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Aqueous geochemistry of the Cambrian–Vendian aquifer system in the Tallinn intake, northern Estonia

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Identification of seawater intrusion is based on intake observation results in the groundwater chemistry and isotopes. Indications of the saline front of marine origin can be obtained from the cation exchange process which is reflected in the groundwater chemical composition by Ca–Cl and Na–HCO$_3$ types of groundwater. The Na–Ca exchange evidences are accompanied by sulfate reduction reaction, dissolution and deposition of carbonates, which are also confirmed by the distribution and evolution of content of stable and radioisotopes in the groundwater of the Cambrian–Vendian aquifer system on the Tallinn intake, northern Estonia.

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INTRODUCTION

As a result of intensive exploitation, a vast depression cone exceeding 100 km has formed at the Tallinn intake situated in the coastal area of northern Estonia. The lowest altitude of the potentiometric level (more than 30 metres b.s.l) is concentrated at the intake center. In 1977, by observation wells of the Tallinn intake, a fast increase in total dissolved solids (TDS) was detected. Chemical and isotopic data indicated that many factors control the rise in groundwater salinity. The resources of coastal groundwater of the Cambrian–Vendian aquifer system are limited and consist mainly of natural reserves formed during the last glaciation. The long-time over-exploitation of the Tallinn intake resulted in salinization not only in the Cambrian–Vendian sandstones but also in the basement water, which kept brackish groundwater because of seawater intrusion. The salinity in the Tallinn intake had been discussed earlier by many authors, but the seawater intrusion was never assessed from the point of view of cation exchange processes formed by Ca–Cl and Na–HCO$_3$ types of groundwater. Based on hydrochemical and isotopic data, it is concluded that the recent seawater intrusion into the aquifer system previously palaeorecharged by glacial water is generally accompanied by ion exchange which caused the present fresh and saline groundwater distribution in the Tallinn intake (northern Estonia).

Increased salinity since 1977 has been observed in many wells drilled into the Cambrian–Vendian aquifer system at Kopli Peninsula site of the Tallinn intake. In earlier studies, several attempts have been made to determine the origin of salinization. One opinion is that salinization is attributed to many sources, such as brackish groundwater upcoming from the basement and seawater intrusion (Mokrik et al., 1987). According others, the detectable intrusion of modern seawater into the aquifer system should be ruled out (Savitski and Belkina, 1985; Yezhova et al., 1996; Karro et al., 2004). Thus, the origin of fresh groundwater in the Cambrian–Vendian aquifer system as well as the brackish basement water is not clear.

METHODS AND PURPOSE

The basic approach of the study was to collect and analyze previously published reports and articles and to use the new interpretative data on groundwater chemistry to define their origin and assess the human impact on water geochemistry in the Tallinn intake. All these data were incorporated into water chemistry database analysis to draw up a more comprehensive vision of groundwater formation and to provide an improved estimate to a qualitative analysis within the aquifers and between the flow system boundaries. The objectives of the Cambrian–Vendian aquifer system study were: (1) to delineate the extent of fresh to saline water in the various hydrogeological units and in basement rocks, (2) to analyze the human impact on groundwater chemistry and on the flow system in the coastal intake, and (3) to assess the current groundwater isotope distribution and to identify the trends of these changes.

Equilibrium thermodynamics of groundwater was interpreted using the PHREEQUE Interactive 2.8 computer code program which calculates mineral saturation states for an aqueous solution by the chemical analysis and physical parameters relative to carbonate minerals and other species.

DISCUSSION

Problems and objectives

In 1977–1978, hydrochemical observations of groundwater in Kopli Peninsula on the Tallinn intake fixed an increase in water salinity (Fig. 1). Here groundwater contained higher concentrations of TDS, chloride, sulfate, sodium, calcium and other constituents relative to the area farther from the coast line and buried valleys. In the other sites, the background chloride concentration of fresh groundwater was about 20–150 mg/l. The most intensive growing of TDS was observed in the Kopli site boreholes 632 and 625, where it reached up to 1.1 g/l at a growth rate 16–70 mg/l per year. In the basement borehole 798, chloride content in 1995–2004 has been growing more rapidly (from 826 to 2367 mg/l). Seawater percolation occurs through the buried valleys, which are largely developed on the coastal and seaside submarine parts and connected with the sea hydraulically. It is difficult to identify sea water intrusion here, because many chemical types of water spread and the isotopic homogeneity is disturbed. Salinization of aquifers is a result of fresh and seawater mixing and is coupled with the ion exchange process. The water–rock interaction processes are often masked by salinization in the boreholes set-
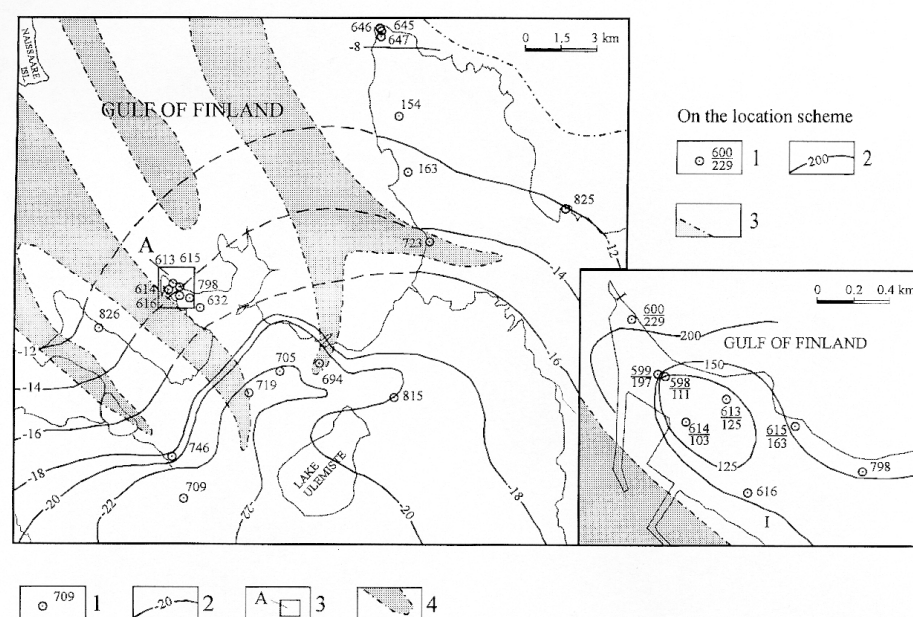
Fig. 1. Map of the study area long Tallin intake, northern Estonia.
1 – observation borehole; *2* – potentiometric contour, m b.s.l.; *3* – location scheme of the Kopli Peninsula; *4* – contour of the buried valley. On the location scheme: *1* – observation borehole, numerator – number of the well, denominator – Cl/Br ratio; *2* – Cl/Br contour; *3* – boundary of the buried valley

1 pav. Talino vandenvietės (Điaurės Estija) tirtø plotø schema:
1 – stebėjimo græþinys, *2* – pjezometrinis paviršius, *3* – Kopli pusiasalio schema, *4* – paleoárёþis. Kopli pusiasalio schemos sutartiniai þenklai: *1* – stebėjimo græþinio ёminys; skaitiklyje – gręþinio numeris, vardiklyje – Cl/Br santykis; *2* – Cl/Br santykio izolinija; *3* – paleoárёþis

ting up to the basal level of aquifers. Previous studies on the ground of the stable isotopes and Br/Cl ratios have shown that groundwater salinity in the Tallinn intake is influenced only by basement water and has no relation with the seawater intrusion process (Savitski and Belkina 1985; Yezhova et al., 1996; Karro et al., 2004). Another opinion is that the seawater intrusion has influenced the salinity increase (Gregorauskas et al., 1988; Mokrik, 1997). The latter opinion was based on the observation of changes of the characteristic coefficient $SO_4^{2-} + Mg^{2+}/ Cl^-$. This coefficient value in the Gulf of Finland water equals to $3 \cdot 10^{-1}$, in the fresh groundwater of the Cambrian–Vendian aquifer system on Kopli Peninsula site from $2 \cdot 10^{-1}$ to $2.5 \cdot 10^{-1}$, and in the basement water ranges between $5 \cdot 10^{-2} – 1.5 \cdot 10^{-1}$. If on the investigated site there is a suction of seawater salinity, the values of the characteristic coefficient must increase by seawater intrusion, together with growth in groundwater TDS values. And *vice versa*, if there is a suction of saline water from the crystalline basement, together with the increase in groundwater TDS its value will decrease.

The low ^{14}C concentration (below 3–4 pmC) could suggest that the age of groundwater corrected by ^{13}C is about 26–34 ka BP, indicating that a recharge because of the cold climate conditions took place before the Late Weichselian, during the Denekamp Interstadial time, when the Estonian territory was not covered by the Late Weichselian ice sheet. A model of palaeorecharge formed during the Denekamp 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 also proposed (Mokrik, 1997). Based on the stable isotope data and noble gas analyses, a tunnel valley subglacial drainage hypothesis was built up (Vaikmäe et al., 2001). A more extended model embraces subpermafrost communication within aquifers with the isotopically depleted surface waters through the talik zones before the Last Glacial period, taking into account also later total effects of subglacial recharge after glacier degradation, Baltic Ice Lake (BIL) influence, the Baltic Sea water intrusion and modern meteoric recharge in the terrestrial part of the Baltic artesian basin. This model was firstly analyzed by Mokrik and Maþeika (2002). As follows from the above, the generally accepted model of groundwater formation in the Cambrian–Vendian aquifer system is complicated and requires further elaboration.

Seawater intrusion identification

Our new re-interpretation of the chemical-isotopic data confirmed that seawater intrusion took place here, because two types of groundwater, $Na–HCO_3$ and $Ca–Cl$, are predominant. If seawat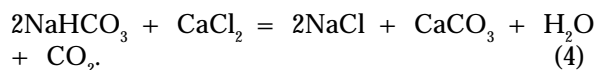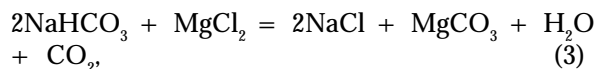er intrudes to the fresh groundwater aquifer, Na^+ ions will be exchanged against Ca^{2+} ions adsorbed on the clays and, *vice versa*, the reverse process takes place with refreshening, when fresh water flushes in saline seawater (Appelo, Geirnaert, 1983; Appelo, Postma, 1993). As a result of the sea and fresh water mixing process via Na–Ca cation exchange reaction, seawater becomes saline of Ca-Cl type and fresh water of $Na–HCO_3$ type. When $Ca–HCO_3$ type groundwater mixes with Na–Cl type water, the calcite dissolution is driven by subsaturation due to loss of Ca^{2+} from solution and formation of $NaHCO_3$ and $CaCl_2$ type groundwater (Appelo, Postma 1993):

$$2NaCl + Ca(HCO_3)_2 = 2NaHCO_3 + CaCl_2. \quad (1)$$
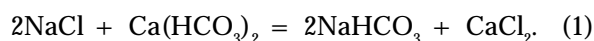
In the $Na–HCO_3$ type groundwater, characteristic is an increase of HCO_3^-, when water pH becomes high because of the evident carbonate dilution process. The Ca–Cl type water is the result of carbonate precipitation driven by enrichment of solution after cation exchange. Dissolution of carbonates moves the mixture on the Piper diamond towards the $Na^+ + K^+ – HCO_3^-$ and $Ca^{2+} + Mg^{2+} – HCO_3^-$ corners. At the beginning of Na–Ca cation exchange intensities resulted increase in the Ca^{2+} content and that effects a lowering of pH and solution due to subsaturated with respect to dolomite and calcite, which move the changes in groundwater chemistry into $SO_4^{2-} + Cl^-$ and $Ca^{2+} + Mg^{2+}$ corner. In this case, deposition of carbonates prevails:

$$MgCl_2 + Ca(HCO_3)_2 = CaCl_2 + CaMg(CO_3)_2 + 2H_2O + 2CO_2. \quad (2)$$
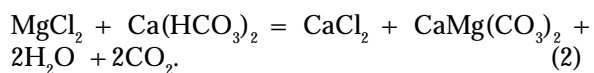
When sodium type groundwater conservatively mixed with Mg–Cl or Ca–Cl types seawater, a Na–Cl type residual solution with a tendency to enrichment by carbonates will be obtained:

$$2NaHCO_3 + MgCl_2 = 2NaCl + MgCO_3 + H_2O + CO_2, \quad (3)$$

$$2NaHCO_3 + CaCl_2 = 2NaCl + CaCO_3 + H_2O + CO_2. \quad (4)$$

The wedges of seawater intrusion in conditions of aquifer reduction coincided to first into sulfate reduction process by the reaction:

$$SO_4^{2-} + 2CH_2O = H_2S + 2HCO_3^-. \quad (5)$$
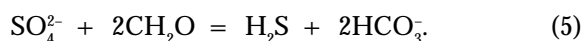
This reaction moved groundwater chemical composition from a conservative mixing line between fresh and saline seawater with parallel shift towards the $SO_4^{2-} + Cl^-$ side on the Piper diamond plot.

The content of ions in groundwater at the Tallinn intake sites is very variable; the dominant anions are HCO_3^- and Cl^- and the dominant cations are Na^+
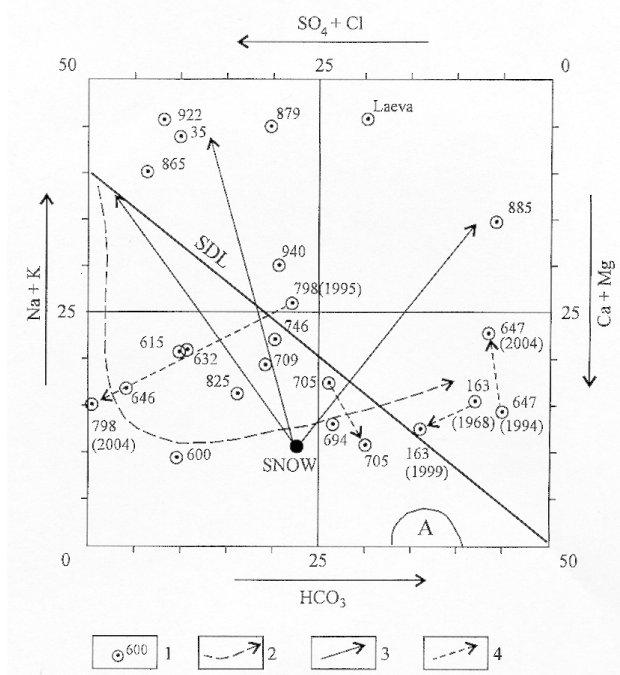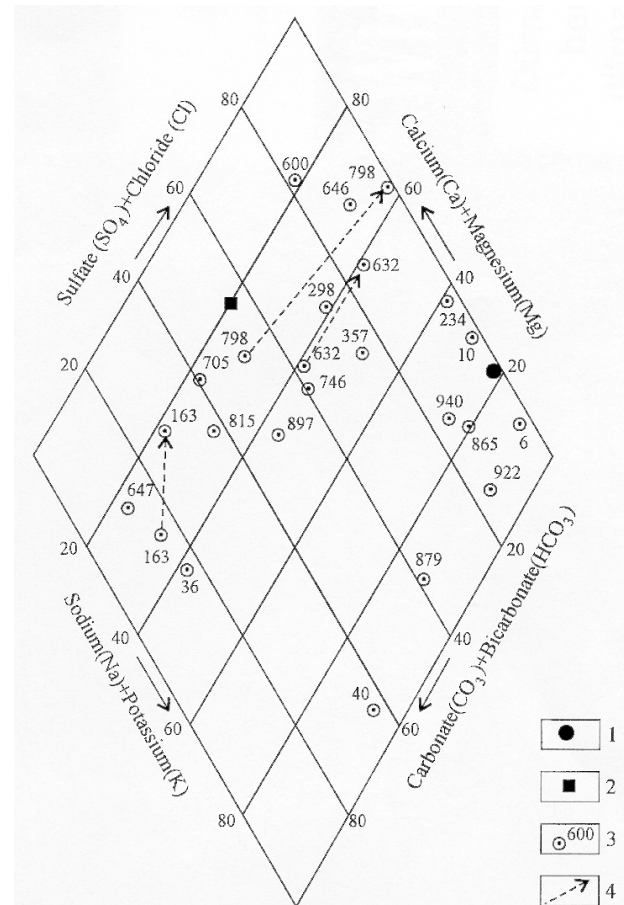
Fig. 2. Chebotarev diagram of the major chemical compounds in the Cambrian–Vendian aquifer system.
1 – borehole number; *2* – seawater intrusion direction; *3* – dilution direction; *4* – change direction of chemical composition; A – groundwater of glacial deposits in buried paleovalley
2 pav. Kambro–vendo vandeningo komplekso poþeminio vandens cheminiø komponentø pasiskirstymas Èebotariovo diagramoje:
1 – græþinio numeris, *2* – jûros intruzijos átakos trendas, *3* – ledyno tirpsmo vandens átakos trendas, *4* – cheminës sudëties pokyèio kryptis; A – paleoáréþiø glacialiniø nuogulø vanduo

Fig. 3. Piper diagram
1 – seawater; *2* – snow water; *3* – borehole samples; *4* – direction of changes in groundwater chemistry
3 pav. Piperio diagrama:
1 – jûrinis vanduo, *2* – sniego tirpsmo vanduo, *3* – ëminys, *4* – poþeminio vandens cheminës sudëties pokyèio trendas

and Ca^{2+}. Groundwater affected by seawater intrusion by the salinity is generally Ca–Cl type, at the same time the SO_4^{2-} content is depleted, because a sulfate reduction is normally decreased if chloride concentration grows. Only periodically in many boreholes (613, 615, 645, 694 etc) a rise in SO_4^{2-} up to 154 mg/l was fixed. Magnesium content on average is also low (10–16 mg/l), except in seawater intrusion places where it rises up to 40–60 mg/l. The main seawater intrusion chemical parameters in boreholes could be calcium, sodium, magnesium chloride and sulfate. After Karro et al. (2004), calcium and potassium levels are high in groundwater, magnesium lies close to the seawater dilution line (SDL), and sodium is depleted with respect to chloride in the production wells. They conclude that this reflects derivation from the weathering of the crystalline basement and is not related with seawater intrusion. The increase in calcium, according to those authors, is attributed to anorthite hydrolysis during its change into kaolinite, when into solution more Ca^{2+} is released. Similarly, they claim

that sodium results from plagioclase alteration, and it is possible that it is later adsorbed on clay minerals (Karro et al., 2004). However, the dominant clay mineral in the Cambian–Vendian section is illite, followed by quartz and K-feldspar (Mokrik et al., 2000). Our chemical thermodynamics calculations, however, revealed that the groundwater on the seawater intrusion site in Kopli Peninsula belongs to the gibbsite, kaolinite, muscovite or seawater stability plots (Mokrik, 2003). The silica content in groundwater is low (mean, 4–11 mg/l) and indicates a weak dissolution of silicate minerals. Thus, plagioclase weathering cannot release many cations into solution. Evidence of sea water Na^+ exchange is taken up by the clays as the exchanger; Ca^{2+} is released into solution and thus changes the palaeorecharged fresh groundwater to a Ca–Cl type water. As an exchanger here act the clayey layers of the Lontova and Kotlin aquitards, also Quaternary clays in the buried valleys and the clayey weathering core of the crystalline basement. The Na–Ca cation exchange process is well displayed in the

diagrams (Figs. 2 and 3). In the Chebotariov diagram, the localities of boreholes 798, 646, 600, 613, 632, 154 are moved far away from the SDL where conservative fresh–saline sea water mixing takes place. The largest movement toward Ca–Cl type was found in the borehole 798, which recovered the basement rocks. Figure 4 shows that in 1995 in the borehole 798 groundwater an active sulfate reduction depleted the SO_4^{2-} content and a sharp increase in Cl^- ion concentration lowered the characteristic coefficient SO_4^{2-} + Mg^{2+}/Cl^-, but then followed a rise in its values, which rapidly changed the groundwater chemistry and moved the sample position in the diagram to the vicinity of Ca–Na–Cl type waters. In Fig. 4, the groundwater composition is represented by the characteristic coefficient SO_4^{2-} + Mg^{2+}/Cl^- relative to TDS, which shows an overall shift of the Cambrian–Vendian and Ordovician–Cambrian aquifer systems as compared to the SDL trend. This deviation from the SDL suggests that these groundwaters in general were formed by glacial water dilution into cryogenically metamorphosed water. The Pleistocene palaeodilution line is parallel to the SDL and is shifted in TDS towards

depletion in groundwater chemistry. In the subarea E are placed cryopegs of the Archangelsk District (boreholes 1, 2, 4, 6), which are of Na–Cl salinity cryogenic brines. In the subarea D groundwater of the northeastern part of Estonia is depleted in Ca^{2+} and Mg^{2+}. This Na–Cl–HCO_3 type groundwater may be a product of glacial dilution of cryogenic brines. Plotted on the subareas B and A groundwaters ions composition is more diluted palaeogroundwater solution and reflects also recent sea water intrusion effort, which evolve moving towards SDL in the water chemistry (boreholes 600, 615, 645, 234, 798, 646 etc). Therefore, Ca–Na–Cl and Na–Mg–Cl ionic compositions prevail. The highest placement relation to SO_4^{2-} + Mg^{2+}/Cl^- coefficient on the palaeodilution trend occur more fresh groundwater, which of Ca–MgvCl–HCO_3, Na–HCO_3 and Ca–HCO_3 chemical compositions were influenced by glacial water at the shallow depths and near the cutting Lontova aquitard buried valleys. Plot G in Fig. 4 shows that this Ca–Mg–HCO_3–Cl type groundwater is additionally recharged by modern meteoric water through buried valleys on the coast. All the other groundwaters in the Baltic Basin lie roughly on the SDL, except the Cretaceous and the Jurassic aquifer systems, where the Eemian Interstadial time sea transgression took place and the Holocene age meteoric water mixing in the western part of Lithuanian and Kaliningrad District lowlands. There occur of Na–HCO_3 type fresh groundwater facies and Ca^{2+} lies near the SDL with respect to Cl^- ions (Mokrik, 2003). Also, two subareas of groundwater chemistry facies in the Baltic Basin are shifted from the SDL to the right: the first of them is placed in the plot I, where SO_4^{2-} rich groundwater is spread, and the second – in plots C and F of Na–Ca–Cl and Ca–Cl type brines occurring at the deepest part of the Baltic and Moscow basins. Thus, the analyzed groundwater chemical composition allows to conclude that in formation of aquifer systems took place not only glacial water, but also permafrost-originated cryopegs and their diluted species.

In the Piper diagram, Ca–Cl type groundwater is placed in the area of the diamond shape where SO_4^{2-} + Cl^- as
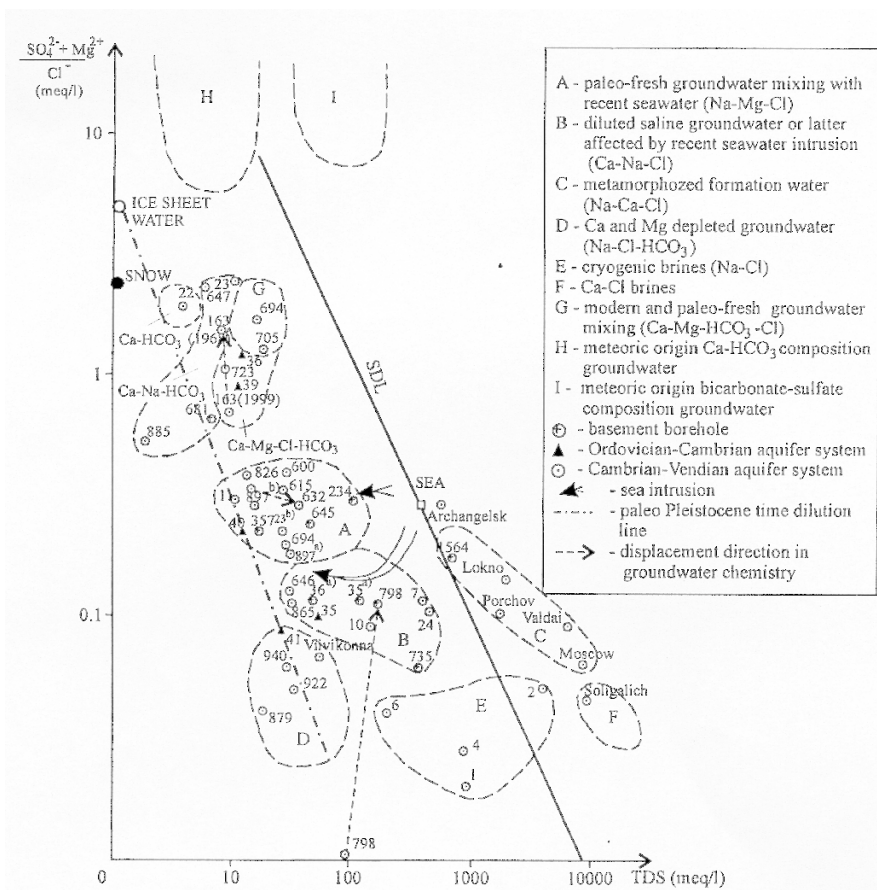

Fig. 4. Characteristic coefficient $\dfrac{SO_4^{2-} + Mg^{2+}}{Cl^-}$ *versus* TDS diagram

4 pav. Charakteringo koeficiento SO_4^{2-} + Mg^{2+}/Cl^- ir bendrosios mineralizacijos pasiskirstymo diagrama

well Ca^{2+} + Mg^{2+} range between 70–90% and are replenished by seawater intrusion tongues. Chemical analyses of these boreholes reflect Na^+ and Ca^{2+} ion exchange between seawater and clays. Characteristic are changes in the borehole 798 water chemistry, as in 1995, by SO_4^{2-} reduction, bicarbonates and CO_2 aggressive to carbonates were actively produced. At that time the locality of this borehole sample was found in a plot where SO_4^{2-} + Cl^- and Ca^{2+} + Mg^{2+} ranged within 50–70%. Intensive seawater penetration in the same borehole followed later, up since, efficacious formation of Ca–Cl salinity and carbonates precipitation. Carbonate deposition is followed by a fall in pH (3–6) and bicarbonate concentration (9–18 mg/l). Such manifestation occurs in many boreholes, *e.g.*, in borehole 646. All in all, a huge deviation from SDL to the direction of Ca–Cl type groundwater is characteristic if the seawater intrusion front is manifested more actively (boreholes 798, 646, 613, 645, 632, 825, 600, 154, 616).

The geochemistry of the Cambrian–Vendian aquifer system groundwater is not expected to be the same in each location, because the chemical composition of mixed recharge water is different. The Na–HCO_3 type groundwater is displaced in the lower part of the Piper diamond shape, indicating that the aquifer system was subjected to the interstadial time seawater and palaeorecharged water mixing process (boreholes 647, 163, 36, 40), and some of these are now via buried valleys on the coastal part in re-freshening position (borehole 705). However, the chemical composition change in the borehole 163 shows that the influence of recent seawater has moved its location towards the SO_4^{2-} + Cl^- side on the Piper diagram, *i.e.* toward a conservative mixing model. Na–HCO_3 type background groundwater originated from the Pleistocene, when the re-freshening mixing of glaciogenic and saline interstadial groundwater of the Cambrian–Vendian aquifer system occurred (Mokrik, 2003). To the modern recharge direction has evolved the groundwater chemistry in the borehole 705 (Figs. 2 and 4). Consequently, chemical changes in boreholes 163 and 705 evidence the recent and interstadial time seawater, also meteoric water influence relative to palaeorecharged groundwaters. Thus, the chemical composition in the borehole 705 has moved to the direction of the present day meteoric water composition. Different residence times of groundwater within the aquifer system hold the key to distinguishing among their origin. The background ^{14}C concentrations in the aquifer system are in the range 2.5–5 pmC, but in areas of the modern meteoric recharge their values grow up to 60 pmC, like in the borehole 705. The highest influence of seawater intrusion into palaeorecharged groundwater, evaluated by ^{14}C, is manifested in boreholes 646 (12.76 pmC), 746 and 815 (about 16.7 pmC) and 298 (33.6 pmC). Also maintain the Br^- content rise in tendency to-

ward the SDL relative to basement water on the Kopli site of the Tallinn intake (Fig. 5). The relation between chloride and bromide in the of water samples of boreholes 600 and 599 is equal to the relation found in the seawater dilution line. However, in samples 614, 598 this relation is close to the basement water dilution trend. Other samples (boreholes 615 and 613) are residual between the basement and seawater lineaments and have a tendency to move towards the recent seawater dilution line.
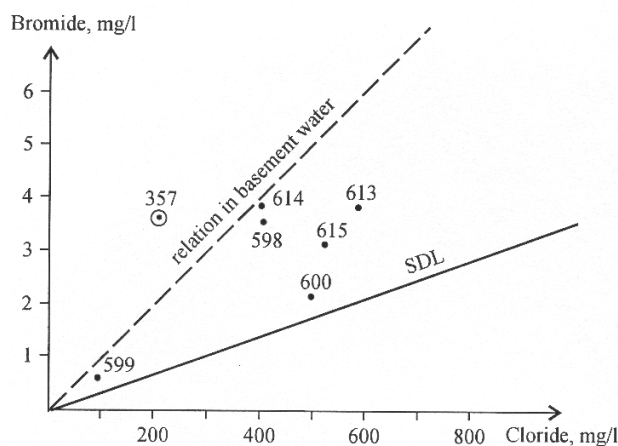

Fig. 5. Br^- *versus* Cl^- diagram
5 pav. Bromo ir chloro jonø pasiskirstymo diagrama

CONCLUSIONS

In the Kopli site of the Tallinn intake, northern Estonia, a clear manifestation of seawater intrusion has been found. Salinization through seawater intrusion and conversely re-freshening during the Late Weichselian of aquifers are accompanied by cation exchange and palaeorecharge processes in which Ca–Cl and Na–HCO_3 types of water are formed. On salinization, the deposition of carbonates is mostly prevented by sulfate reduction. In the case of a faster salinization, carbonate deposition took place, because sulfate reduction was depleted. At the re-freshened part of the aquifer system where modern meteoric water leakage from the buried valleys prevails, the reverse process occurs when groundwater changes into Na–HCO_3 and Ca–HCO_3 types. The re-freshening reactions are accompanied by a decrease of calcium and magnesium contents and lead to a renewed dissolution of carbonates.

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KAMBRO–VENDO KOMPLEKSO POÞEMINIO VANDENS GEOCHEMIJA TALINO VANDENVIETËJE (ÐIAURËS ESTIJA)

S a n t r a u k a

Per pastaruosius ðeðiasdeðimt metø intensyviai eksploatuojant poþeminá vandená Talino vandenvietëje prieð penkiolika metø ëmë reikðtis jûrinio vandens intruzija. Dël katijonø mainø su ekranuojanèiais moliais vietomis formavosi didesnës mineralizacijos kalcio jonø turtingas vanduo. Kambro–vendo vandeningo komplekso poþeminio vandens cheminës sudëties analizë patvirtino, jog Talino vandenvietëje, priklausanèioje Vakarø Estijos monoklinai, dël jûros vandens intruzijos didëjant mineralizacijai formuojasi kalcio choridinis vandens tipas. Rytø Estijos monoklinoje, kur jûrinio vandens skverbimosi á sausumà nenustatyta, vyrauja natrio hidrokarbonatinis ir natrio chloridinis poþeminis vanduo. Talino vandenvietëje, Kopli pusiasalyje (Ðiaurës Estija), nustatytos ryðkios jûros intruzijos apraiðkos. Formuojantis sûriam poþeminiam vandeniui vyksta aktyvûs Na-Ca katijonø mainai ir sulfatø redukcija, kuriø metø vanduo prisotinamas karbonatais. Padidëjus chloro jonø koncentracijai ir silpnëjant sulfatø redukcijai ið poþeminio vandens tirpalo iðsiskiria kalcitas ir dolomitas, suaktyvëja vandenilio jonai ir iki minimumo sumaþëja hidrokarbonatø koncentracija. Intruzijos metu poþeminio kalcio chloridinio vandens susidarymà lemia prisotinimas karbonatais, o natrio hidrokarbonatinio, kuris susiformavo Pleistoceno pabaigoje, prieðingai – karbonatinio cemento tirpinimas.

Ðîáåðò Ìîêðèê, Ëåõòå Ñàâèöêàÿ, Ëåîíèä Ñàâèöêèé

ÃÅÎÕÈÌÈß ÏÎÄÇÅÌÍÛÕ ÂÎÄ ÊÅÌ ÁÐÎ-ÂÅÍÄÑÊÎ ÃÎ ÊÎÌ ÏËÅÊÑÀ ÒÀËËÈÍ ÑÊÎ ÃÎ ÂÎ ÄÎ ÇÀÁÎ ÐÀ (ÑÅÂÅÐÍ À ß ÝÑÒÎ Í Èß)

Ð à ç þ ì å

Çà ïîñëåäíèå 60 ëåò ýêñïëóàòàöèè ïîäçåìíûõ âîä íà Òàëëèíñêîì âîäîçàáîðå ïðîèçîøëî çàñîëåíèå, âûçâàííîå ïîñòóïëåíèåì ìîðñêèõ âîä. Â ïðîöåññå èíòðóçèè ìîðñêèõ âîä îáðàçîâàëèñü âîäû òèïà Ca-Cl è Na-HCO₃ òèïû ïîäçåìíûõ âîä çà ñ÷åò ïðîöåññîâ îáìåíà ìåæäó ïðåñíûõ è ñîëåíûõ âîä, êàòèîííîãî îáìåíà è ñóëüôàòðåäóêöèé. Â âîäîíîñíîì êîìïëåêñå îäíîðàçîâîì èäåò ì åñò êèê âûùåëà÷èâàíèå êàðáîíàòîâ ñ îáðàçîâàíèå Na-HCO₃ òèïà âîä, òàê è èõ âûïàäåíèå â îñàäîê (Ca-Cl âîäû). Ï îñëåäíèå îáðàçîâàëèñü â îñíîâíîì çà ñ÷åò ïðîöåññîâ êàòèîííîãî îáì åíà ñ ýêðàíèðóþùèì è ñåðóõ ãëèíàì è. Ôàêèé õìè÷åñêîãî ñîñòàâà ðàñïðåäåëåíû ñëåäóþùèì îáðàçîì: íà âîñòî÷íîé ýñòîíñêîé ìîíîêëèíàëè ðàñïðîñòðàíåíû Na-HCO₃ è Na-Cl, à íà çàïàäíîé ýñòîíñêîé ìîíîêëèíàëè – Ca-Cl, Na-HCO₃ è Ca–HCO₃ òèïû ïîäçåìíûõ âîä.