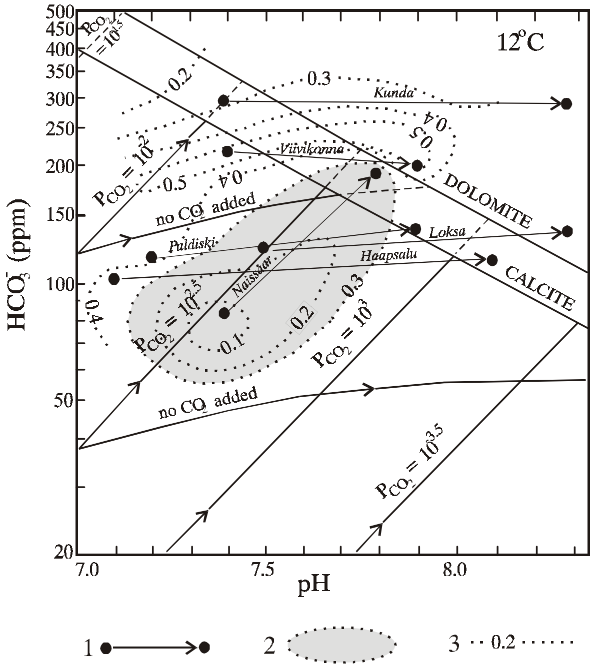

Fig. 7. Cambrian-Vendian aquifer system groundwater composition equilibrium with calcite and dolomite in open and closed systems with respect to CO_2. *1* – groundwater composition change direction in observation well during 1960–1975; *2* – subglacial melted water plot; *3* – isolines of groundwater mineralization, g/l

7 pav. Kambro–vendo komplekso požeminio vandens pusiausvyros su kalcitu ir dolomitu diagrama priklausomai nuo CO_2 parcialinio slėgio (uždara arba atvira sistema). *1* – požeminio vandens sudėties pokyčio kryptis stebimajame gręžinyje 1960–1975 m.; *2* – amžinojo įšalo paveikto požeminio vandens zona; *3* – požeminio vandens mineralizacijos izolinija g/l

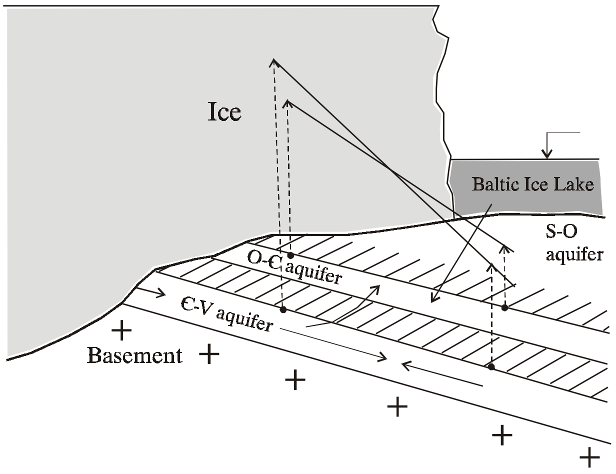

Fig. 8. Principle scheme of groundwater flow formation during ice sheet recession

8 pav. Požeminio nuotėkio principinė schema ledyno recesijos metu

es equal 60% of ice thickness. The initial ice meltwater $\delta^{18}O$ values were prescribed as –35‰. The modelling was done for unsteady state conditions from the Late Weichseilian glaciation recession state (Pandivere phase) until the present. In the model case, meltwater driven out from beneath the ice sheet continues to flow through all aquifers to the depth of 450 m under a potential gradient. The discharge zone was found to be in southern Estonia. The simulated maximum retreating ice pressure on, the western and northern boundaries of Estonian Homocline was presented from 1 to 0.6 km, and at ice margins close to southern Estonia the sub-surface pressure was distributed similarly as today. The integrated groundwater velocities driven by these heads in the aquifer are shown in Figs. 9 and 10.

In the Cambrian-Vendian aquifer, diffusion-dispersion and mixing of subglacially recharged and residual groundwater of cryogenic metamorphism and laterally transported old deep groundwater with sodium chloride salinity could also be expressed. These changes were still active in the Holocene period, when the isostatic rise of the territory continued, resulting in a stadial evolution of the Baltic Sea to the present contour of its extension.

The suggested approach was initiated and in future will be examined in detail by a reconstruction of groundwater flow in the aquifers overpressured by the last ice sheet and exposed to the consequen-

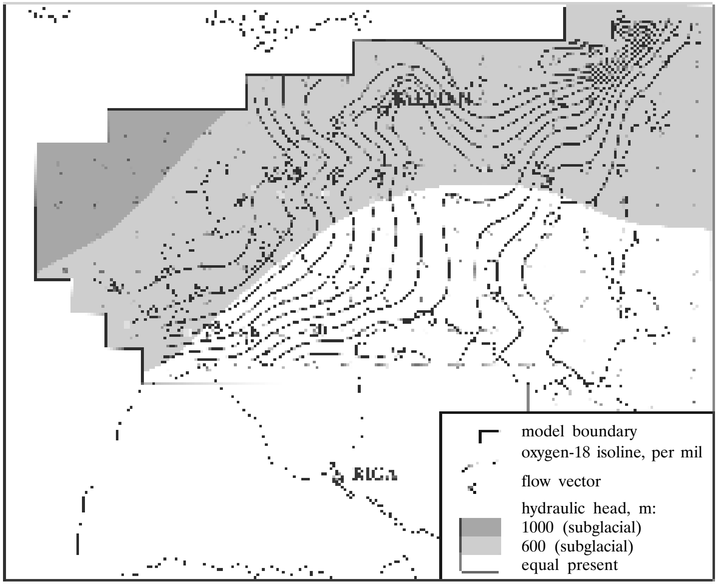

Fig. 9. MT3D model of oxygen-18 distribution in the Cambrian-Vendian aquifer 12 ka BP

9 pav. Deguonies-18 izotopo pasiskirstymo kambro–vendo vandeningame komplekse prieš 12 tūkst. metų 3D modelis

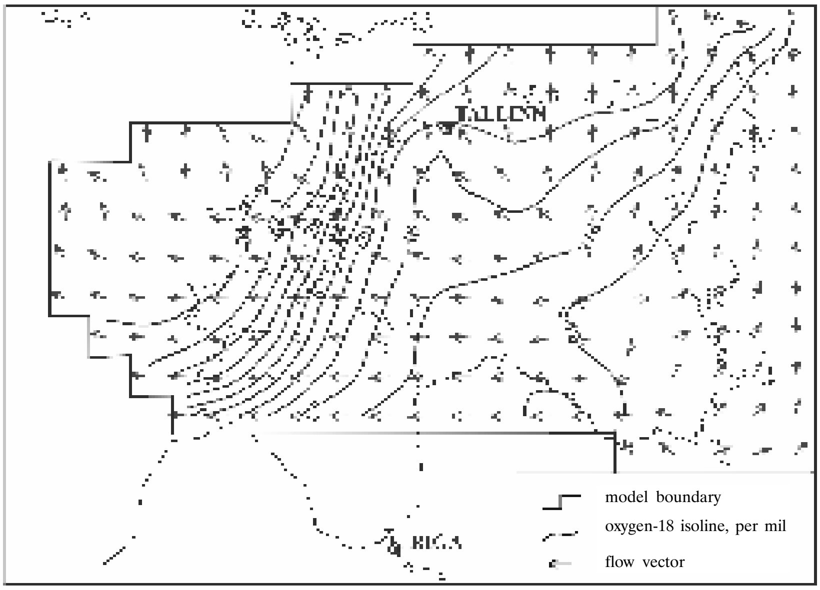

Fig. 10. MT3D model of oxygen-18 distribution in the Cambrian-Vendian aquifer at present
10 pav. Deguonies-18 izotopo pasiskirstymo kambro–vendo vandeningame komplekse šiuolaikinis 3D modelis

ces of deglaciation (isostatic rise, changes in hydraulic gradients and flow rates, reversal regional flow directions, etc.), basing on numerical modelling.

CONCLUSION

The Late Glacial permafrost environments and ice cover retreating in the Baltic territory had a significant influence on the formation of the groundwater isotope composition. Much evidence support the hypothesis that the permafrost phenomenon which led to water circulation processes into aquifers from surface water and from subglacial meltwater through talik zones as well as areal palaeorecharge during retreating phases took place here.

In future, detailed modelling studies are still needed to establish the model of groundwater formation in the Baltic region during the Late Pleistocene and Holocene.

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Robertas Mokrikas, Jonas Mažeika

BALTIJOS BASEINO POŽEMINIO VANDENS MITYBOS SĄLYGŲ PALEOHIDROGEOLOGINĖ REKONSTRUKCIJA PASKUTINIOJO APLEDĖJIMO LAIKOTARPIU

Santrauka

Egzistuoja kelios požeminio vandens su nedidele deguonies-18 izotopo koncentracija Estijos monoklinoje kilmės hipotezės. Tokio tipo požeminis vanduo aptinkamas ir Latvijos, Lietuvos pajūryje bei Vidurio Lietuvos žemumoje. Aktyvios apykaitos zonoje deguonies-18 stabilaus izotopo reikšmės kinta nuo –7,7 iki –13,9‰. Be to, ganėtinai mažos šio izotopo reikšmės (nuo –18 iki –22,5‰) nustatytos kambro–vendo vandeningame komplekse Estijoje. Šiek tiek mažesnės izotopo koncentracijos požeminis vanduo aptinkamas ir ordoviko–kambro vandeningame komplekse. Lengvos izotopinės sudėties požeminis vanduo Estijos teritorijoje slūgso iki 450 m gylio. Tačiau panašiame gylyje Gotlando saloje Švedijoje paplitusio požeminio vandens sudėtyje minėto izotopo koncentracija padidėja iki –5,7 ÷ –6,1‰. Tokia kaiti požeminio vandens sudėtis paaiškinama skirtingais jo formavimosi procesais paskutinės Nemuno apledėjimo stadijos metu: amžino įšalo procesai, talikinių zonų poveikis bei ledyno tirpsmo vandens mityba.

Radioaktyvios anglies koncentracija parodo, kad maišymesi su ledyno tirpsmo vandeniu dalyvavo iki paskutiniojo apledėjimo susiformavęs požeminis vanduo.

Роберт Мокрик, Йонас Мажейка

ПАЛЕОГИДРОГЕОЛОГИЧЕСКАЯ РЕКОНСТРУКЦИЯ УСЛОВИЙ ПИТАНИЯ ПОДЗЕМНЫХ ВОД БАЛТИЙСКОГО БАССЕЙНА В ПЕРИОД ПОСЛЕДНЕГО ОЛЕДЕНЕНИЯ

Резюме

Существует несколько гипотез о происхождении подземных вод с низкими концентрациями изотопа кислород-18 на Эстонской моноклинали. Следы с пониженными концентрациями указанного изотопа обнаружены также в подземных водах Балтийского побережья Латвии, Литвы и на Среднелитовской низменности. В целом в зоне активного водообмена значения изотопа кислород-18 варьируют в пределах от –7,7 до –13,9 промилле. Кроме того, весьма низкие его значения (от –18 до –22,5 промилле) установлены в кембро-вендском водоносном комплексе на территории Эстонии. Там же в ордовикско-кембрийском водоносном комплексе значения данного изотопа на несколько промилле выше. Мощность зоны распространения подземных вод облегченного изотопного состава достигает 450 м. Однако на таких же глубинах на о. Готланд (Швеция) распространены подземные воды со значениями концентрации кислорода-18 от –5,7 до –6,1 промилле. Столь неоднородный состав подземных вод по содержанию стабильного изотопа кислород-18 объясним различными процессами при их формировании во время последней стадии Валдайского оледенения: распространением вечной мерзлоты, наличием таликовых зон питания и смешением подземных вод с талыми ледниковыми водами. Данные радиоуглеродных определений в подземных водах свидетельствуют о том, что в процессе смешения участвовали подземные воды допозднеледникового времени.