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Investigations on the covered saline karst in Slănic-Prahova area (Romania)

**Ioan POVARĂ, Viorel HOROI,
Constantin MARIN, Tudora NICOLESCU & Mihai BACIU**[1]

ABSTRACT

The mechanical disequilibria due to the mining works undertaken in Slănic-Prahova area have determined the occurrence within the salt massif of a network of fissures that favored surface water infiltrations. The infiltration paths had a rapid evolution concentrating in well-organized drains the water accumulated within the Badenian deposits (siltic clays and marls) that cover the salt massif. The detailed morphological analysis of the massif and the monitoring of the flows, temperatures and chemistry of the infiltrations allowed the establishment of the water sources and the preferential flow directions, offering therefore the necessary elements for reducing the hydrogeologic risk.

Key words: karst processes in salt-rock, underground flow, mining works infiltrations.

Recherches sur le karst en sel de la zone de Slănic-Prahova (Roumanie)

RÉSUMÉ

Les déséquilibres mécaniques survenus à la suite des travaux miniers souterrains exécutés à Slănic-Prahova, en vue de l'exploitation ont déterminé l'apparition dans le massif de sel d'un réseau de fissures favorables aux infiltrations de surface. Les voies d'écoulement, une fois formées, ont évolué rapidement, concentrant en drains bien organisés les faibles accumulations aquifères des dépôts Badéniens (argiles silteuses et marnes) recouvrant le massif de sel. L'analyse détaillée de la morphologie du massif et le monitoring des débits, des températures et du chimisme des infiltrations ont permis de préciser les sources d'alimentation et les directions préférentielles d'écoulement, offrant les éléments nécessaires pour la diminution du risque hydrogéologique.

Mots clés: processus karstiques en sel, écoulement souterrain, infiltrations dans les travaux miniers.

GENERAL DATA

The salt accumulation in the Slănic salt formation (98% NaCl), estimated to 11.37×10^8 tons, has the shape of a 500 m thick pillow and extends over a 10 km^2 area, at 0–100 m depth (STOICA & GHERASE, 1981). About 35% of the accumulation is situated above the level of the hydrographic network, on both sides of Slănic stream. The industrial exploitation of the salt has started before 1688 in natural outcrops and continued by means of bell shaped mining works, then in trapezoidal shaped working chambers (55 m height, 35 m aperture at the bottom at –293 m maximum depth) with central pillar, while subsequently to 1970 chambers with square pillars, distributed over 11 levels have been used (DRĂGANESCU, 1993). Some of the old bell shaped working chambers have been flooded after being abandoned, with the water raising up to the ground surface.

[1] Institutul de Speologie "Emil Racoviţă", str. Frumoasă 11, R-78114 Bucureşti 12, Romania.

Weak infiltration in the mining works started to occur since the beginning of this century, but subsequently to 1991 the water amount increased to an alarming level, endangering the safety of the exploitation works. At ground surface negative landforms of sinkhole type have occurred, while the salt cap rock underwent subsidence that affected the buildings in Slănic town. In order to reduce the hydrogeological hazard to which the mining works are exposed and to stop the progressive deterioration underwent by the buildings situated above or close to the active-karst areas, the infiltration supply area as well as the main flow directions had to be identified, so that a remedial solution was substantiated.

GENERAL GEOLOGICAL SETTING AND SPECIFIC FEATURES OF THE SALT MASSIF

The salt accumulation at Slănic Prahova is of Badenian age; the Badenian formations include 4 distinct levels (DRĂGANESCU, 1993): the zeolitiferous tuffs and the bottom *Globigerina* marls level, followed by the evaporitic-bitumen facies, to which the salt massif also belongs, overlain by the salt breccia, over which the marly level of the *Globigerina* shales and *Spirialis* marls is deposited.

When considered from a structural-tectonic point of view, the deposits form a NE–SW striking syncline, with its north-western limb dipping at 30°–40°, while the south-eastern limb is very steep or vertical. To the west the syncline becomes an overturned fold, while in its central part it displays many secondary folds, frequently accompanied by longitudinal faults. The continuity of the syncline along its strike is broken by two transverse faults, with the block in between deeply downthrown.

THE SALT MASSIF TOPOGRAPHY

The overall geometry of the salt massif was outlined based on information provided by drill holes, and for a smaller area, on seismic surveys (MANJ & GEORGESCU, 1990). The contour maps of the top of the salt prepared by BONCIU (1996) indicate a trough like negative form extending on a N–S direction, that the authors interpret as a former, abandoned course of the Slănic stream.

By interpreting and processing the data of 425 drill holes, a detailed map of the salt topography was obtained in the area concerned by the infiltration phenomena (Fig. 1), as well as a block diagram of the salt topography, with the ground surface also plotted on it (Fig. 2). Both images suggest that the potential supply sources originate in the left side bank of Slănic stream and in its streambed.

INVESTIGATION BACKGROUND

Due to its high solubility and plasticity and to its reduced hardness, salt occupies a distinct place among the soluble rocks which are liable to engender karst processes and landforms. The average salt solubility is 350 times larger than that of the limestone, while the ratio between the calcite and halite saturation indexes, *IScalcite/IShalite* is 6. As a result of folding halite is subject to tensions, while the cracks induced by natural or anthropic causes are quickly closed. Provided that there are no mining works to maintain a karst base level inside the salt massif, the latter cannot be pierced by the underground flow. Hence dissolution will act only on the surface of the massif (the salt back), if the overlying formation has water storage properties and if a water supply source exists. The salt - cap rock interface will act as an impervious bed, with the flow being directed toward depression areas or toward the outcrops on the hill slope. The underground flow paths will have a very rapid evolution, but the aggressivity of the solution will rapidly decrease along the flow direction to eventually fade out, provided the path is long enough. The karsto-saline voids on the salt back will induce the collapse of the overlying formations, and as a result the ground surface will undergo slow or sudden subsidence processes.

The fast evolution of the karsto-saline processes renders the infiltration counteracting by means of conventional hydrogeological methods difficult.

The mechanical disequilibria of the salt massif induced by the mining works carried out inside the massif favored the occurrence of a flow path directed toward the karst base level situated at –230 m. The new flow direction rapidly evolved by dissolution, acting as a drain for the water accumulations on the salt back.

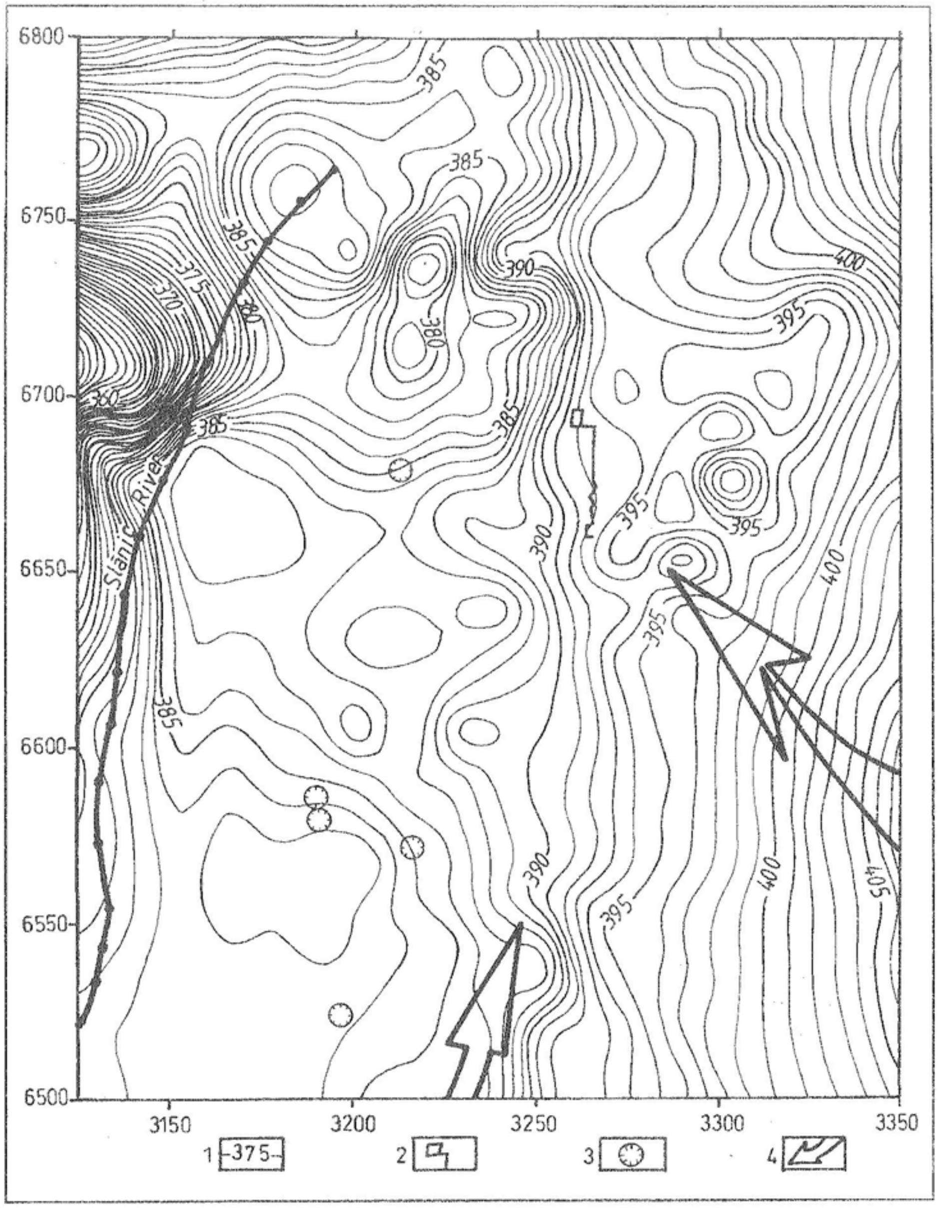
The attempts of injecting sealing curtains at the salt–cap rock interface failed to restrict the infiltration, but the sections sealed by this procedure contributed to concentrate the underground flow along very fast evolving pathways.

The investigation works addressed three subjects: the hydrologic regime of the total cumulated infiltration at –230 m, the groundwater saturation degree with respect to halite, and the supply origin of infiltration and preferred flow directions.

Fig. 1.

The salt topography map. 1. contour line; 2. Unirea mine shaft, subject to infiltration; 3. Suffosion sinkholes excavated into the overlying formation; 4. The most probable groundwater flow directions on the back of the salt body.

La topographie du massif de sel. 1. contour des isobathes ; 2. Le puits de la mine Unirea, point d'infiltrations; 3. Dolines de suffusion creusées dans les formations de couverture ; 4. Les plus probables directions d'écoulement souterrain sur l'interface sel–couverture.



HYDROGEOLOGIC ISSUES

The salt back deposits consist of a shale layer, then follow sandy-marly deposits deprived of bedding, yet displaying a sorting trend (larger components at the bottom), inside which the permeability coefficients vary over a wide range (0.1–22 m/24 h); the total thickness ranges from 0 to 60 m. In the lower part of the valley these Late Badenian formations are overlain by terrace deposits with coarse gravel at their bottom, covered by sandy shale. In those deposits on the top of the salt two sections have been identified (CALANGIU, 1971, in DRĂGANESCU, 1993):

- an area situated beneath the local erosion level (the Slănic stream), with salt saturated water at the contact level;
- an area situated above the local erosion level, with a more intense flow and unsaturated water.

The underground seepage occurs either through the fracture zones located above the local erosion level, or through the mining works that cross the debris/salt contact, on the contact area. The occurrence of concentrated flows (2.5–4 l/s) on the salt-debris interface has been proven by means of tracers over distances of 0.35 km (POVARĂ *et al.*, 1982) or inferred from the occurrence of low salinity levels in the anthropo-saline lakes (LASCU *et al.*, 1984, in DRĂGĂNESCU, 1993).

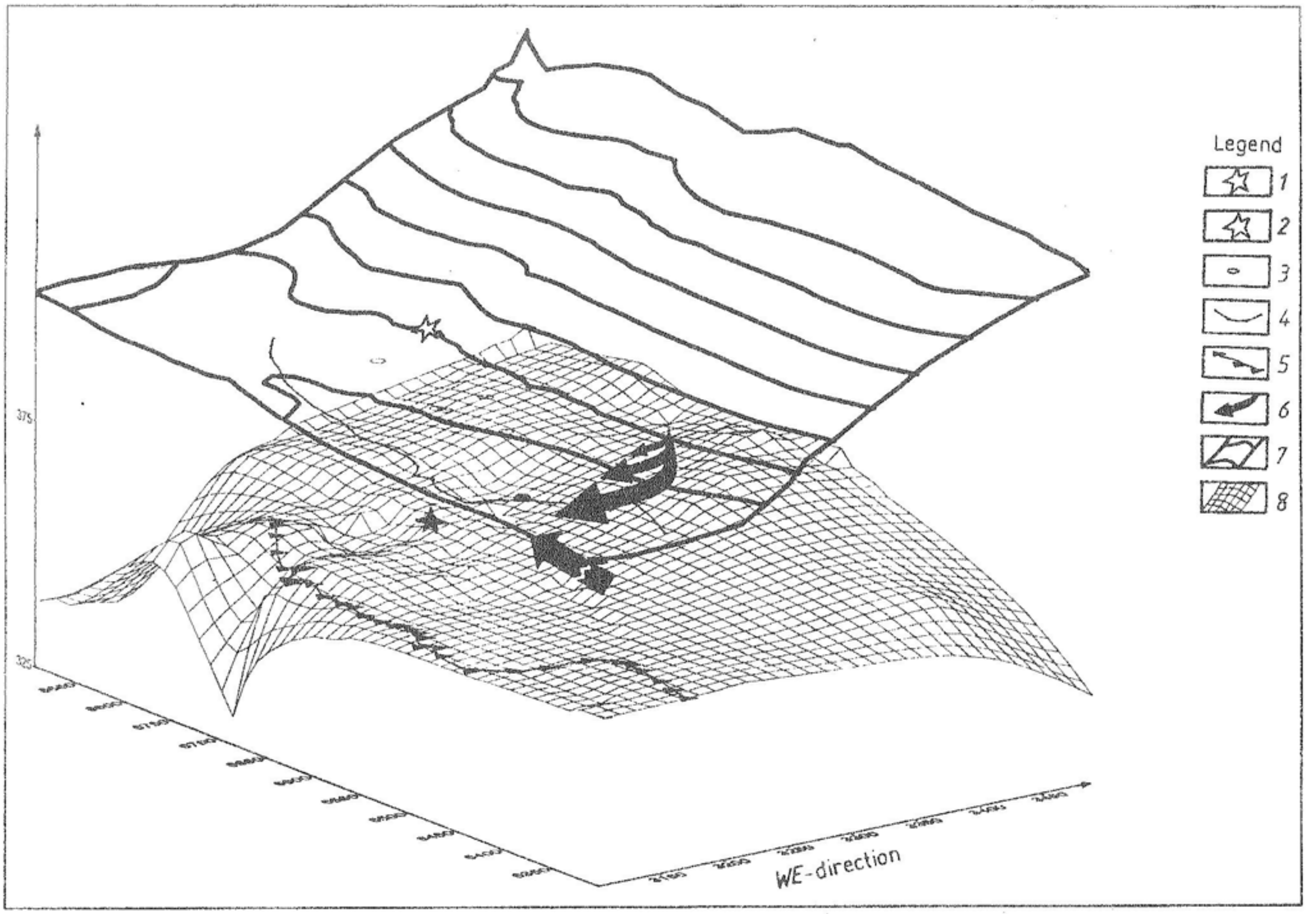


Fig. 2. Block diagram illustrating the position of the salt body with respect to the ground surface. 1. position of the Unirea mine shaft at the surface; 2. intersection of the Unirea mine shaft with the back of the salt; 3. suffosion sinkholes; 4. the Slănic streambed; 5. projection of the Slănic stream on the salt body; 6. inferred infiltration supply directions; 7. isohypses; 8- the salt topography.
Représentation tridimensionnelle du block de sel par rapport à la surface topographique. 1. la position du puits Unirea à la surface; 2. point d'intersection entre le puits Unirea et la surface du block de sel; 3. dolines de suffusion; 4. la rivière de Slănic; 5. projection de la rivière de Slănic sur la surface du sel; 6. directions supposées des infiltrations; 7. contours de la surface; 8. surface de sel.

The electrometric survey performed over successive traverses south of Unirea mine outlined distinct water flow paths which run along a N-S direction (probably concentrated at conduit level)[2]. Within a year time span, several collapse sinkholes, 2–4 m in diameter and of 2.5 m maximum depth, developed above. The series of measurements performed successively at certain time intervals have proven the unstable character and the very fast evolution of those drainage corridors.

The drilling of a dense network of wells (327, out of which 43 piezometric wells), which surround the main shaft of Unirea mine, supplemented with geoelectric, piezometric, thermometric and hydrochemical measurements, filled up the hydrogeologic image of the area, to result in the following conclusions:

1. The water bearing properties of the covering formations are quite diverse. The permeabilities vary over a wide range, being the largest in the terrace deposits and close to nil in the detritic-mudstone facies on the salt back.
2. The salt massif can be regarded as an impervious body. Provided that no open cracks exist, the underground drainage takes place on the salt/debris interface, or in its close neighborhood, as a result of cracks becoming active; the flow rates along such lineaments can reach 12 l/s.
3. The mining works have opened within the massif body a drainage level located very deep beneath the local erosion level at the ground

[2] GEORGESCU *et al.*, (1996) *Deep detail electrometric measurements in the area of Unirea shaft and of the eastern slope.* (unpublished report).

surface, drainage level that may collect the groundwater flow, provided that a network of cracks occurs, to generate an efficient flow path between the surface and the latter. Such a cracks network is currently developing within Unirea mine, induced by mechanic disequilibria due to the salt extraction and, most probably, by some activities at the ground surface.

4. The evolution of the karst-saline processes is extremely fast and it is mirrored at the ground surface by slow suffosion processes and by the occurrence of sinkhole type landforms.
5. Within some of the old salt mines, which at present have become lakes, there have been identified certain levels of a more fresh water occurring at depths up to 25–30 m (the limit down to which divers could reach), supplied by surface infiltration; they prove that once established, a karsto-saline drainage can be sustained.

INFILTRATION IN UNIREA MINE

The flow rates infiltrated in the mining works have been tapped in a collecting channel provided with a 30° weir box and a limnigraph, at the level of the deepest excavation (–230 m). Over the time interval March-June 1995, the flow rates displayed a variation range of 3.35 l/s (between 0.47 and 3.82 l/s). While the water gauging was performed, wells were drilled for injecting cement, in order to make the debris/salt interface impervious. The separation of the two components on the flow rates regime diagrams indicated the following results:

- the natural variations ranged between 0.47 and 1.15 l/s;
- on the flow rates diagrams several peaks induced by the drilling activity have been recorded, which indicates that karst passages of high drainage capability had been intercepted;
- the additional flow rates originating in the drilling fluid varied as a function of the depth of the hole and of the position of the well with respect to the Unirea mine shaft, the hill slope and the Slănic stream. The largest values were recorded during a 3 hours interval, in a period deprived of rainfall (42.6 m^3, of which 28.8 m^3 were supplied by the well which was drilled at that moment).
- there has been identified a weak dependence of the underground seepage on the rainfall, with a 16 days delay, and no correlation with the discharge of Slănic stream could be substantiated.

ASSESSMENT OF THE CL^- CONCENTRATIONS IN THE WATER OF THE PIEZOMETRIC WELLS

One of the investigation assumptions was that different Cl concentrations may delineate areas or lineaments with different hydrodynamic characteristics. The analysis method has taken into account the fact that the analyzed groundwater, that from a chemical point of view is characteristic to the aquifers that adjoin the diapiric structures, belongs to the type of multi-component solutions with a very high concentration. The assessments performed on samples collected from the piezometric wells grid, in a section of the hole which corresponds to the debris/salt interface, outlines a status of undersaturation with respect to halite at all the investigated points, being recorded a trend of water saturation with respect to mineralisation according to an exponential law.

The obtained chloride concentrations have been used in preparing a contour map, which suggests the following (Fig. 3):

- a general trend of increase of the Cl^- concentration, from all directions toward the Unirea shaft;
- the clustering of the high concentration values in the salt topography depressions (123.3–155.8 g/l Cl^-) or in the plateau areas (122.8–161.8 g/l Cl^-);
- the steep "slope" of the contours indicates the large variation of the concentrations over relatively short distances, which would correspond to a negligible inflow and a slow flow that secures a high dissolution rate, which is opposite to the small slope areas, that are due to a significant inflow and a fast flow.
- Unirea shaft occurs between the 80 and 90 g/l Cl^- contours and is surrounded by three areas of larger concentrations: to the west F6–F8 (>120 g/l Cl^-), to the north F13–F15 (>140 g/l Cl^-), and to the east F39–F55 (>139 g/l Cl^-). The low concentration areas are located around the wells F4 (<30 g/l Cl^-) and F14 (<50 g/l Cl^-). Under these circumstances, by assuming that the inflow areas are those with low concentrations and that the flow direction is from a small concentration toward a larger concentration, it can be inferred that the main supply area is situated to the south, while the fastest flow direction is that traced by the wells F53, F47, F8, F19. The areas around the wells F4 and F14 are inflow areas of only secondary interest.

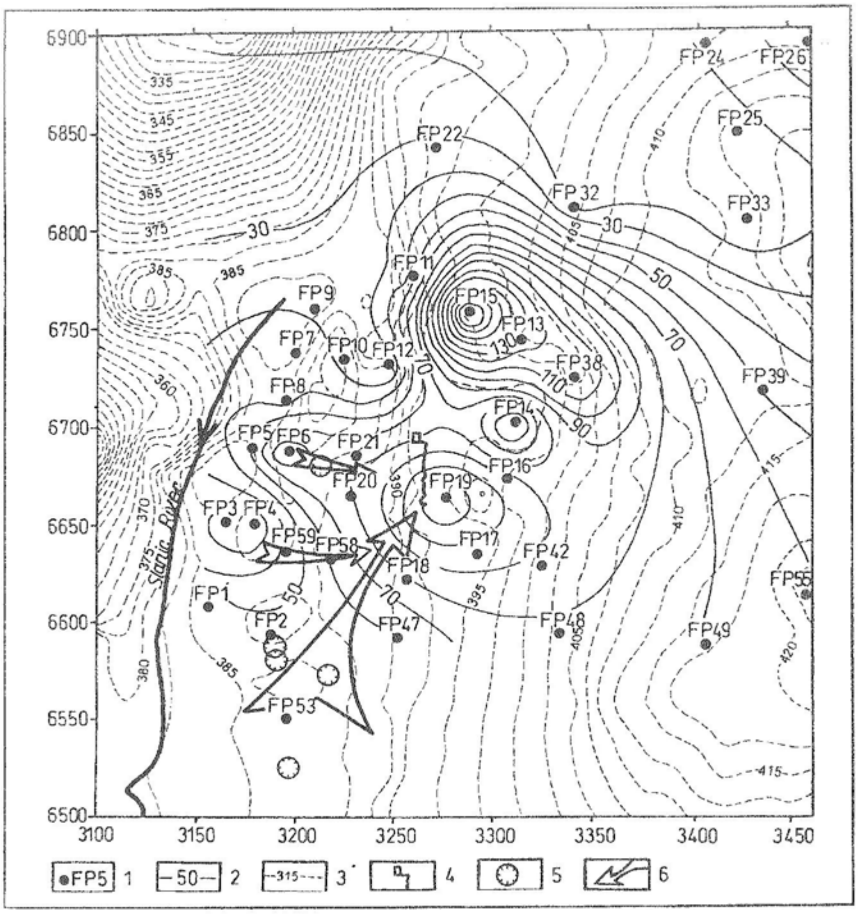


Fig. 3.

Distribution of the NaCl content contours on the 15 October 1996. 1. piezometric well; 2. NaCl content contour; 3. back salt contour; 4. Unirea mine shaft; 5. sinkhole; 6. probable flow directions.

Contours du contenu en sel le 15 Octobre 1996. 1. Piezomètre; 2. Contours du contenu en sel; 3. Contours de la surface de sel; 4. Puits minier Unirea ; 5. doline; 6. directions probables d'écoulement.

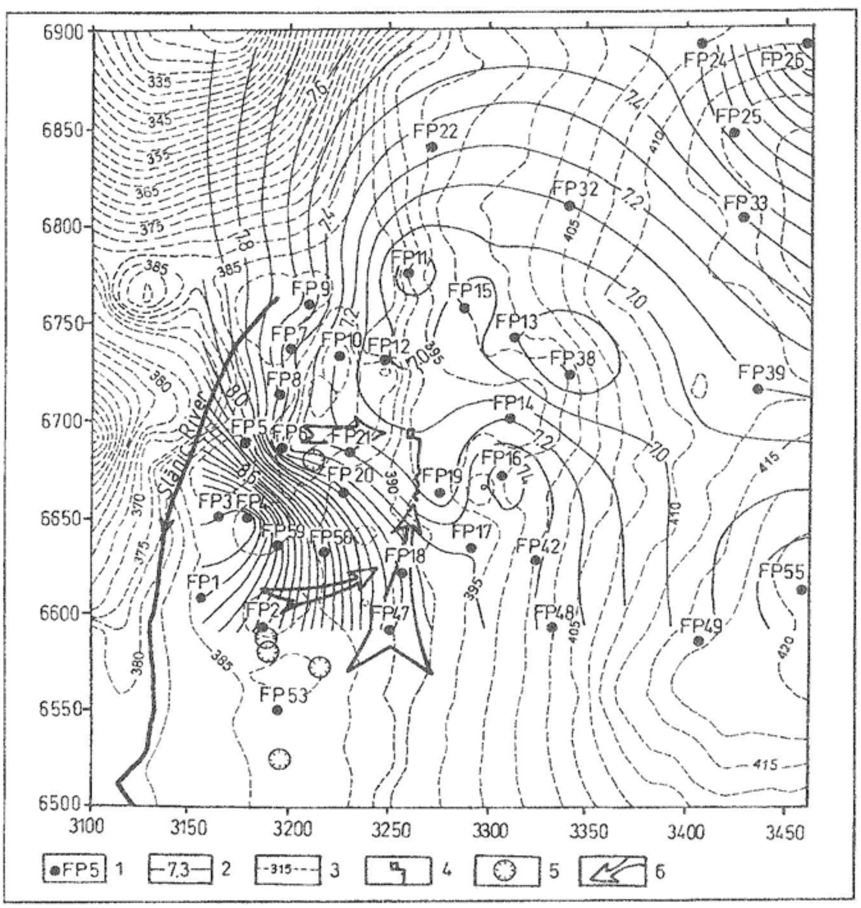


Fig. 4.

Groundwater temperature distribution on the October 15, 1996, based on measurements performed in piezometric wells. 1. piezometric well; 2. isotherm; 3. back salt contour; 4. Unirea mine shaft; 5. sinkhole; 6. probable flow directions.

Distribution des températures le 15 Octobre 1996 d'après les mensurations en forages piézométriques. 1. Piezomètre; 2. Isothermes; 3. Contours de la surface de sel; 4. Puits minier Unirea ; 5. doline; 6. directions probables d'écoulement.

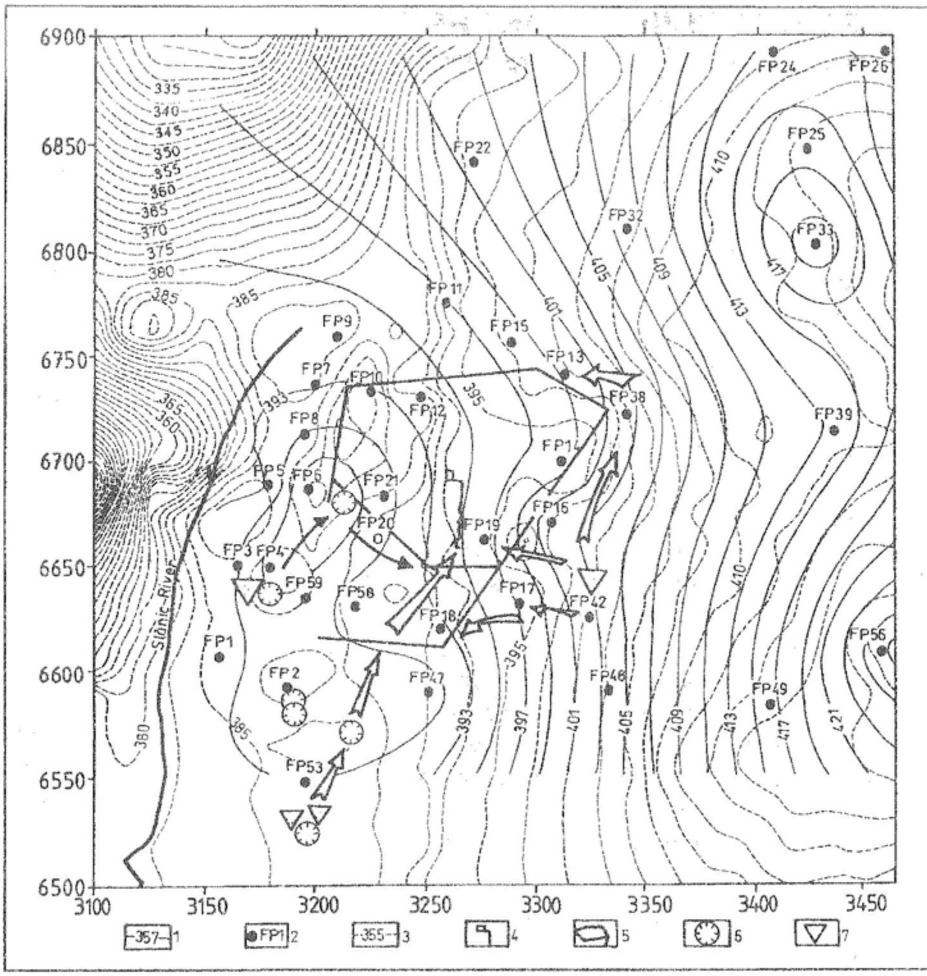


Fig. 5.

Groundwater flow directions established by means of tracer experiments. 1. Piezometric wells; 2. Piezometric contours; 3. Back salt contours; 4. Projection of Unirea mine shaft and the tapping gallery; 5. Cement injection lines; 6. Suffosion sinkholes; 7. Tracer launch-point; 8. Flow directions.

Directions d'écoulement souterrain établies à l'aide des traçages. 1. Forages piézomètriques; 2. Contours piézomètriques; 3. Contours de la surface de sel; 4. Projection du puits Unirea et de la galerie de captage; 5. Lignes d'injection du ciment; 6. Dolines de suffusion; 7. Point d'injection du traceur; 8. Directions d'écoulement.

TEMPERATURE MEASUREMENTS IN PIEZOMETRIC WELLS

Simultaneously with collecting water samples in the piezometric wells, temperatures at the salt/debris interface have been also measured, by means of a 0.01°C resolution and 0.05°C accuracy thermometer. There have been performed two sets of measurements (October 25, 1996 and November 14, 1996), that have been used to prepare water temperature contour maps. In interpreting the latter it was assumed that a slow flow provides the necessary time for obtaining an equilibrium between the water and the rock, while a fast flow, that involves more important flow rates, will engender visible alterations with respect to the local background of the groundwater temperature. The analysis of the temperature contours in Figure 4 indicates that:

- the temperature increases toward all directions, starting from the axis that connects the wells FP11, FP13, FP38 and FP55; the minimum temperature has been recorded in F55 (6.3°C), while the maximum one in F4 (9.5°C);
- the wells that parallel Slănic stream (FP1–FP9) display the largest deviation with respect to the background, induced, most probably, by a groundwater inflow from the streambed;
- the thermal maxima in the wells FP3 and FP4 outline a local inflow of constant flow rate and temperature;
- along the lineament traced by the wells FP47—FP18—FP19 occurs the transition from a steep slopes area, situated to the west, to the area of reduced slopes, indicative of a thermal equilibrium, located to the east;

It results that the thermally stable areas, i.e. those which are weakly influenced by the external stimuli, occur next to the wells FP13, FP12 P39, and that the areas undergoing a significant superficial supply correspond to the Slănic streambed, west and south of Unirea mine.

(EXISTING) CIVIL ENGINEERING WORKS FOR COUNTERACTING THE INFILTRATION

In order to isolate the main shaft against infiltration originating on the back of the salt massif, sealing curtains have been performed, in successive stages, by injecting cement at the salt/debris contact area. They have been placed perpendicularly on the inferred or previously proven supply directions and in the end have "closed" the shaft on every side.

TRACER EXPERIMENTS

The check of certain results obtained by previously discussed methods has been made by means of three tracer experiments. There has been used fluorescein, rhodamine and potassium bicromate, injected in two wells that exhibited permeability coefficients larger than 2 m/24 h and in a sinkhole recently formed at the ground surface, south of the mine shaft (Fig. 5). The tracers arrival has been monitored in the piezometric wells network, as well as in the underground, in the mining works. The tracer experiments have outlined the following:

- the sealing curtains divert the ground water flow along them and induce flow rates concentration at their extremities, thus favoring the process of concentration into well developed drains. In the areas with reduced sealing effect there occurs also a process of undertraversing by means of conduits excavated in the salt;
- along a north-south direction (marked by the wells FP47—FP18—FP19), the underground flow has average theoretical velocities of 230 m/h or larger, which can be only a result of the presence of well developed karst conduits.

CONCLUSIONS

1. Infiltration into Unirea mine does not originate in a single source. It results from adding various water volumes which flow mainly from the south, most probably from the Slănic stream loop, and in subsidiary from the aquifer that is developed on the left side of the valley, and, most probably, also from the west. The conceptual model concerning the organization of the drainage toward the shaft is simple: a north-south directed conduit, marked at the surface by collapse sinkholes; this conduit also collects the water diverted toward the southwest by the sealing curtain.
2. The groundwater flow directions are not equal: the maximum values are recorded along the conduit, where they reach 238 m/h. Such a value is characteristic to a free surface flow, which, under the circumstances of the high salt solubility induces a fast descending evolution, having as a result collapse processes at the ground surface. As a consequence the soil stability is endangered mainly along the direction the conduit is developed and in its immediate neighborhood.
3. The sealing curtain has limited efficiency, being impervious only over certain sections. By tracing the groundwater flow it resulted that the curtain is pierced or crossed in some areas on its east, south and west sides. We believe that such a technical solution provides only a temporary remedy in the case of a saline karst.
4. The groundwater flow directions that are not influenced by the sealing curtain reasonably correspond with the topography of the salt back.
5. The assessments performed over water samples collected from the piezometric wells indicate a status of undersaturation with respect to halite at all sampling sites, the trend of water saturation with respect to the mineralisation following and exponential law. This means that dissolution is active along all the flow directions.
6. The –230 m level of the Unirea mine must be regarded as the level toward which the groundwater flow is directed. Since close to the mining works the massif is subject to active fracturing, there is a permanent hazard that a network of fissures connecting the salt back with the underground excavations is intercepted.

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