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HYDROGEOLOGICAL EVOLUTION OF THE UPPER CRETACEOUS ARTESIAN BASIN OF THE GDAŃSK REGION

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Abstract: The hydrogeological conditions of the artesian basin of the Gdańsk area are presented basing on the palaeohydrogeological studies. There were three successive hydrogeological cycles in the geological history of the analysed structure: the first – Albian to Montian, the second – Late Eocene to Early Miocene, and the third – Miocene up to the present. Each cycle consisted of a sedimentary stage with an elision hydrodynamic system and of an infiltrational one with a gravitational hydrodynamic system prevailing. The evolution of the groundwater chemistry is considered; especially the changes of a Cl–Na type of water of marine origin into meteoric groundwater of HCO_3–Na–Ca type. A number of geological processes which occurred in the basin in the past directly influence the present hydrodynamical conditions of the Cretaceous water-bearing strata.

Key words: artesian basin, groundwater circulation, groundwater evolution, Cretaceous, Peribaltic Depression, Gdańsk region.

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INTRODUCTION

In this paper an attempt is made to show the connection between phenomena occurring at present and processes which took place during the geological evolution of the investigated part of the Peribaltic Depression. The palaeohydrogeological analysis permits one to extrapolate hydrogeological parameters determined in isolated points in whole area of the basin (over 4000 km^2).

The data obtained from water wells and deep boreholes, drilled by the Geological Institute, have been utilized along with the published materials concerning the geology and hydrogeology of the northern part of Poland.

I would like to thank Doc. B. Kozerski and Doc. J. Dowgiałło for the discussion and critical remarks I received during the final elaboration of the results of my research, more comprehensively presented in my Ph.D. dissertation.

SKETCH OF THE GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

The artesian basin in the Gdańsk region is located in the southwestern part of the Peribaltic Depression. The water-bearing structure under consideration belongs to the Permian and Mesozoic sedimentary cover of the East European Platform. Its upper part was deposited during the Cretaceous transgression (Fig. 1). The Tertiary brown-coal bearing sediments and the Pleistocene fluvioglacial sediments, over 300 metres in thickness, are situated in the Kashubian Lake District. In the area of the Vistula River delta the Tertiary strata are strongly eroded whereas the Pleistocene and Holocene deltaic series are 80—100 metres thick. The top of the Upper Mesozoic strata is nearly flat and can be considered as situated approximately 100 metres below sea level. In the area under consideration, the sediments of the Albian to Maastrichtian age are differentiated in the vertical profile. In the borehole Sopot IG-1 (Płochniewski, 1974), the clayey and silty sediments of the Cenomanian and the Turonian, over 100 metres thick, overlie the Upper Jurassic strata. The succeeding fine-grained sands with glauconite represent the uppermost Turonian to the lower Campanian; their thickness is over 150 metres. Gaizes, siliceous limestones and marls of the Campanian, 60 metres thick, form here the youngest Cretaceous strata. The Mid-Polish Anticlinorum was finally formed during the end of the Mesozoic and at the beginning of the Cainozoic (Dadlez & Marek, 1969; Wagner *et al.*, 1980; Jaskowiak, 1966; Jaskowiak-Schoenaich & Pożaryski, 1979). This process influenced the facies differentiation of the Upper Cretaceous sediments. The Coniacian and Santonian sands wedge out in the eastern and southern parts of the Vistula River delta and along the Starogard Gdański—Kościerzyna—Bytów line. The sandy deposits of the Upper Cretaceous transgression do not occur within the Łeba Uplift (Jaskowiak, 1966).

The geological structure and the diversity of the topographic relief of the region under consideration resulted in formation of the basin with artesian conditions (Pazdro, 1958). The recharge zone of the water-bearing system includes the area of the Kashubian Lake District, where the mean altitude is approximately 200 m a.s.l. The discharge zone of the basin is located on the terrains of the Vistula delta, the Reda—Łeba marginal valley, the seaside terrace and the Gdańsk Bay. The head of the Cretaceous aquifer in the centre of the Kashubian Lake District attains 150 metres a.s.l., whereas within the Vistula delta it drops to approximately 5—10 m a.s.l. and at the latitude of the Hel Peninsula to the sea level (Sadurski, 1977). In the Gdańsk

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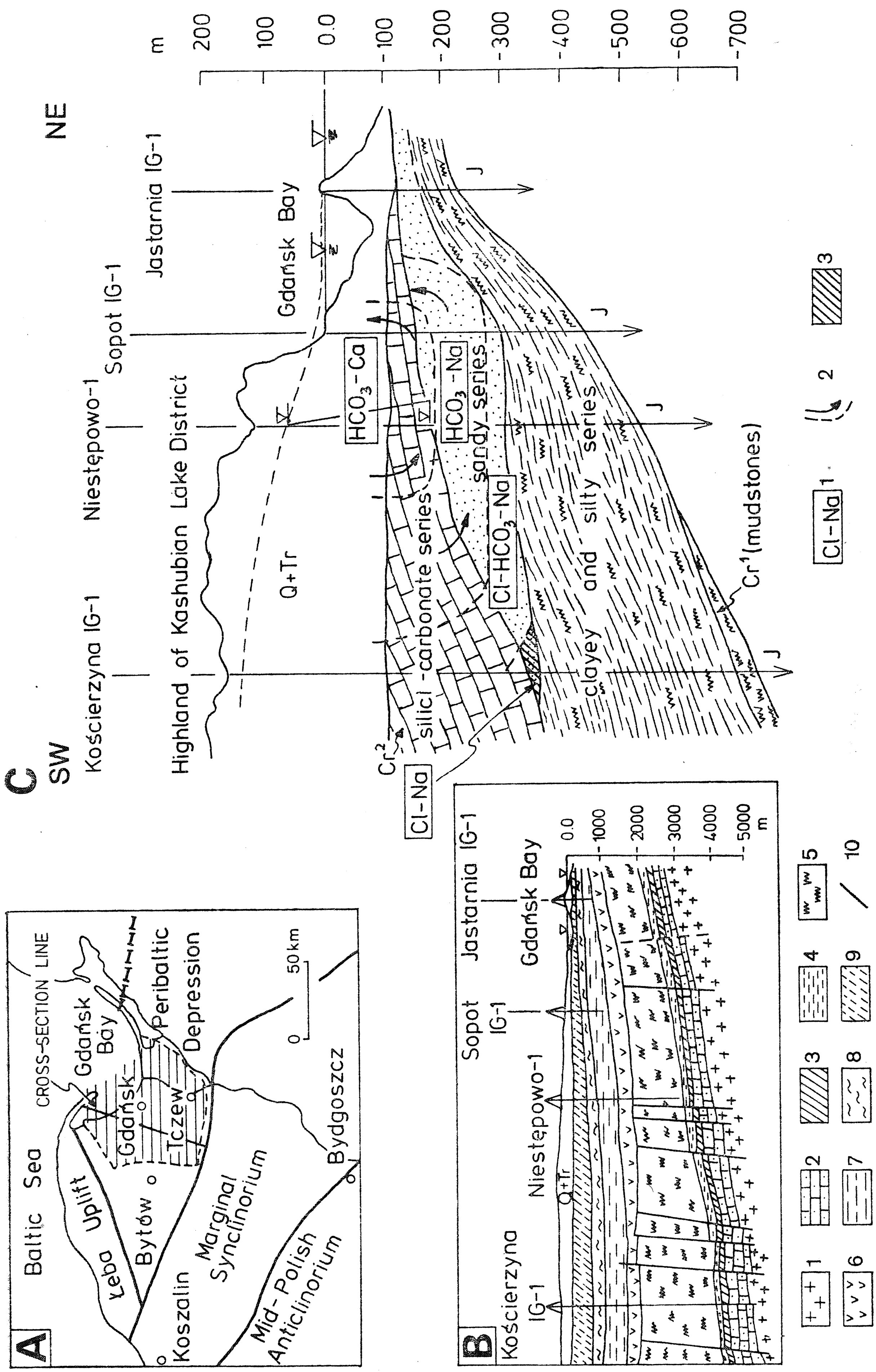
Fig. 1. Geological setting of the study area. *A* — Upper Cretaceous basin against a background of structural units of northern Poland; *B* — geological cross-section according to Modliński *et al.* (1982), borehole Kościerzyna IG-1: *1* — crystalline basement, *2* — Cambrian, *3* — Ordovician, *4* — Lower Silurian, *5* — Upper Silurian, *6* — Permian, *7* — Triassic, *8* — Jurassic, *9* — Cretaceous, *10* — faults; *C* — hydrogeological cross-section of the Upper Cretaceous basin: dashed line denotes groundwater table, Q+Tr — Quaternary and Tertiary strata, Cr^1 — Lower Cretaceous, Cr^2 — Upper Cretaceous, *J* — Jurassic, *1* — type of water, *2* — hydrodynamic flow systems and directions of water movement, *3* — stagnant relic water


C
SW
NE
Kościerzyna IG-1
Niestępowo-1
Sopot IG-1
Jastarnia IG-1
Highland of Kashubian Lake District
Gdańsk Bay
Q+Tr
silici-carbonate series
sandy series
clayey and silty series
Cr¹(mudstones)
Cr²
HCO3-Ca
HCO3-Na
Cl-HCO3-Na
Cl-Na
J
m
200
100
0.0
-100
-200
-300
-400
-500
-600
-700
Cl-Na 1
2
3
A
Baltic Sea
Łeba Uplift
Bytów
Koszalin
Marginal Synclinorium
Mid-Polish Anticlinorium
Gdańsk Bay
CROSS-SECTION LINE
Gdańsk
Tczew
Peribaltic Depression
Bydgoszcz
0 50 km
B
Kościerzyna IG-1
Niestępowo-1
Sopot IG-1
Jastarnia IG-1
Gdańsk Bay
Q+Tr
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basin, the regional groundwater movement (Toth, 1963) is demarcated by the limits of extension of sandy series towards the south and the east, by the groundwater divide running meridionally through the Raduńskie Lakes in the west, and by the boundary of the Łeba Uplift in the north. The interface between the brackish sea water and groundwater in the Cretaceous aquifer occurs at the lattitude of the Hel Peninsula. This belt can be assumed as a northern limit of the investigated structure.

CHEMICAL COMPOSITION OF THE UNDERGROUND WATER

WATERS OF THE UPPER CRETACEOUS SUBSTRATUM

Groundwater sampling from the Cretaceous strata has been done on the basis of deep boreholes of the Geological Institute. In the Peribaltic Depression, Bojarski (1978) distinguishes the following four water-bearing levels: (*1*) Cambrian, (*2*) Permian, (*3*) Mesozoic (subdivided into Triassic, Jurassic and Cretaceous sublevels), and (*4*) Cainozoic (comprising Tertiary and Quaternary sands and including a fissured Cretaceous roof).

In the Lower Palaeozoic deposits there are Cl-Na type brines with a mineral content of over 100 g/dm^3. Water of this type occurs infrequently in the Permian strata. It contains higher concentration of the SO_4^{2-} ion. In the Triassic, Jurassic and Lower Cretaceous sandstones there occurs the Cl-Ca type of groundwater, according to Sulin's genetic classification (see Bojarski, 1978). The content of dissolved substances varies clearly within the vertical profile, from ca. 60 g/dm^3 in the Triassic to ca. 5 mg/dm^3 in the Lower Cretaceous (Jastarnia IG-1). In this saline groundwater, bromide and iodide ions occur in high concentration. An increased concentration of dissolved substances can also be seen at the particular levels, from the northern boundary to the southern one. In the light of the most recent studies, this water is a mixture of relic sea water released from sediments in the process of compaction and Zechstein post-crystallization mother-liquids (Szpakiewicz, 1983).

UPPER CRETACEOUS WATER

The chemistry of the water from Upper Cretaceous deposits has been determined in over 150 wells exploiting both fissure water of the Cretaceous roof and water of the Cretaceous sandy series. These wells are mainly located in the Gdańsk conurbation and in the Vistula delta area. There are only 9 wells with Cretaceous water on the Kashubian Lake District morainic plateau. The results of the chemical investigation of water samples make it possible to determine changes in concentration of the main ions, and to define types of water in the Upper Cretaceous basin. In the area under consideration, water with a low mineralization, from 220 to 500 mg/dm^3, has been found, except the zone extending from Starogard Gdański through

Tczew, Długie Pole to Nowy Dwór and Nowakowo, where the dissolved substances in the water exceed locally 1000 mg/dm^3 and come up to 5000 mg/dm^3. The high content of dissolved substances corresponds to the increased chloride ion concentration and to the salty-water zone in the Vistula delta area (Agopsowicz & Pazdro, 1964; Kozerski & Kwaterkiewicz, 1984; Sadurski, 1985).

The fissure brackish water of the Cretaceous roof occurs particularly in the northeastern part of the Vistula delta, its range corresponding approximately to the zones of saline water within the Quaternary. The long-term studies at selected water-intakes point to a drop in the content of the Cl^- ion in the water (Sadurski, 1985). This indicates that the origin of salty water in the northeastern part of the Vistula delta is different from that in the central part of the area between Długie Pole, Nowy Dwór and Tczew, where the content of dissolved substances in the Cretaceous deposits increases with depth. In the northern zone of the structure analysed, between Wejherowo, Gdynia and Sopot there occur waters of the HCO_3—Ca type. The waters exploited in the central portion of the basin, from Oliva to Sobieszewo and Pruszcz, are of the HCO_3—Na or HCO_3—Ca—Na types. Salty waters of the Cretaceous deposits are of a different chemical composition, mostly of the Cl—HCO_3—Na, or even Cl—Na type (the borehole at Starogard Gdański). The chemical composition of water from selected wells in the above mentioned zones is given in Kurlov's formula in the following sequence (from the north to the south):

(1) Rumia: $$M^{0.23}\frac{HCO_3^{88}SO_4^{6}Cl^{5}}{Ca^{66}Mg^{17}Na^{12}},$$

(2) Gdańsk—Lipce: $$M^{0.43}\frac{HCO_3^{93}Cl^{4}SO_4^{2}}{Na^{54}Ca^{31}Mg^{13}}$$

(3) Długie Pole: $$M^{1.3}\frac{Cl^{67}HCO_3^{31}SO_4^{2}}{Na^{90}Ca^{6}Mg^{4}}$$

Noteworthy is an exceptionally low, sometimes only trace content of sulphates in the waters from Cretaceous aquifers and a low content of magnesium ions, especially in salty water occurring in that formation. Water of the HCO_3—Na type is soft (total hardness values below 1.0 meq/dm^3). An increased water hardness is recorded for the fissured aquifer of the uppermost Cretaceous and for the salty water of the Vistula delta.

The hydrochemical zonation of the Gdańsk basin indicates a close relationship to the dynamics of the groundwater (Sadurski, 1985). The water exchanged at the highest rate, near the morainic plateau edge, and in the top part of the Cretaceous deposits, is of the HCO_3—Ca type, whereas in the older water the Na^+ ion dominates over the Ca^{2+} ion (Fig. 1c). In the southern zone of the basin with a low water exchange rate where the oldest water occurs, the concentration of chlorides increases, and the water appears to be of the Cl—HCO_3—Na composition.

PALAEOHYDROGEOLOGICAL ANALYSIS

THEORETICAL BACKGROUND

The term palaeohydrogeological analysis was introduced by Czervinski in 1926 (see Karcev *et al.*, 1969) and it referred to the influence of groundwater on the metallogenic processes. In the later papers by Silin-Bekczurin (1949) and Karcev *et al.*, (1969) the tasks of this analysis were defined and the theory of hydrogeological cycles was introduced. Each cycle of this analysis is divided into two stages: elision (sedimentary) and infiltrational ones. At the elision stage, during sea transgression, there accumulate sediments which subsequently become aquifers. As a result of the accumulation of large amounts of sediments, there arise lithostatic pressures greater than the hydrostatic ones, whereas the great porosity of the sediments deposited on the sea floor becomes reduced in the course of compaction.

In the course of compaction, especially of silty sediments, large amounts of connate water are released. It moves to zones of the lowest pressures, along the hydraulic gradient. In silty deposits the "compaction stream" is directed towards the top of the layer (Engelhardt & Gaide, 1963; Dowgiałło, 1971), while in sandy layers with a high hydraulic transmissivity this water moves towards zones of the lowest subsidence. The large portion of synsedimentary water from silts is lost, being pressed out as the deposits are buried to the depth 1200—1500 metres (Oszczypko, 1981). At the infiltrational stage, following a sea regression, meteoric water replaces synsedimentary salty water. Then the water moves according to the hydraulic gradient within the water-bearing strata, between recharge zones and discharge zones. A decrease in the lithostatic pressure below the hydrostatic pressure causes water movement along the dip of the strata and towards the discharge sites.

The palaeohydrogeological analysis allows conclusions to be drawn concerning the origin and chemical composition of the waters of sedimentary basins. The possibility of a complete exchange of waters is checked by determining the water exchange index, separately for the elision and the infiltration stages (Karcev *et al.*, 1969). At the elision stage this index is of the form:

$$W_{we} = \frac{V_i}{V_p},$$

where: $V_i = V - n$ — volume of the waters pressed out from silty strata, V — volume of the stratum analysed, n — its porosity, V_p — volume of free intergranular spaces in a sandy stratum.

The palaeohydrogeological reconstruction takes into account the changes in thickness and depth of occurrence of rock strata during the geological time. The amount of waters "pressed out" during sediment compaction can be calculated on the basis of the data concerning the reduction in the porosity of sediments, as a function of the depth of their deposition (Fig. 2), given e.g. in the papers by Weller (1959), Chilingar *et al.* (1963), Larsen & Chilingar (1967), Füchtbauer & Reineck (1963), Hagendorf *et al.* (1973).

In the course of the sediment compaction and diagenesis, a number of physico-chemical processes influencing the chemical composition of synsedimentary waters take place. The processes involved are mainly hydration, hydrolysis, dissolution, ion exchange and crystallization (Vu-Ngoc-Ky *et al.*, 1981). A reduction in sulphate concentration in the groundwater is mainly brought about by the decomposition of the organic matter in silty and clayey deposits (Szczepańska *et al.*, 1981).

During the processes of ion exchange between the solid phase (rock) and the liquid phase (solution) the Mg^{2+} and Ca^{2+} ions are retained due to the sorption capacity of the mud, and these are primarily the Na^+ ions that pass into the pore water. It must be noted here that in sediments *in statu nascendi*, forming a several

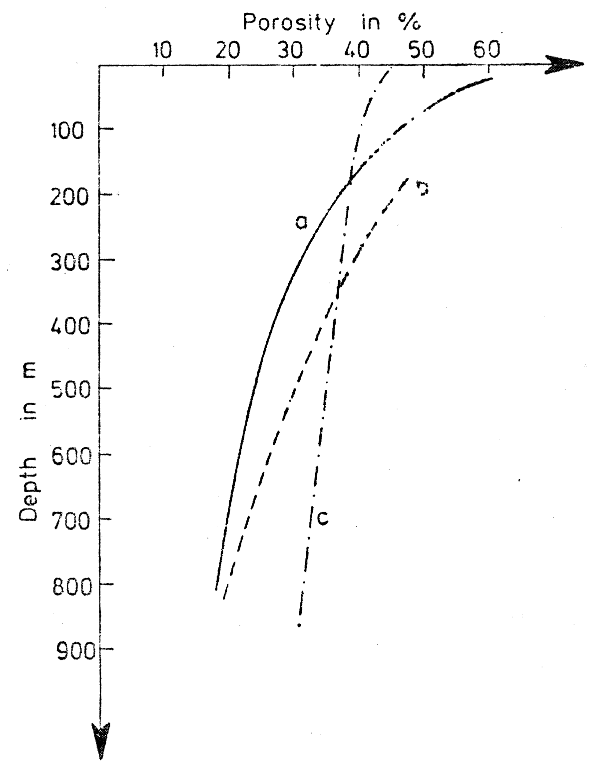

Fig. 2. The graph of porosity versus depth. *a* — clayey and silty sediments, *b* — siliceous-carbonate sediments, *c* — sands (after Hagendorf *et al.*, 1973; Weller, 1959; Füchtbauer & Reineck, 1963; Chilingar *et al.*, 1963)

metres thick layer on the sea floor, the exchange of ions proceeds at a high rate. In the course of compaction the rate drops gradually.

The movement of groundwater through silt layers is connected with the membrane effect, the so-called ultrafiltration. Silt and clay particles with mainly negative electric charges repel anions. The most mobile among the cations that pass through are those with the lowest polarization. According to Neglio (1979, *fide* Oszczypko, 1985), the mineral content in the waters "pressed out" from silts decreases in geological time due to ultrafiltration. In the light of this theory, the water present beneath the Upper Cretaceous silt and clay bed should be the most mineralized one. The stratification of saline water in sedimentary basins can be explained according to the theory of gravitational ion differentiation presented by Filatov (1956), and with regard to water of the Cl—Na—Ca type of the Gdańsk basin — also according to Smirnov's (1974) theory of diffusive migration of dissolved salt deposits. According to this theory, the transport of water on a regional scale is mainly effected through diffusion, and hence water of the Cl—Na type and concentration similar to that of sea water may be preserved at the bottom of the aquifers of sedimentary origin. In the top portions of the aquifer analysed, it is the convection transport of dissolved substances that plays the most important role. In the area under study, the cyclic nature of the sea transgressions and land emergence, should have caused disturbances in the primary hydrochemical zonation of the basin. It is, therefore, possible that in the Cretaceous strata in the Gdańsk region there occurs at present a mixture of genetically different groundwaters.

HYDROGEOLOGICAL CONDITIONS BEFORE THE UPPER CRETACEOUS TRANSGRESSION

Before the Albian, in the Portlandian and throughout the Early Cretaceous the Peribaltic Depression area was the edge of the land. Marine conditions occurred on the southern side, in the marginal trough (including the so-called Danish-Polish channel, see Marek & Raczyńska, 1973; Raczyńska, 1979). Among the sediments deposited at that time there are claystones and mudstones, locally interbedded with sandy mudstones. In the centre of the marginal trough they are several hundred metres thick. The northern extent of the Lower Cretaceous beds corresponds approximately to the Malbork-Tczew parallel. In the area analysed, groundwater occurred in sandy limestones and calcareous mudstones of the Kimeridgian and the Oxfordian. It was isolated from the substratum by Callovian, Bathonian and Triassic claystones intercalated with mudstones and fine-grained sandstones (borehole Gdańsk IG-1). The groundwater region moved southwards, to the sea. The Łeba Uplift and the Peribaltic Depression along with the area of the present southern Baltic were the feeding zone. Because of the length of the continental period, the groundwater became diluted by meteoric water down to the depth of about 100—150 metres, i.e., to the Callovian clay bed. The Jurassic, little consolidated, clayey deposits with mudstone interbeddings may have retained in their pores synsedimentary water of the Cl—Na or SO_4—Cl—Ca—Na type.

FIRST CYCLE OF THE UPPER CRETACEOUS BASIN

Sedimentary stage

In the upper Albian, the sea encroached upon the eroded and levelled surface of the area under consideration, except the Łeba Uplift. Marine sedimentation lasted until the Campanian inclusive, and in the southern and eastern parts of the area until the Danian (Jaskowiak, 1966). The succession of strata had a great influence on the exchange of the synsedimentary water of the sandy series. At first, the clayey--silty series and the siliceous-carbonate series at the top, favoured the formation of a compaction stream because of an increasing pressure of sediments deposited at their top. A volume reduction of silts and clays led to the penetration of waters from these deposits into the sandy series. With increasing pressure and pH decreasing as a result of the decomposition of organic matter accumulated in the silts, a partial replacement of the calcium carbonate in limestones by silica may have taken place. The highest lithostatic pressure occurred in the southern part of the basin where the thickness of the clayey-silty sediments reached its maximum. At the end of the sedimentary stage, the sandy series contained waters which had been released during compaction from the clayey series. Part of these waters percolated downward into the Jurassic strata of low permeability. According to Jacquin and Poulet (*fide* Oszczypko, 1981), in the course of compaction, sedimentary water from 1/5 of the clayey strata penetrated into the floor bed, while water from 4/5 of the clayey strata moved upwards. Excess water was conveyed by the Jurassic sandstones and Upper Cretaceous glauconite sands towards the northern periphery of the water-bearing system. The magnitude of pressures caused by the overlying deposits may have been greater than expected considering the deposit load, due to tectonic strains. They arose, no doubt, during the uplifting of the Mid-Polish Anticlinorum, as indicated by the eastward shifting of the axis of the Peribaltic Depression (Jaskowiak--Schoeneich & Pożaryski, 1979; Wagner *et al.*, 1980; Dadlez, 1980).

Infiltrational stage

The regression of the sea from the Gdańsk region initiated the infiltrational stage at the end of the Cretaceous. However, in the south-eastern area the sea extended as far as Tczew, Malbork and Elbląg untill the Danian. The highest heads occurred in the most lowered zone, i.e., at the outermost part of the Marginal Synclinorium. Their magnitude was controlled by the hydraulic transmissivity of the Upper Cretaceous strata and of their substratum. It may, therefore, be presumed that until the decline of the Upper Cretaceous sea, groundwater freshening in the structure discussed was low because synsedimentary water, pressed out of the synclinorium and of the eastern part of the depression, moved northwards and westwards, i.e. towards the existing land. On the basis of Terzaghi's consolidation theory (see Liszkowska, 1985) and adopting the data such as the clay volume consolidation coefficient of $m = 0.02$ cm^2/kG, the consolidation time has been calculated for the clayey-silty series. For the southern region of the depression the time is approximately 200 thousand years, and for the region of Gdańsk – about 50 thousand years. The difference is due to differences in the thickness of the clays and the depth of their occurrence.

At the beginning of the Tertiary, the area considered here was a land. The surface of the area was modelled by epeirogenic movements and peneplanation processes. It may be assumed that there were land elevations in the area of the Łeba Uplift and north of the Hel Peninsula of today. The terrain generally sloped towards the marginal trough, hence the course of the outflow of groundwater and its freshening proceeded from the north in the southwestern direction (Figs. 3, 4).

By analogy to the similar present hydrogeological conditions (a groundwater movement velocity of 1 m/year, a surface area of the regional stream in cross-sec-

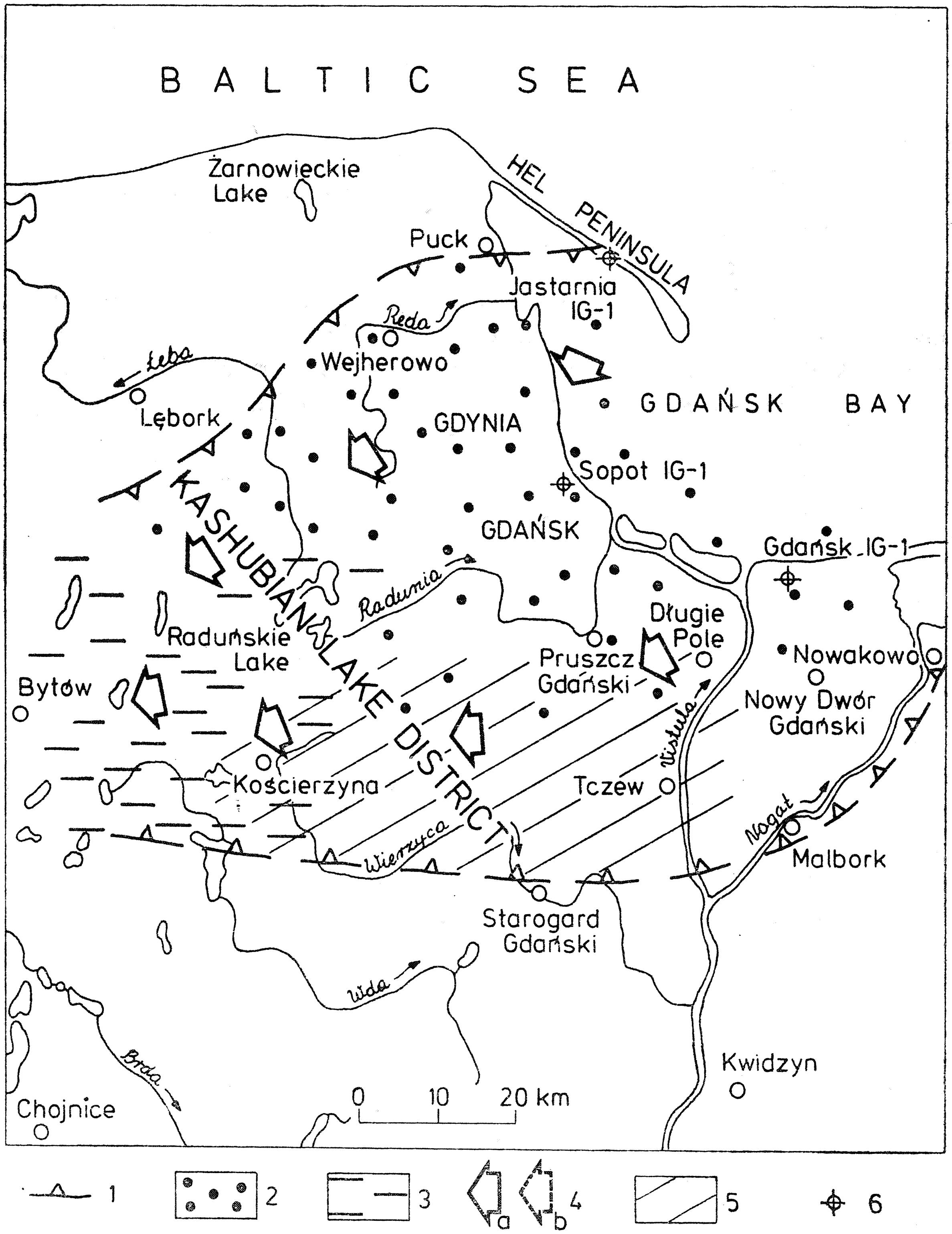

Fig. 3. Schematic map of hydrogeological conditions during the first infiltration stage (Danian to Montian). *1* — boundaries of the Cretaceous aquifer, *2* — recharge area, *3* — discharge area, *4* — direction of regional flow of groundwater, *5* — zone of dominant lithostatic pressure, *6* — boreholes

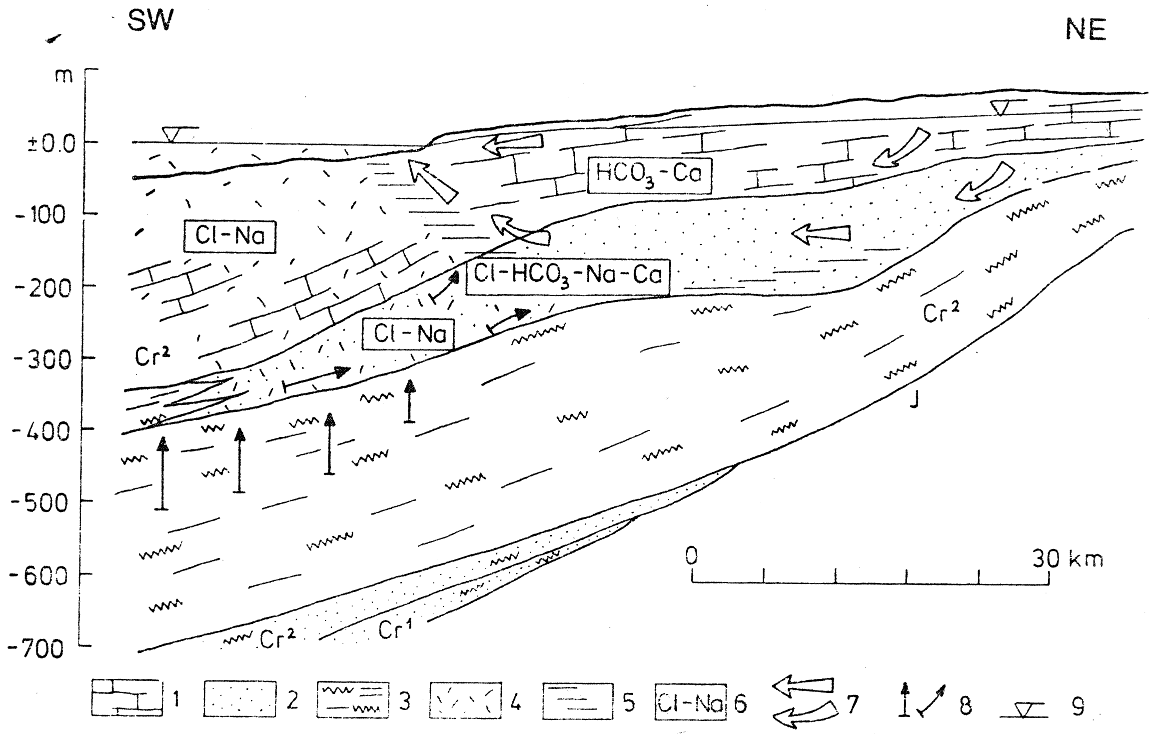

Fig. 4. Hydrogeological cross-section of the basin during the first infiltration stage (Danian to Montian). The line of the section is marked in Fig. 1A. *1* — siliceous-carbonate series, *2* — sandy series, *3* — clayey-silty series, *4* — sea water, *5* — zone of dispersion, *6* — types of groundwater, *7* — direction of infiltration flow, *8* — direction of sedimentary flow, *9* — water level

tion $F = 5 \cdot 10^6$ m^2, and a total porosity volume of the sandy series $V_p = 2.3 \cdot 10^9$ m^3), an exchange coefficient W_{wi} for the Montian-Eocene period can be assumed. The value of this coefficient is ca. 800 (Sadurski, 1977). It shows that the total exchange of synsedimentary water for meteoric one took place in the sandy series during the period under consideration.

SECOND CYCLE OF THE UPPER CRETACEOUS BASIN

The successive sea transgression of the Late Eocene and the beginning of sedimentation of sandy and silty deposits initiated the sedimentary stage of the second cycle. The infiltration water in the Cretaceous sediments was probably replaced by sea waters. This was accompanied by the movement of mineralized water, released from deeper clayey-silty strata due to an increased lithostatic pressure of the Oligocene sediments over 100 metres thick. The southeastward recession of the sea is indicated by the general sloping of the terrain towards the marginal synclinorium. This was probably also the direction of the groundwater movement at the infiltrational stage, i.e., since the Late Oligocene—Early Miocene until the Burdigalian inclusively (Figs. 5, 6). The Gdańsk region was then probably a peneplanated area with numerous depressions filled with lakes and swamps. The groundwater circulation in the basin under consideration was extremely slow. This water may have remained in the Upper Cretaceous sandy series as the relic groundwater of the previous cycle, because of frequent changes of the drainage base, poorly varied morphology of the surface and the considerable thickness of the poorly permeable rocks.

Taking into account active epeirogenic movements at that time (Pożaryska & Odrzywolska-Bieńkowa, 1982) and compaction processes, one can presume that there occurred an inflow of saline, mineralized water, into the Mesozoic strata. Thus, in the northern part of the sandy series there was probably a mixture of

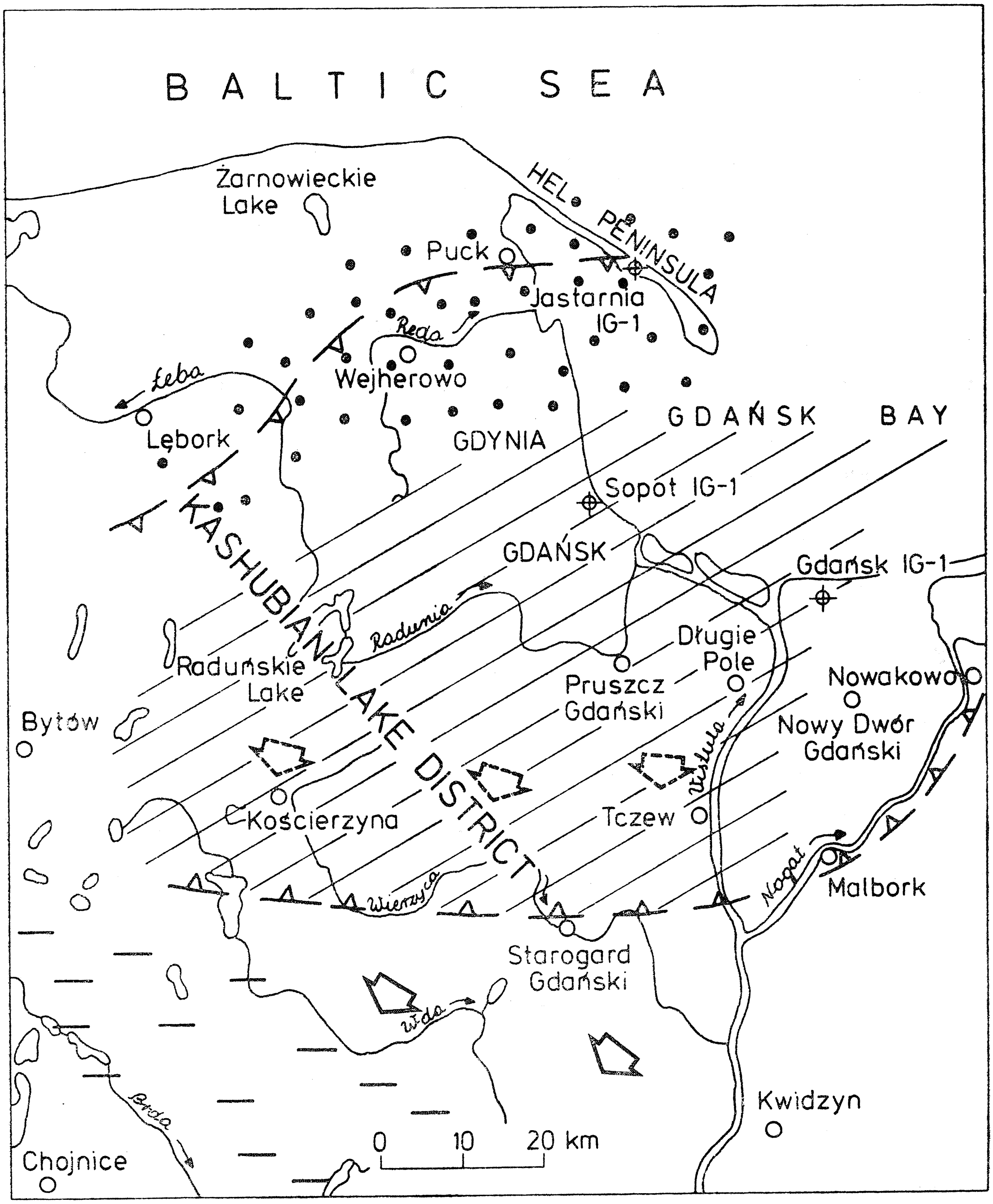

Fig. 5. Schematic map of hydrogeological conditions during the second infiltrational stage (Oligocene-Miocene). Explanations as in Fig. 3

HCO_3—Ca and Cl—Na groundwater, and in its southern part there was Cl—Na—Ca groundwater. Sulphide ions were precipitated as iron sulphide. This is confirmed by the presence of small pyrite and chalcopyrite crystals common in the Oligocene deposits.

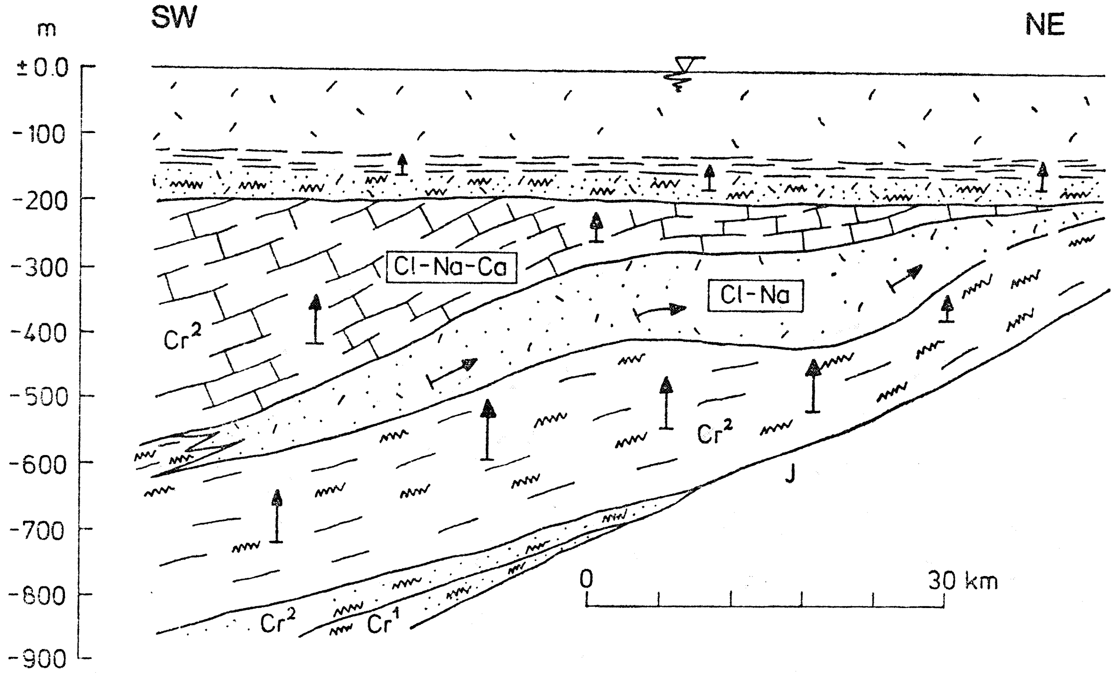

Fig. 6. Hydrogeological cross-section of the basin during sedimentary stage (elision stage) of the second cycle. Explanations as in Fig. 4

THIRD CYCLE OF THE UPPER CRETACEOUS BASIN

The successive sedimentary stage may be connected with the origin of an inland body of freshwater in which an intensive accumulation of sediments 50—100 metres thick took place (Łyczewska, 1958; Ciuk, 1966). There were probably many changes in the extent of the basin during the Miocene. The water movement within the Upper Cretaceous sediments was directed vertically because of the increased lithostatic pressures. The decline of the inland water body began in the Late Miocene. During the Pliocene there was a continental period, i.e. an infiltration stage started in the Gdańsk region. In the warm climate of the Pliocene deep river valleys were formed (Ciuk, 1966) which in places dissected Tertiary deposits down to the top of the Cretaceous. This caused an intensive northwestward groundwater movement, in accordance with the inclination of those valleys. This situation lasted until the Pleistocene glaciation (Fig. 7).

In the Pleistocene, an accumulation of fluvioglacial deposits took place, in places up to the thickness of 200 metres, as well as a cyclic loading of the surface by the Scandinavian continental ice-sheet. For this reason, a glacio-sedimentary hydrogeological sub-stage is distinguished in the glaciation period. A new outlook on the groundwater changes in that period was presented by Michalski (1984, 1985); following Fotev's (1978) theory of frost-induced changes, he points out calcite and mirabilite precipitation can occur in permafrost, which leads to stratification of

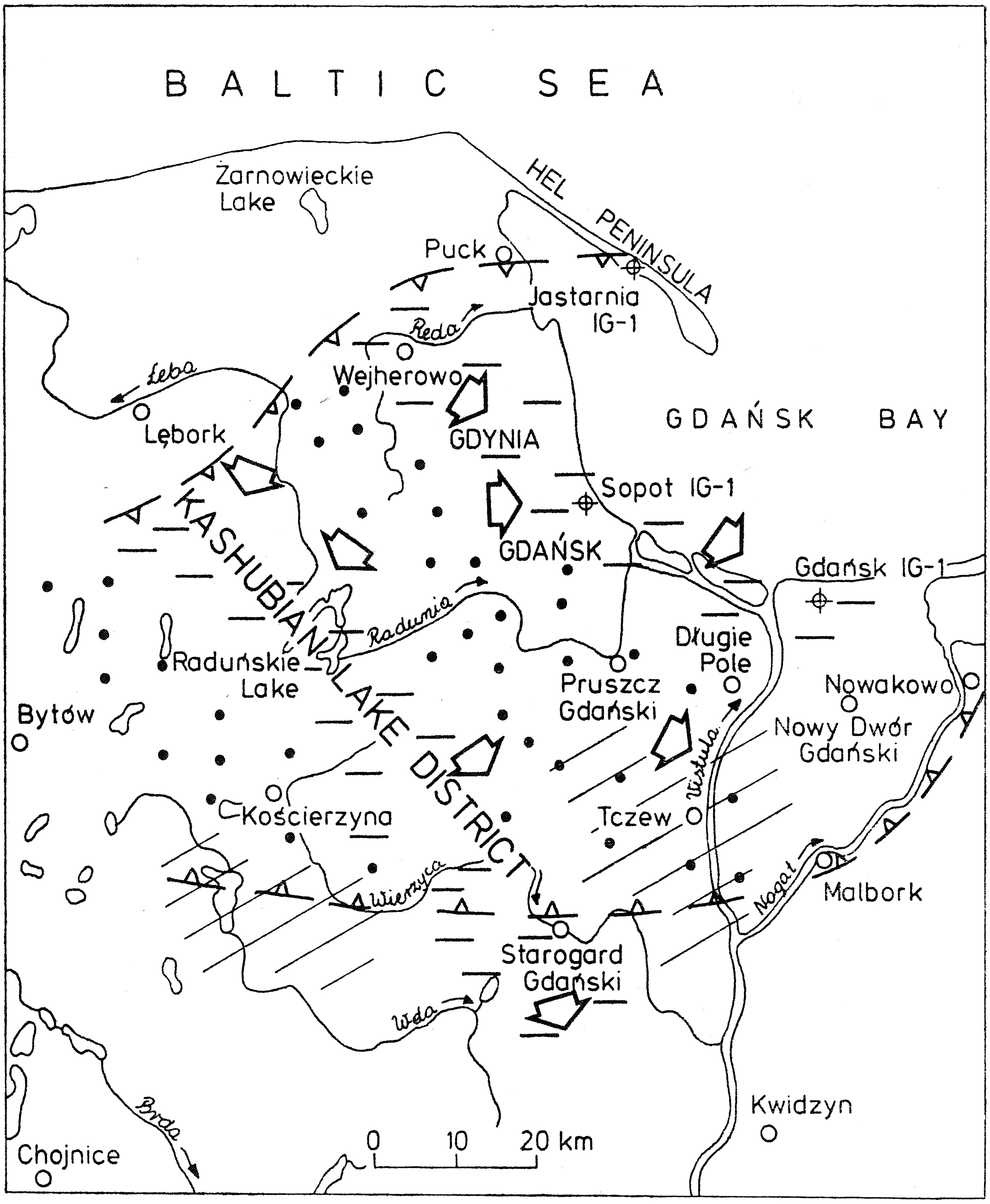

Fig. 7. Schematic map of hydrogeological conditions during the beginning of the third infiltrational stage (Pliocene-Eopleistocene). Explanations as in Fig. 3

water of different chemical compositions. Apart from this, the ice-sheet load caused sediment compaction, especially of clayey sediments, which resulted in an increased pressure and, consequently, in the release of pore water. Warm groundwater moving in along tectonic loosened zones caused local thawing of the permafrost. The movement of this water might have been particularly intensive along the northern boundary of the Upper Cretaceous sandy series (Fig. 8). The sandy series played the role of a drain-pipe conveying the compaction water released from the underlaying clayey strata. Along the northern and northeastern boundaries of this series,

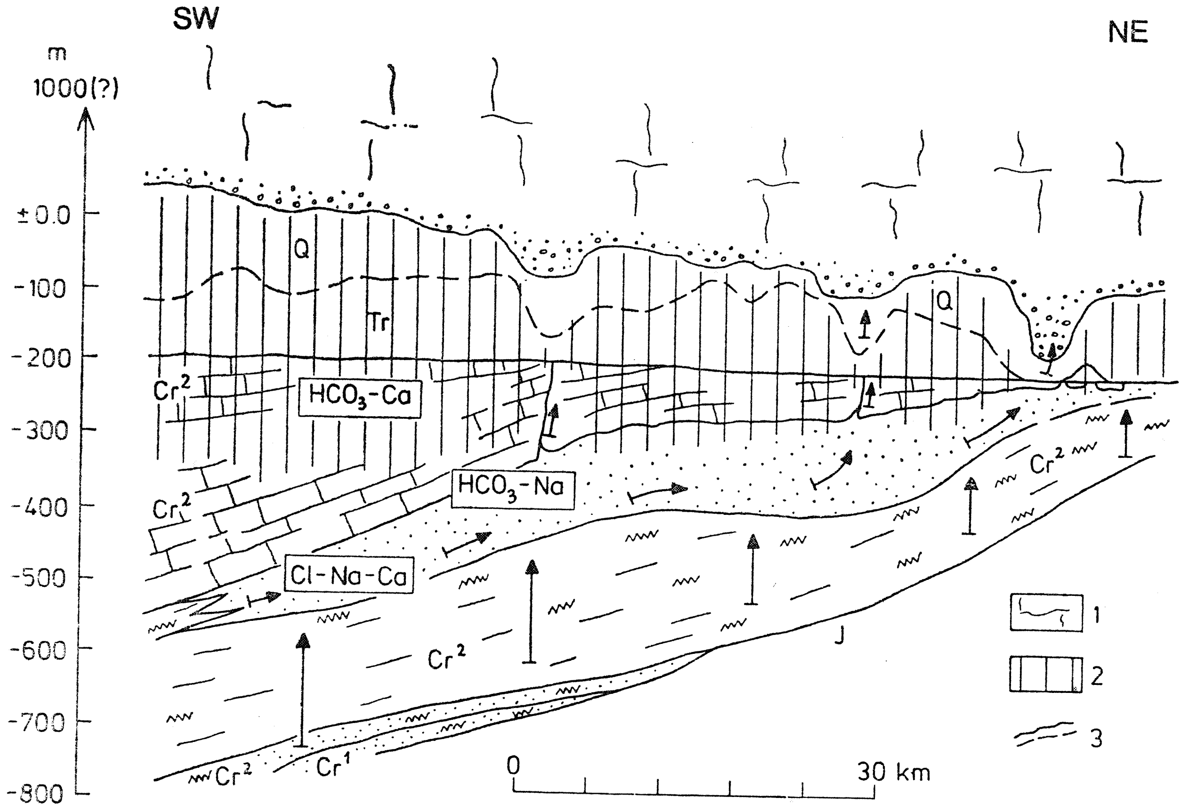

Fig. 8. Schematic cross-section of the basin during the Pleistocene glaciation (glaci-sedimentary sub-stage). *1* — ice body, *2* — permafrost, *3* — lithologic and stratigraphic boundaries. Other explanations as in Fig. 4

there occur deep Pleistocene erosion valleys, e.g. the Reda marginal meltwater valley with its probable continuation on the Hel Peninsula, and the Kaczynos-Elbląg depression. According to Michalski (1985), the ice-sheet recession and permafrost thawing caused an increase in deposit porosity, and a relaxation of strains. As a result, meteoric water from the surface of the area and the permafrost meltwater poor in minerals but containing sodium (the effect of frost) could penetrate to the deep water-bearing layers.

The cyclic nature of the above discussed phenomena was connected with the successive glaciations. It should be noted, however, that there was a time lag between the deglaciation and the beginning of the regional groundwater movement. The thawing of the permafrost continued for several thousand years. In the case of the last glaciation the regional water movement within the Cretaceous aquifers began probably only in the Preboreal (Petelski & Sadurski, 1985).

The glacio-sedimentary sub-stage as distinguished in the evolution of the Gdańsk basin had a significant influence on the groundwater quality. Water released due to reduced porosity, mainly from the Upper Mesozoic clayey series, contained more minerals and was probably of the Cl—Na—Ca type. The development of the permafrost and the freezing of groundwater may have caused the change of the HCO_3—Ca type of meteoric water into the SO_4—Cl—Na—Mg type. Water that underwent freezing, mixed with pressed-out synsedimentary or palaeoinfiltration water moved upwards along the sandy series towards marginal zones northwards and northeastwards of the basin. In the interglacial periods, groundwater outflow was similar to that of today (recharge area in the Kashubian Lake District). After the thawing of the permafrost, in the marginal zone of the morainic upland, along its extent (Wejherowo, Gdynia, Pruszcz Gdański), an intensive water exchange began. In the southern zone of the basin between Starogard Gdański and Tczew, groundwater exchange started latest of all. For this reason, the chemical composition of Cretaceous water is closely related to its dynamics (Fig. 1c). Calculated for the Holocene, the water-exchange index W_{wi} amounts to about 4.6 but the mean time of water exchange in the structure analysed is about 2000 years (Sadurski, 1977). It may, therefore, be assumed that in the southern and central parts of the basin, permafrost meltwater which penetrated into the Cretaceous beds during the Eemian interglacial period could have survived till recent times.

SUMMARY

In the geological evolution of the Upper Cretaceous basin in the Gdańsk region three hydrogeological cycles can be distinguished. In the first cycle, the sedimentary stage corresponds to the Albian—Danian period. The upper boundary is not isochronous as in the vicinity of Gdańsk the sea withdrew at the end of the Campanian, while east and south of Tczew it still existed during the Maastrichtian and the Danian. In the Palaeocene, an infiltration stage began in the whole area under consideration. Until the next sea transgression in the Late Eocene, there prevailed continental conditions. The second hydrogeological cycle started in the Upper Eocene. In the Upper Oligocene at the end of the Rupelian and the beginning of the Chattian, the infiltration stage of the second cycle began. This cycle lasted until the Miocene. In the Middle Miocene the third hydrogeological cycle started. The sedimentary stage in the Miocene lasted a short time and ended in the Late Miocene. The infiltration stage of the third cycle lasted from that time to recent.

The groundwater of the Gdańsk Cretaceous basin have been exchanged many times, and at present it is predominantly meteoric water that originated from infiltration through the Tertiary and Quaternary strata in the Kashubian Lake District. The water exchange rate depends on the hydraulic transmissivity of the Upper Cretaceous sandy series and younger deposits, and on the hydraulic gradient between the recharge and discharge zones. Hydrochemical anomalies, characterized by a higher content of dissolved substances and by the presence of $Cl-HCO_3-Na$ or $Cl-Na$ water types, arise in the zone along the southern boundary of the basin, where exchange is difficult, and probably also in connection with an ascension of salty synsedimentary water of the Mesozoic in tectonic loosened zone in the centre of the Vistula delta. The synsedimentary water during the above enumerated elision stages attained the maximum TDS of 35 g/dm^3, equal to that of oceanic water, and was of the $Cl-Na$ type. Water with so high content of minerals is not found in the Upper Cretaceous sediments at present, this indicating its exchange. Evaporites are not present in the Cretaceous and Cainozoic marine deposits found in the area explored, which allows one to assume that the SO_4-Ca groundwater facies and concentrated mother-liquids were absent. Mesozoic clayey deposits played an

important role in controlling of the chemistry of the Cretaceous water. They constituted a clayey membrane for the chlorine-sodium brines from the Zechstein strata. At the present stage of exploration of the Peribaltic Depression, the intensity of particular hydrogeochemical processes in the past cannot be established.

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Streszczenie

HYDROGEOLOGICZNY ROZWÓJ GDAŃSKIEGO GÓRNOKREDOWEGO BASENU ARTEZYJSKIEGO

Andrzej Sadurski

W hydrogeologicznej ewolucji górnokredowego basenu w rejonie Gdańska (Fig. 1) wyróżniono trzy cykle hydrogeologiczne składające się z etapów elizyjnych (sedymentacyjnych) i infiltracyjnych. Elizyjny etap pierwszego cyklu obejmował

okres od górnego albu do dano-montu. W paleocenie na całym obszarze rozpatrywanego basenu trwał etap infiltracyjny. Od kolejnej transgresji morza w eocenie rozpoczął się drugi cykl hydrogeologiczny, którego etap elizyjny trwał do przełomu rupel/szat. Po zakończeniu sedymentacji i regresji morza oligoceńskiego rozpoczął się etap infiltracyjny, który zakończył się w środkowym miocenie. W tym czasie zapoczątkowany został, wskutek akumulacji osadów w zbiorniku śródlądowym, elizyjny etap trzeciego cyklu. Od pliocenu do czasów współczesnych ma miejsce infiltracja. Zrekonstruowane warunki hydrogeologiczne basenu gdańskiego przedstawiono na schematycznych mapach (Fig. 3, 5, 7) oraz na przekrojach wzdłuż linii Kościerzyna—Sopot—Jastarnia (Fig. 4, 6). W okresie plejstoceńskich zlodowaceń wyróżniono podetap glaci-elizyjny przez analogię do okresów akumulacji osadów w zbiornikach wodnych. Kierunki przepływu „wyciskanych" wód podziemnych z warstw górnego mezozoiku, znajdujących się pod warstwą zmarzliny, oraz miejsca ich ascenzji wskazano na Figurze 8.

Ilość uwalnianych *connate waters* z ulegających kompakcji warstw górnego mezozoiku oszacowano na podstawie wykresu zmian porowatości w funkcji głębokości ich występowania (Fig. 2). Obliczono wskaźniki intensywności wymiany wód podziemnych (Karcev *et al.*, 1969) basenu gdańskiego w poszczególnych etapach infiltracyjnych.

Wody podziemne basenu gdańskiego były w przeszłości wielokrotnie wymieniane i aktualnie są to wody meteoryczne typu HCO_3—Ca—Na, pochodzące z przesączania przez osady czwartorzędu i trzeciorzędu na obszarze Pojezierza Kaszubskiego. Istnienie anomalii hydrochemicznych, polegających na zwiększonej mineralizacji oraz obecności wód typu Cl—HCO_3—Na lub nawet Cl—Na, związane jest ze strefą utrudnionej wymiany wzdłuż południowej granicy basenu (Starogard Gdański—Tczew) i prawdopodobnie z ascenzją słonych wód synsedymentacyjnych lub paleoinfiltracyjnych mezozoiku wzdłuż stref rozluźnień tektonicznych w centrum Żuław (Długie Pole—Nowy Dwór Gdański).

Chemizm wód kredowych eksploatowanych współcześnie w rejonie Gdańska jest uzależniony od hydrodynamiki basenu. Obliczony dla holocenu wskaźnik intensywności wymiany wynosi 4,6. Średni czas wymiany wód w basenie przekracza 2000 lat (Sadurski, 1977). Można zatem sądzić, że w południowej i centralnej części rozpatrywanej struktury przetrwały do czasów współczesnych wody pochodzące z wytopienia zmarzliny ostatniego zlodowacenia. Zapewne dlatego wody podziemne tych stref basenu są typu HCO_3—Na i odznaczają się małą mineralizacją.